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Lessons Learned in Risk Management on NCSX

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***Abstract*— The National Compact Stellarator Experiment (NCSX) was designed to test physics principles of an innovative stellarator design developed by the Princeton Plasma Physics Laboratory and Oak Ridge National Laboratory. Construction of some of the major components and sub-assemblies was completed, but the estimated cost and schedule for completing the project grew as the technical requirements and risks became better understood, leading to its cancellation in 2008. The project's risks stemmed from its technical challenges, primarily the complex component geometries and tight tolerances that were required. The initial baseline, established in 2004, was supported by a risk management plan and risk-based contingencies, both of which proved to be inadequate. Technical successes were achieved in the construction of challenging components and sub-assemblies, but cost and schedule growth was experienced. As part of an effort to improve project performance, a new risk management program was devised and implemented in 2007-08. It led to a better understanding of project risks, a sounder basis for contingency estimates, and improved management tools. Although the risks ultimately were unacceptable to the sponsor, valuable lessons in risk management were learned through the experiences with the NCSX project.**

Keywords –stellarator, NCSX, risk, management

I. THE NCSX PROJECT

The National Compact Stellarator Experiment (NCSX) was designed to test the physics of a compact, quasi-axisymmetric stellarator (QAS) configuration.[1,2] The QAS uses three-dimensional stellarator magnetic fields for steady-state, disruption-free operation but has a tokamak-like magnetic field symmetry in magnetic coordinates. A steady-state QAS reactor would have a net toroidal current due to the bootstrap effect but would not require externally-driven current profile control, nor active feedback control of ELMs and other instabilities. The NCSX design and construction project was undertaken as a partnership between Princeton Plasma Physics Laboratory and Oak Ridge National Laboratory.

The NCSX design was based on a magnet configuration that was generated by a numerical optimization process to provide plasmas with attractive physics properties within engineering feasibility constraints. The three-period magnet system consisted of 18 modular coils (six each of three different shapes), plus toroidal field, poloidal field, and trim coils. The modular coils and plasma are depicted in Fig. 1. The major radius R is 1.4 m, the aspect ratio $R/\langle a\rangle$ *is 4.4,* the magnetic field on axis B_0 is ≤ 2 T, toroidal currents I_P up to 320 kA are supported, and the pulse length is 0.5 to 2 s depending on the magnetic field strength.

Accurate realization of the magnetic configuration was a key NCSX requirement, one that has been achieved in the construction of previous stellarators, e.g., HSX[3], Wendelstein 7-AS[4], LHD[5] and ATF[6], as well as Wendelstein 7-X[7] (under construction). Comparable accuracy requirements apply to tokamaks, including ITER.[8] Of greatest concern for NCSX were low mode-number resonant magnetic field perturbations which can produce islands at magnetic surfaces where the rotational transform goes through rational values. The project's strategy to minimize resonant field errors in design and construction consisted of:

- Accurate construction (tolerance on the completed modular coil system ±1.5 mm, or ~R/1000 as is typically achieved in stellarator construction)
- Low magnetic permeability ($\mu_r < 1.02$ for components close to the plasma).
- Low eddy currents (material choices; insulating breaks in

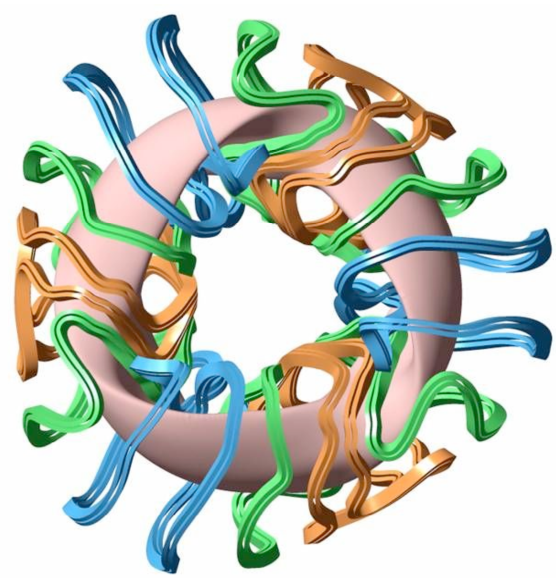

Fig. 1. Modular coils and plasma configuration.

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structures)
- Low stray fields from coil leads, feeds, crossovers.
- Stellarator-symmetric design.
- Minimization of coil deflections under load.
- A system of trim coils for field error control.

The complex coil geometry and the accuracy requirements, especially the fabrication and assembly tolerances, were recognized from the outset as major technical risk factors.

A self-consistent design (Fig. 2) satisfying all mission requirements was presented in 2003. Construction began in 2004 but was terminated by the sponsor in 2008. By then, with the project about half complete as a result of significant technical accomplishments[9], the estimated cost at completion had increased by about 70% and the forecast completion date had slipped by about 4 years. A major factor, perhaps the dominant factor, in the cancellation decision was the lingering uncertainty, well into the construction phase, in the cost and schedule forecasts. The project was unable to meet the sponsor's expectations for cost and schedule predictability; hence its failure was in essence a failure to adequately manage the risks. This paper, written by responsible members of the project's management team, presents an analysis of NCSX risk management efforts with lessons learned based on project experience and results

II. Design Measures to Mitigate Technical Risks

The engineering design of the modular coil array was based on a thick-section shell-type structure, with the coils supported on the inside surface, to minimize the risk of deflections under operating conditions (Fig. 3). The entire magnet system was designed to be pre-cooled to cryogenic temperature (80 K) with heat removed between pulses. This robust

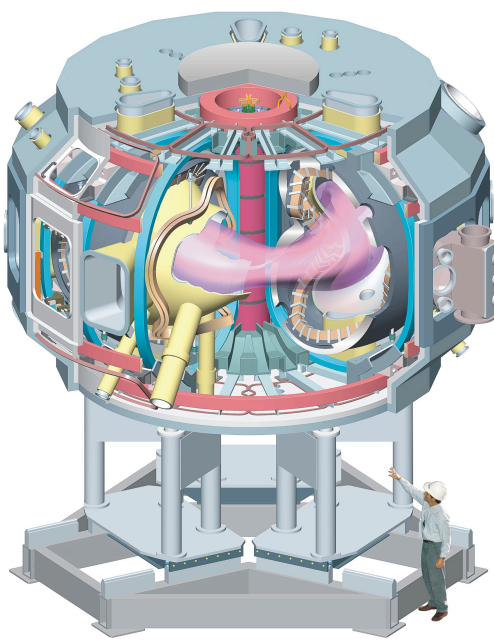

Fig. 2. NCSX stellarator device design (CAD model).

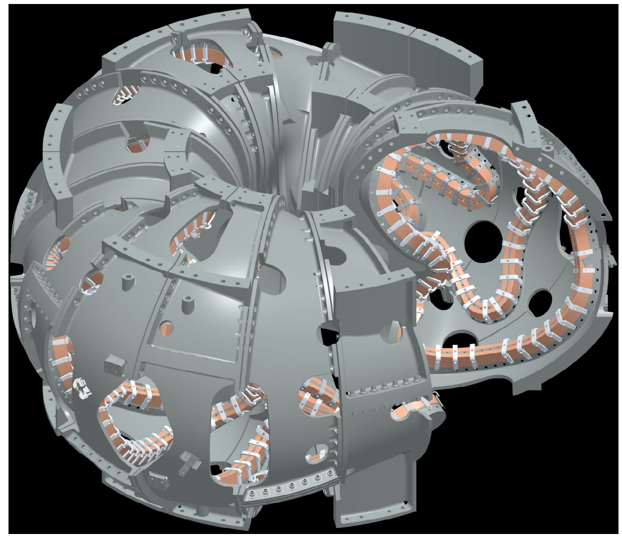

Fig. 3. Modular coil system design.

concept was adopted in the early design stages to minimize the risk of concept failure (which would have had enormous schedule consequences) as the design development progressed and the requirements became better understood. The modular coil shell was divided into eighteen sectors, one per coil. The coils were wound directly onto accurately machined support features on these shell sectors, called modular coil winding forms (MCWF, Fig. 4). The coils were wound with copper conductor and then epoxy-impregnated. (Fig. 5) All 18 modular coils were fabricated.

The NCSX vacuum vessel was designed to provide as much interior volume as possible to minimize the risk of encroachment into the plasma. The size was limited by the minimum assembly clearance (5 mm) required for installation of the modular coils over the vessel sectors (with ports removed). This resulted in a vacuum vessel shell (Fig. 7) with a non-axisymmetric shape that resembles that of the plasma and which had to be realized within ±3 mm accuracy. The vessel was constructed in three identical sectors, one per field period.

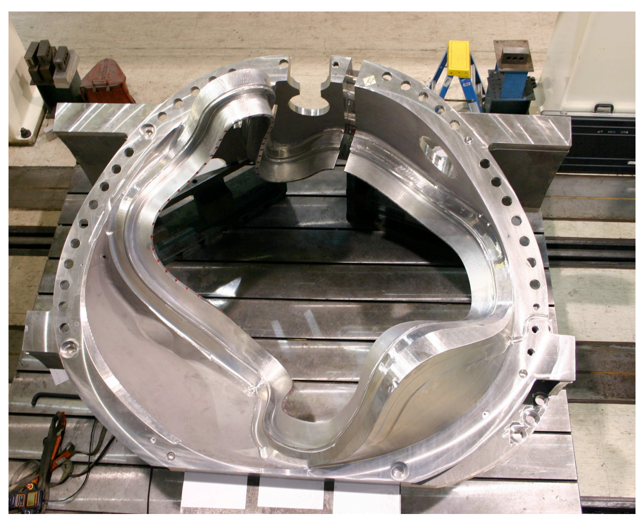

Fig. 4. Modular coil winding form.

Fig. 7. Vacuum vessel sector with installed service.

Inconel was chosen as the vessel material to reduce magnetic permeability and eddy current risks. Fabrication of all three sectors and their associated ports, and installation of external services (e.g., cooling lines), were completed.

The machine assembly plan was based was on the construction of three modules, or field periods. The critical field period assembly steps are illustrated schematically in Fig. 8. The completed modular coils are first assembled into half-period subassemblies of three coils each, two of which are installed over a vacuum vessel sector, complete with insulation and other installed services. After installing ports and outfitting the three field periods with additional equipment, they would be brought together and joined to complete the torus assembly. Due to the stringent tolerance requirements, sophisticated metrology systems and frequent measurements were needed throughout the fabrication and assembly processes in order to ensure compliance. The cost and schedule impacts of metrology operations and the associated engineering analysis activity proved to be a major cause of cost and schedule growth (a risk that was recognized but under-appreciated at the project outset). During the design process and, later, when evaluating the vacuum vessel inspection data against acceptance criteria, CAD simulations of coil installation over the vacuum vessel with its installed services were performed to reduce risks of interferences during assembly. Special assembly tooling including a novel guidance system was designed and fabricated to further reduce those risks. Two half-period coil subassemblies were fabricated and a trial installation of a half-period over a vessel sector were completed.

A system of trim coils, consisting of 48 rectangular coils arranged around the machined, was planned for controlling field errors. Monte Carlo simulations of potential construction errors, i.e. displacements of coils and subassemblies from their nominal positions, and an inventory of field errors from known sources such as coil leads, magnetic materials, etc., were used to set requirements. Analysis showed that the coils could reduce magnetic islands to acceptable size in the presence of simulated and known construction errors. A safety factor of at least 2 in the required current could be provided cost-effectively, providing extra margin that could be used if necessary to compensate for out-of-tolerance construction errors. Trim coils thus provide the option of accepting such variances and avoiding the costly and time-consuming re-work needed to correct them. In this sense, trim coils offered a means of mitigating cost and schedule risks during construction and performance risks during operation. Their potential was not fully explored, however, before the project closed.

III. Management of Project Cost and Schedule Risks

A. Establishment of Project Baseline, 2004

The project cost and schedule baseline was established in February, 2004 following a preliminary design review and two cost and schedule reviews in the Fall of 2003. At that time, the top-level project requirements were well established (and remained stable thereafter) and engineering design development had been in progress for about three years. Subsystem designs varied in their degree of maturity, with the modular coils and vacuum vessel having received the most attention due to their high technical risks, and therefore being the most advanced. The estimates for those components were supported by manufacturing and cost studies performed by competent industrial suppliers. Prototypes had not yet been manufactured, but in view of the recognized technical challenges, well-defined plans for manufacturing process development and prototype fabrication by competing suppliers were included in the project baseline. Assembly planning was at a conceptual level.

The project's baseline was accompanied by a risk management plan that established line responsibilities for risk management and defined the project's program for identifying, mitigating, tracking, and retiring risks. The plan was not quantitative, however, in that there was no provision for assessing the probability of a risk occurring, nor its cost and schedule consequences if it did occur. The plan did recognize the risk of cost and schedule overruns due to many factors. Design delays, with attendant cost growth, had a been a problem throughout conceptual and preliminary design and were seen as a continuing risk. The cause was attributed to the difficulty of the design itself, which had challenged the technological

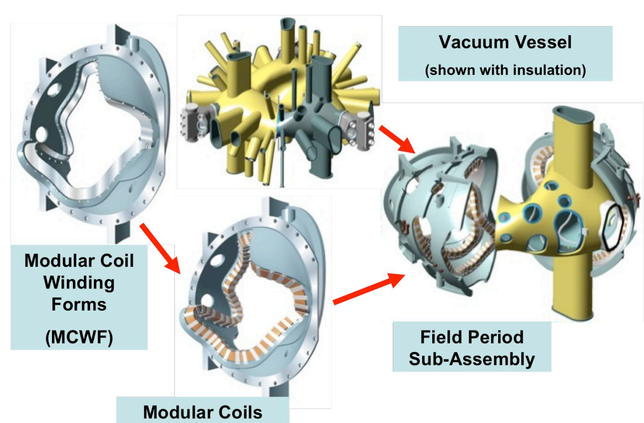

Fig. 8. NCSX Field Period Assembly Schematic

limits of even the most powerful computer-aided design (CAD) tools in the hands of highly skilled design engineers. Unforeseen time extensions had been required to overcome such limitations. Fabrication risks were also expected, since it was foreseen that the design would challenge the tools and experts in manufacturing and inspection as it had in design. The mitigation plans included a vigorous system engineering program, a manufacturing R&D program involving qualification of competing suppliers, and contingency. Notably, assembly risks were not identified. This was because the assembly process design had not matured enough to make the risks apparent and because assembly risks were judged, based on past experience, to be small in comparison with the manufacturing risks associated with the modular coils and vacuum vessel.

The project baseline included a cost contingency of 28% and a schedule contingency of 5 months (~10%) to help manage risks. The cost contingency was developed by rating each work package on an industry-standard "risk factor" scale, based on the novelty of the design, impact on the critical path, and the quality of the basis of estimate (i.e., catalog price of an off-the-shelf item *vs.* engineering judgment of a highly developmental design). The maximum work package contingency was 40%. Schedule contingency was based on management judgment and experience with previous, albeit less complicated, projects. In summary, while the cost contingency was developed using a bottom-up "risk-based" methodology, the contingency estimates were not based on a detailed quantitative analysis of risk consequences.

B. Project Execution, 2004-2007

Following sponsor approval of the baseline budget and schedule, the project proceeded immediately with its R&D plans for the modular coils and vacuum vessel, and it continued to develop the engineering design of the system. All costs, including R&D, were charged against the project budget; there was no separate budget for development costs.

The manufacturing R&D program for the modular coil winding forms (MCWF) and the vacuum vessel segments was technically successful. [10] Competing suppliers developed detailed manufacturing plans, built prototypes, and produced sound proposals for production. Similarly, PPPL developed processes for modular coil fabrication, produced a demonstration coil, and estimated production costs and schedules. [11] Using the processes developed through these R&D activities, the project and its suppliers went on to fabricate the vacuum vessel and all modular coils in accordance with project requirements. However, the cost of these three R&D/prototyping activities themselves exceeded the baseline estimate by 34% [12] even though a crucial prototyping operation, MCWF machining, was cancelled by the project. (It was decided instead to defer machining process development to the production phase.) Moreover, the experience of fabricating actual prototypes showed that the baseline production cost estimates were low. Ultimately, the actual cost to the project for production of these components exceeded estimates by 90% and 60% for the modular coils and vacuum vessel, respectively, [12] and the critical path was impacted by several months. Significantly, process development for MCWF machining, the only major operation that had not been prototyped, accounted for most of the schedule delay.

The project continued to encounter challenges in its design activities, resulting in cost overruns and schedule delays. Design costs for the modular coils, toroidal field coils, and vacuum vessel exceeded baseline estimates by 210% [12]. More importantly, the attendant delays in these tasks kept the project's top design engineers from moving on to other problems, for example the design of critical interface hardware and assembly processes. Although the partnership arrangement between PPPL and ORNL provided valuable flexibility in meeting engineering staffing needs, the project was unable to retain all of its key engineers for such protracted periods in the face of higher-priority needs for their services elsewhere in the fusion program.

Faced with these challenges, the project nevertheless sought to manage its cost and schedule risks. Broadly speaking, cost risks were managed by deferring to the operations phase any scope that could be deferred without compromising the safety of the machine or personnel, or the ability to satisfy end-of-project acceptance criteria. Even so, cost contingency had to be drawn at an unsustainable rate. Schedule risks were managed by giving priority in the allocation of funds to keeping current critical path fabrication activities on schedule (e.g., the use of double-shift operation in modular coil fabrication). For a time, this strategy succeeded in meeting high-level milestone commitments on schedule and maintaining the schedule contingency at 5 months. However, after critical-path needs were met, the remaining funds were insufficient to keep design work on schedule, especially after the project's year-to-year funding profile was reduced in 2005. This led to a delay of nearly one year in the start of critical-path assembly operations in 2007. These delays were not foreseen because the project's risk management approach did not focus adequately on the risks in future work.

During this period, the project used a relatively simple critical issues tracking list as its main risk management tool. This was a living document which management used to ensure visibility of, and attention to, project risks. Newly recognized risks were added to the list, mitigation plans were documented and implemented, status was updated approximately quarterly, and risks were removed from the list when retired. It eventually became clear that this system was too informal, too qualitative, and too near-term focused to successfully manage the project's risks.

C. Risk Management Reforms, 2007-2008

In 2007, the project undertook an overhaul of its risk management program, one of several measures taken in an attempt to improve overall project performance. The critical issues list was replaced with a more complete, more detailed, and more quantitative risk register. More importantly, the risk register was used by the project team as a tool for systematically improving: 1) identification and assessment of risks; 2) mitigation of risks; 3) establishment of risk retirement deadlines; 4) quantification of risk cost and schedule consequences as a basis for contingency estimates; and 5) tracking of risks to retirement. Detailed descriptions of the risk register mechanics and contingency analysis methodology are provided elsewhere [13]; here we focus on the management aspects.

Risk identification. The whole project team became involved in identifying risks. The risk-identification exercise was coupled with a bottom-up analysis and re-estimate of all remaining work, an ideal context for simultaneously conducting a thorough risk assessment. A series of brainstorming meetings was efficient in taking advantage of the team's mature (by then) understanding of project risks. The interaction was vital for ensuring that past cost and schedule problems were considered in evaluating future risks, and for making work package managers aware of problems arising in other areas which could affect theirs. For example, assembly managers gained a full appreciation of the costs and risks associated with metrology only after understanding the metrology problems experienced in modular coil fabrication. Difficulties in design often foreshadowed difficulties in fabrication. The risk register entries included a description of the risk; the impacted work packages if the risk were to occur; and the risk "owner," the individual responsible for tracking the risk.

Risk mitigation. As risks were identified, mitigation plans were identified and entered in the risk register. The associated work (e.g., R&D, analysis, testing) was estimated, budgeted in the appropriate work package (not necessarily the impacted work package), and assigned to a responsible individual.

Risk retirement deadlines. While the goal is to retire risks and avoid their impacts, it is recognized that risk mitigation plans might not always fully succeed. In that case, the residual risk consequences must be accepted and incorporated into the project baseline. For each risk, a retirement deadline (usually a scheduled event such as a design review or the start of a particular assembly operation) was established and entered in the risk register. If the risk were not retired by the deadline, project management was prompted to make a decision to either apply contingency in order to absorb the consequences or, if warranted, to extend the deadline.

Risk quantification as a basis for contingency estimates. Each identified risk was assessed in terms of its likelihood of occurrence, from not credible (probability of occurrence <1%) to very likely (>80%), taking into account any mitigation plans. Also assessed were the cost and critical-path schedule impacts if the risk were to occur. These estimates and their basis were entered in the risk register. They provided quantitative input to a probabilistic analysis that was used to estimate the cost and schedule contingency required to manage risk. (A related analysis was performed to estimate the contingency required to cover estimating uncertainty).

Risk tracking. Once an adequate risk register was established, it was actively maintained as a living document and used as a risk management tool. Monthly earned-value status meetings with work package managers were expanded to also cover risk status. Risk owners provided monthly updates on the status of their risks and any mitigation activities. It was found that risk likelihoods tended to decrease from month to month, as concerns abated with experience and as risk mitigation activities progressed.

Results. In April, 2008 the project presented a new bottom-up estimate for completing the project, including cost and schedule contingencies of 36% and 19 months (40%), respectively. Risk accounted for cost and schedule contingencies of 15% and 12 months (25%), respectively; the remainder was due to uncertainty. The larger relative contingencies (as compared with the original baseline) reflect a greatly improved understanding of the project work requirements and associated risks as a result of design advancements and fabrication experiences, as well as improvements in risk assessment and contingency analysis. Improved understanding also led to increased estimates of the cost and time duration for completing the remaining work. Unfortunately, the rising trends in the recognized risks and costs were unacceptable to the sponsor and led to the decision to close the project.

While the new baseline was not accepted, the project was allowed to complete certain tasks after the cancellation decision. This provided an opportunity, albeit limited, to implement the new risk management program for a few months. Coil production was nearing completion at the time of cancellation and was thus assessed as a low-risk activity by then. Completion of the work was routine. However, the assembly of three-coil half-period modules was just beginning and had multiple risks due to the many technical challenges in meeting the ±0.5 mm assembly tolerance allocated to that step. The project was able to complete two modules within tolerance before final project closure, and in so doing retired several of the risks. The overall cost risk in completing the remaining four half-period modules was reduced by 70% and schedule risk was reduced by 100% as a result of completing these two modules. The project was also able to trial-install a half-period module over one of the vacuum vessel sectors, resulting in cost and schedule risk reductions of 25% and 20%, respectively, in the coil-to-vessel assembly step. The total number of risk register items was reduced from 94 to 65.

IV. Lessons Learned

The NCSX project achieved important technical successes, including the fabrication of major components and subassemblies with complex geometries, meeting stringent tolerance requirements. Risk reduction strategies incorporated into the design and R&D planning succeeded in a technical sense. Prototyping reduced the risks in complex manufacturing processes in advance of production; when prototyping was not performed, adverse cost and schedule impacts resulted. Cost and schedule performance was not satisfactory, in part because the project's initial risk management program was inadequate. Important risk management lessons were derived from both the success and failures on NCSX. The project sought to incorporate these lessons in a new baseline, including an improved risk management program, for completing the project. Unfortunately, there was little opportunity to test the efficacy of these reforms. However, it seems likely that they were a step toward improved visibility and management of risks and more predictable outcomes. We summarize the lessons learned in the expectation that they may be valuable to other high-risk projects.

1. Adoption of a design concept that is robust against the uncertainties that exist in the early stages of a project is an effective risk mitigation strategy.
2. Manufacturing R&D, including the fabrication of prototypes, is an effective strategy for reducing risks and improving estimates for production.
3. Trim coils can be used to compensate for field errors due to construction errors and to control island widths, according to magnetic analysis. Given the importance of magnetic field accuracy in toroidal device design and the high cost of meeting stringent tolerance requirements, trim coils have the potential for mitigating cost and schedule risks during construction and performance risks during operation. Their potential should be more fully explored.
4. Adequate engineering staffing, especially in the design and R&D phases of a project, is critical for advancing the understanding of risks and costs as rapidly as possible. (The Wendelstein 7-X team drew similar conclusions.[14]) Conversely, the possibility of losing engineering staff, especially key individuals with unique or specialized skills, can be a risk with significant cost and schedule consequences.
5. The completeness and accuracy of risk assessment grows with design maturity and fabrication experience. Early risk assessments may miss or underestimate project risks. Risk assessment must continue throughout the project to ensure that emerging risks are recognized and managed. Ideally, complete as much of the design and R&D as possible before committing to an estimate.
6. An up-to-date understanding of requirements, costs, and risks in all of the remaining work to complete the project must be maintained and must be used to support risk management decision-making. Too near-term a focus may yield near-term successes at the cost of major downstream failures.
7. A risk register, tabulating risks along with their consequences, mitigation plans, owners, retirement deadlines, and current status, is most effective if developed early in the project, updated frequently, and actively used as a risk management tool. A documented, quantitative, bottom-up risk assessment provides a sound and defensible basis for estimating both cost and schedule contingencies at any stage of the project. It can be used to track risks and mitigation activities on a monthly basis and to inform management decisions.
8. Cross-work package communication is essential for risk assessment. Problems encountered in one work package may cause risks in another. Risks encountered in one work package may portend similar risks for other work packages, especially if similar technologies are used.

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