LESSONS LEARNED

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Don Rej wrote a comprehensive project closeout report with a section on lessons learned. I will only add suggestions in areas where I feel we made some miss-steps in the execution of the NCSX project and where I feel improvements might be made on future projects. Before providing the details I believe it's worthwhile to add some background information to form some bases for my comments. About 40 years ago I joined Grumman on a fellowship program that had a goal to enhance the design engineering discipline. I was involved in the early design phase of a number of large programs; the F14, a forward swept wing research airplane (HIMAT), the EF111 composite wing development program and the space shuttle. If I recall most (if not all) of these programs were completed with program cost over runs. I witnessed the first F14 test flight crash and saw the program nearly bankrupt the company. The navy eventually agreed to accept the F14 program higher production cost. They decided not to walk away and the F14 fighter plane provided the navy with years of outstanding service. It is very difficult to accurately estimate the cost of a first of a kind project. To have a chance the conceptual design stage must have sufficient funds to fully develop the design and the needed R&D to support it. The NCSX project did not operate in this condition. Few fusion projects do.

Some areas where the NCSX project fell short or where I feel improvements might be achieved are highlighted below.

Design Integration

Overview

NCSX design integration (DI) activity initially was staffed through engineering by me at PPPL and Mike Cole at ORNL with added design support from both institutions. Design integration efforts early in the project focused on developing an integrated design configuration; establishing the geometry of key stallarator components and their special relationships to obtain manageable mechanical interfaces and assembly clearances. This effort was done in conjunction with design activities being carried out at ORNL who was responsible for the two major device core components (the modular coils and vacuum vessel). The TF and PF arrangement was established within DI with sizing input provided by Wayne Reiersen. The vacuum vessel ports were established to meet the diagnostic requirements. The cryostat went through a few configuration changes in its early conception and settled on a simple frame and panel design in a topology that provided the build for insulation space and openings for the vacuum vessel ports that dominated its interface. Facility models were generated to properly form an integrated core / facility arrangement that set preliminary space allocations for auxiliary systems and services.

Comment

The design integration process that was successfully executed early in the project became less effective later as the project moved into the detailed design phase due to the dilution of the DI effort by the reassignment and/or over extension of key participants. Design integration has a number of rolls to perform. One roll was to develop a fully integrated design in the conceptual design phase and then follow the WBS generated design details from a Q/A standpoint to ensure interfaces and assembly characteristics are properly maintained. I became involved with the diagnostic WBS group in developing the magnetic loop coils on the vacuum vessel within the DI development roll. Mike Cole started this effort but due to other comments the effort was passed on to me. Unfortunately due to insufficient design support and the complexity of the loop design process we did not pass on the DI developed design to the diagnostic group. I felt that I could perform the detail design task and still maintain my DI oversight roll. This worked out okay until I became the WBS manager responsible for machine assembly tooling which further diluted my DI efforts. Within the auspices of design integration a five step assembly plan was developed that defined the machine core assembly process starting with service installation on a vacuum vessel half period segment and ending with the full installation of three field periods and intersecting three spool pieces. In retrospect responsibility of the machine tooling effort should have been passed on to another individual. A final dilution of design integration activities came with the reassignment of Mike Cole to take over the

ORNL project engineering role caused by the departure of Brad Nelson to the ITER project. The diluted design integration activities resulted in us missing some pending interface problems which should have been picked up by looking at the assembly model details. One example was the interference between the modular coil chill plates on one winding form of the adjoining modular coil shell that was found during a component test fit-up. Another short fall was that because of WBS responsibilities (machine tooling) I did not have the time to provide the design and analysis checking of sub-system design efforts. One resent example here was the early structural arrangement of the trim coils that incorporated discreet bolted connections to the magnet structure; an arrangement that I judged to be inadequate. I did not have the time to make a model and perform some rather simple FEA calculations. The trim coil structural support approach was eventually changed, however time was lost pursuing an earlier arrangement.

My conclusion here is that the design integration effort should be staffed by experienced design engineers with designer support. This group should remain intact through out the project and although design approaches can originate from this group no DI staff should have subsystem WBS responsibilities.

<u>Documentation and control</u>

The NCSX project instituted a comprehensive documentation and control system which would probably rival any billion dollar project. It is my judgment that the NCSX control system was very onerous given the project cost structure and staffing level. Can a control system be constructed that better fits the project cost and staffing structure? Do all component WBS levels need to adhere to the same documentation rigor? Can a documentation structure be devised that allows WBS system requirements be provided in a list form without all the prose and boiler plate? It may be valuable to have some interaction with one of the NCSX subcontractors (possibly Major Tool) to see if a simplification can be made in the specification documents that would still afford them the information needed to fabricate the parts.

<u>CAD software training for the engineering staff</u>

I feel that some opportunities were lost because of the lack of training and CAD proficiency on the part of some of the engineering staff. At times designers (who are very capable) expended energies moving in one direction only to find their design approach redirected when analysis or further engineering input required them to change direction. If the responsible engineers were actively involved in developing the initial concept within the CAD environment in interaction of the full assembly models and with supporting FEA scoping analysis, a more timely and efficient design solution could be generated. I would recommend that internal CAD training be provided to design engineers to increase their CAD design and analysis capabilities.

All mechanical interfaces and clearance conditions are available within the CAD models. More engineers and managers need to be actively involved with this data base.

<u>External manufacturing involvement</u>

The NCSX project participated in a number of prototyping activities on the vacuum vessel and modular coil in an effort to gain design and fabrication experiences in supplying these critical NCSX components. Even with this effort the awarded contractor still was unable to deliver the components at the original contracted price. I feel it would be beneficial if high risk component fabrication efforts were structured in a two part contract; the first part being a cost plus fee structure and the second part a standard fixed cost contract. Using the modular coils as an example, a two phase contract could include a cost plus fee portion to involve the fabrication of one each of the Type-A, B and C modular coils and an assembled half period. In the first phase Major Tool would be part of the team contributing to the manufacturing engineering efforts. It would be beneficial to bring them into the design phase at a point in time where they could contribute to the design process, better assuring that what is being designed can be fabricated. Once the first phase of the contact was completed the subcontractor would be in a better position to make a final cost estimate to inter the fixed cost phase of the contract.