Appendix H

Lessons Learned

Number	Level	WBS	Success or Opportunity	Category	Description & Discussion
01	1	ALL	**S**	Safety	The attention to worker safety resulted in only 5 minor reportable minor injuries in over 550,000 hours worked. While we have a robust safety organization and up front Management buy-in, it came down to people not taking risks or short cuts in the name of schedule or cost. The safety culture at PPPL is one of its strongest assets.
02	1	1.7	**S**	Supervision	Work control center provided real value in establishing daily communication and coordination of field activities. Support needs (QC weld inspections, Safety support for walk downs, Health Physics) were determined in this daily 10 minute meeting. This process was established during the TFTR D&D project which was successful in finishing safely on schedule and $3.6M under budget.
03	2	1.1	**S**	Technology	Technology Risk: The project was not risk adverse on employing new processes or technologies to provide engineering solutions. The project utilized 7 fabrication and assembly techniques that benefited the construction of the new center stack magnet and vessel upgrade; (Ref Appendix ____ for detailed presentation) 1. Friction stir welding of copper was used to join high strength to high conductivity copper grades in the TF center bundle conductors. 2. A new non-ionic soldering process was developed. 3. Wire Electric Discharge Machining (EDM) was used in the manufacture of the critical TF High-Current Connector. 4. A carefully planned Vacuum Pressure Impregnation (VPI) process with hard metal molds were used to assure the strength and electrical integrity of the center stack. 5. Cyanate Ester / Epoxy Resin was chosen because of its maintenance of strength at elevated temperature. 6. Electron Beam Welding was used to manufacture the TF Lead Extensions and Passive Plate expansion connectors. 7. A water-soluble casting material, “Aquapour”, was used to maintain a thermal expansion gap between the center stack TF and OH winding. This process proved beneficial in winding the CS OH conductor, ***however,*** we were not able to remove the aqua pour as planned due to it being impregnated with epoxy. This setback resulted in a critical path schedule delay and will impose additional operational considerations. This presented PPPL with a sobering lesson learned opportunity. See next LL below.

Number	Level	WBS	Success or Opportunity	Category	Description & Discussion
04	1	1.1	**O**	Technology	Aqua pour affair. A water-soluble casting material, “Aquapour”, was used to maintain a thermal expansion gap between the center stack TF and OH winding. This process proved beneficial in winding the CS OH conductor, however, we were not able to remove the aqua pour as planned due to it being impregnated with epoxy. This setback resulted in a critical path schedule delay and will impose additional operational considerations Even though this event was postulated in the risk registry, we could have excised additional engineering due diligence to better understand the failure mechanisms that could result in the aqua pour being non removable. For example; while we did perform two R&D simulations we did not subject the process to the epoxy impregnation step. This would have flushed out a failure mode of epoxy migrating into the aqua pour area due to thermal expansion of the conductor and mold. A better sealing scheme perhaps could have been envisioned or this may have resulted in the abandonment of the aqua pour technique in favor of using a different boundary material. We need to better think through technical, fabrication and assembly risk and determine engineered mitigation plans. At the very least we could have had a better understanding of the cost and schedule impacts. It must also be pointed out that our project’s design underwent multiple external reviews with many outside labs participating so this is should not be looked at as a failure but an opportunity to take stock and learn. Root Cause: PPPL has very talented and experienced people having performed similar operations and fabrication tasks successfully in the past. This is good and the reason our projects are technically successful. However, experience and familiarity could easily turn into an air of overconfidence or “trust us we’ve done it before” mindset. We need to maintain a healthy dose of skepticism in evaluating our work. For example while we do have good design reviews perhaps we need to incorporate a failure modes and effects analysis. It’s the underlying human mindset we must recognize and change.
05	2	1.7	**O**	Management	KPP definition could be improved in the Project Execution Plan (PEP). Along with more clearly documenting scope contingency up front (At CD-2) we should define what CD-4 Project Completion will look like in PEP at baseline. A better defined CD-4 expectation could have helped the project and saved a lot of wasted energy in defining this with multiple stakeholders in real time.
06					(BLANK)

Number	Level	WBS	Success or Opportunity	Category	Description & Discussion
07	2	1.7	**S**	EVMS	EVMS the good; monthly statusing methodology adopted, CPR reports, change control mandated good discipline. EVMS an Opportunity; The requirement for written variance analysis reports provide little value to the project management office. Causes of cost and schedule variances were discussed real time during the formal monthly status meeting. Staffing issues that drove schedule slippages were resolved many times by the PPPL engineering division and department heads that were in attendance.
08	2	All	**S**	Policy/Procedures	Adherence to PPPL engineering procedures eng-033 provided discipline in the design process. However, the project provided additional requirements that; 1) provided for tracking and QA verification of design review chits and 2) Required calculations to be signed by the cog engineer whom was the ultimate customer
09	1	ALL	**O**	Loss of key personnel	Loss of our DCPS CAM (due to his sudden death) as well as the temporary loss of the Magnet CAM (due to lengthy illness) resulted in impacts to the project schedule as other stepped up to "fill-in". The secondary imp[act was an increase in project cost as lesser experience personnel took longer to come up to speed and carry on the work.
10	1	1.5	**O**	Personnel/Management	DCPS was a project unto itself and had too many conflicting "cooks" spoiling the soup. The specifications and requirements changed very late in the project after our main FDR. The functional organization stepped in and inappropriately communicated ways yet made key improvements to the requirements. Software was new and made use of new tools and languages not employed at PPPL much before. Teaming among the several branches of the project was very low and communication was at times poor or non-existent except that the COG who was gifted in many areas of this project held it all together. Unfortunately we lost this COG and had to make do. Yet, the effect of this loss on this team was a cautious yet palpable coming together to finish their own scope such that the system arrived on time. The false starts, rework, changes in direction early, and the overall inefficiency cost dollars and clock time but it came together in the end.

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11	1	1.1	**O**	Organization/Staffing	Better balance in assigning CAM's to scope. The centerstack design and fabrication was assigned to one CAM who was the laboratory's expert in coil manufacturing. The work scope should have been distributed to at least 3 CAM's. The failure to do so led to some oversights in procurement inspections, timely reconciliation of cooling wave analysis, more complete field supervision, and support of EVMS CAM duties. The Center stack WBS relied heavily on one senior CAM who quickly became overloaded. This led to a bottleneck in fabrication tooling which required a lot of attention. Some earlier support on engineering the tooling might have helped save rework. Additionally, an overloaded CAM impacted our schedule since we tended to focus on the near critical path and big ticket procurements or those that are technically challenging. While this helped us to successfully navigate the 6 largest risks on the project (i.e. Vacuum Pressure Impregnation (VPI) of the centerstack) this led to smaller procurements of hardware to receive less attention until it came time for assembly. Some of these components had to be re-worked by PPPL to meet specification which led to internal schedule delays and diversion of critical staff (i.e. welders, machinists). • Next time: Ensure CAM's are not overloaded and adequately staff are assigned for oversight and supervision. Ensure PPPL QC has adequate resources to support the receipt inspection process.

Number	Level	WBS	Success or Opportunity	Category	Description & Discussion
12	1	All	**O**	Quality Control	Earlier recognition of the need for an independent QC receipt inspector. During the last 20 years PPPL has reacted to budget challenges by reducing overhead cost (and staff) by transferring work scope to directly funded project staff. One of the positions eliminated was a full time QC receipt inspector whose responsibilities were transferred to the project procurement technical representative (CAM in most cases). Mid way through the project it became apparent that hardware deliveries for non critical, small hardware (at the time) did not receive timely and complete inspections. The project requested, and PPPL agreed to hire a QC inspector which offloaded the CAM's..
13	1	ALL	**O**	Procur ement	Causal Analysis – Vendor "X", Inc. February 2/8/2013. (Detailed report available upon request) Multiple awards (6) to a new, unknown supplier for NSTX/U components resulted in unacceptable quality, rework, and/or re-award of contracts, all of which resulted in a delay in schedule for the project and additional costs. After award, one of the work activities covered by these six awards became part of the critical path and, as a result, had a significant impact on the schedule. As a result, PPPL initiated an analysis to identify the causal factors so that actions can be taken to prevent this from recurring. The root cause identified was the evaluation and oversight of the vendor was inadequate. Contributory causes were: A. Inadequate incoming inspections and supplier oversight due to lack of appropriate resources assigned to these procurements. B. Inadequate hold points/first article inspections for jobs requiring weld preparation. Recommendations include; 1. Develop a process for the evaluation and oversight of new and unknown fabrication suppliers until adequate confidence is achieved. Such a process should consider financial stability, types of contracts to be awarded to this supplier, time frames of the contracts, performance parameters, risks associated with work to be done, references, timely feedback from first wards, etc 2. Insure adequate staff for the timely inspection of hardware and components. 3. Insure hold points/first article inspections, which are especially important for vacuum welds or other welds with high loads.

Number	Level	WBS	Success or Opportunity	Category	Description & Discussion
14	2	ALL	**O**	Resources	Key pacing resources like welding required careful handling and often became pinch points. Veteran welders were in high demand throughout the project. The PPPL Tech Shop work order system was well managed and the Work Control Center (WCC) did an outstanding job applying timely use but early training of welders in anticipation of this peak need might have eased project problems. Late in the project an outside Blanket Ordering Agreement (BOA) was set in place to add additional welders when needed to increase available welder resource.
15	2	1.2	**O**	NBI Armor	The original armor had many foibles and as-built conditions to make do and make fit back in year 2000. The original engineer on the armor upgrade job was less experienced that was thought or expected and took a very cut and paste approach except for the supports. This approach was less than adequate in analyzing those as-built problems. After a new engineer took over the armor job, she worked her way through many issues and we improved the design especially on the tiles, but things like the water pipes needed better design from the beginning because their wall thicknesses and bend radii gave the vendor fits and took rework to fix. The port at Bay H needed a ton of work because the port and its feedtrhoughs had not really been included. As time went on, the cog engineer was forced to do a lot of rework herself because some things could not be built as expected. Had the cog engineer been on the job from the start we could have sifted the old design better, found the problems, avoided rework, and improved cost efficiency and schedule. Nevertheless, to the cog's credit, the job turned out very well. The inexperience of the first engineer took a lot of hard work to rectify.

Number	Level	WBS	Success or Opportunity	Category	Description & Discussion
16	2	1.7	**O**	Management/Organization	Project reviews. The time spent in preparing for, conducting and follow-up from both PPPL and DOE initiated reviews was under estimated. This project conducted 34 high level reviews that utilized over 72 externals reviewers from 22 institutions. While somewhat beneficial, the impacts to project cost, schedule , and resources should have been more adequately budgeted. Effective project meetings; DOE-PSO led IPT, weekly Director's meeting, daily WCC meeting, 8:30 meeting, project weekly team meetings during the design phase. Opportunity for improvement;: The all encompassing external global final design review did not allow for enough detailed review of technical aspects. The project would have benefited from individual focused internal reviews of some subsystem hardware in lieu of global design reviews
17	2	1.7	**O**	Resources	Sharing analysis engineers with the ITER project led to delays in the completion of calculations. This led to late receipt of drawings and subsequent late delivery of materials/components to the field. This required the project plans to be adjusted on a weekly basis which resulted in cost inefficiencies. While this did not impact critical paths tasks it did impact the cost and schedule for machine assembly (i.e. structural supports).
18	2	1.7	**O**	Policy/Procedures	Institutional overtime policy led to lost scheduling opportunities during those weeks that included holidays. Holidays or snow days were not counted toward the 40 hour work week calculation for premium time therefore technicians were less likely to want to work extended days or Saturday.
19	2	ALL	**O**	Design	Consider better management of design tolerances. Be surgical in requiring small tolerances. This will drive the vendor's procurement cost, require extensive in-house engineering time to disposition nonconformance reports (NCR's), and increase assembly time. The impact manifests itself in both increased cost and schedule stretch-out. This has been a chronic challenge on projects at PPPL. 'Better is the enemy of good enough"

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20	2	1.1	**O**	Design	PPPL calculation documentation was complete and accurate but lacked clear and definitive conclusions and summaries. This led to misunderstandings and time wasted in completing designs/drawings. Crisp conclusions and design direction needs to be included in the final closing statements.
21	2	1.1 and 1.5	**O**	Resources	Personnel single point failures has led to schedule impacts when critical people were not available (due to prolonged illnesses and deaths). These could not have been anticipated but for projects spanning long periods of time they are likely to occur and should be factored into cost and schedule contingencies. Also, critical corporate skills should be identified with backup people assigned to be mentored.
22	2	ALL	**O**	Estimating	Under estimates of several skills manifested itself into resource shortages and schedule delays. The work estimating procedure should be revised to require supervisors of the skill organizations (i.e. welding, machining, field crew installation, drafting etc.) to review and provide input to all work estimates. Furthermore, technician supervisors should be required to attend design reviews to better promote value engineering. At the very least ensure early on that what is designed can be built.
23	2	1.1	**O**	Design	Some of the components designed for this project did not take as-built field conditions into consideration**.** Accurately manufactured parts required re-work before they could be assembled to components that did not match the NSTX CAD model. **Recommendation**: Individuals responsible for the design should engage with the field (inspect/measure the field condition and speak with operations people) to ensure that the designs for new components integrate into the imperfect, as-built conditions that actually exist. This should be addressed now, while the areas of nonconformance are fresh in people's minds. No one will remember where the problems were 5 years from now. Suggest updating the global CAD model to current as-built conditions to benefit future upgrades/modifications.
24	3	1.7	**S**	Management/Organization	Project was very well organized from the beginning. We have an excellent, very strong project team. We had excellent project initiation, requirements were well defined if over the top here and there, and the work planning and WAFs were outstanding. Project Controls went very well. Project status and EVMS went nearly flawlessly. We were very well supported but NSTX Researchers.

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25	3	1.1	**O**	Design	We spent too much conceptual mechanical engineering design and analysis time trying to meet the GRD full power supply recommendations and eventually had to punt and do DCPS. Recommendation would be to craft the GRD more carefully or consider ramifications sooner. CDR was extreme.
26	3	1.1	**O**	Design	GRD shot spec was also over the top. 60000 full power shots eventually became 20000 shots total, 2000 full power on OH with 6000 full power plasmas. Chewed up a lot of analysis and fatigue allowables.
27	3	1.1 and 1.2	**O**	Procur ement	Associated Fabricators LL report speaks for itself. What a mess. Cost us time and money and kept us from doing other things.
28	3	1.2	**O**	Resour ces	On beams we had some trouble with jobs taking too long. We had some new people and bringing the crew up to speed took a lot of hard work and training. In the end though not only did we build a new beam we built a new Beam Team too.

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29	3	1.2	**O**	NBI Controls	On controls, given the scope of work it became apparent last summer that we were resource limited in executing the scope. We received our new transfer staff member about 4-5 months late so we had to supplement our workforce with a blue sheet subcontractor who has worked out very well. The estimated hours required has worked out OK in terms of costs; yet, we were supposed to finish much earlier so in terms of schedule we needed 4 individuals instead of 2. This problem was somewhat masked because we had the rework on the trays due to the drafting problem I mentioned earlier. Therefore we could keep two techs moving and limit the damage where 4 would have been left standing around. Because other items were also late and we needed to rework the BL water pipes this staffing issue never became a critical path issue. Also, we were very fortunate to get the blue sheet individual that we did as he has a lot of experience that has been brought to bear.
30	3	ALL	**O**	Procurement	Ensure that supplier fabrication contracts are awarded based on best value and not best price. More thoroughly vet suppliers qualifications.
31	3	ALL	**O**	Procurement	Verify that selected subcontractor can perform the work required prior to award. Add selection criteria to procurement process to facilitate this. Several instances were encountered where the vendor chosen to fabricate our components did not possess the capability to perform the job correctly. This adds cost in lost time and rework. Recommendation: we establish criteria for matching vendor capabilities to fabrication complexity.

Number	Level	WBS	Success or Opportunity	Category	Description & Discussion
32	3	1.1	**O**	Coil Molds	TF Inner bundle molds are too tight-fitting around copper. Imperfect molds and imperfect copper bars resulted in quadrant and ultimately full bundle to be larger diameter than designed. This resulted in modifications to many of the parts that interfaced to the coil's over-sized diameters and also resulted in the misaligned TF connector faces. The only factor that allowed the coil to fit into the case was the fact that we had thicker ground layer around the TF Inner bundle and the OH coil. The compliance of the ground layers allowed us to "squeeze" the TF and OH coils into their molds. Conversely, if we did not have a generous ground layer we might have been able to get the TF and OH into their molds. **Recommendation:** If we had more fiberglass on the individual TF legs, we could have built quadrants much closer to the design dimensions.
33	3	1.1	**O**	Coil VPI	It's my conclusion that we should plan to sand off resin rich areas from coils VPI'd in hard molds. Epoxy typically cures at ~100 centigrade, a temperature at which the mold had expanded, resulting with coils that have larger than nominal dimensions. I observed this as far back as the NCSX racetrack coil, ~10 years ago. **Recommendation**: we allocate schedule and labor costs in future projects to reflect the time that we will spend sanding.

Appendix H

Lessons Learned (continued)

Number	Level	WBS	Success or Opportunity	Category	Description & Discussion
34	3	1.4	**O**	Estimating	George and I were talking about Drafting. In general it is my impression that drafting was somewhat underestimated by most jobs. Use of ProE modeling was valuable but took time. Making drawings and approving them took more time. The estimate of 40 hours per drawing may have been useful and approximate but might need tweaking. Not all ProE designers use ProE to its fullest or in the same way. Some jobs require modeling with many details and huge amounts of the global model. Some designers were slowed by the size of their models. Some computing requirements were reported but not addressed for some while which led to inefficiency and therefore increased drafting costs. The designers did not all, and for those that did, did not fully check their models and drawings against the global model or the as built machine. A notable example was the coil bus runs that needed total rework. This was perhaps more commonplace than realized because we had a lot of rework in the field. The whole drafting arena probably needs more input that just mine.