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NESC-RP-06-019

Composite Crew Module: Primary Structure

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National Aeronautics and
Space Administration

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May 5, 2011

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Approved:	*Original Signature on File*	8/23/11
	NESC Director	Date

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1.0	Initial Release	Mr. Michael Kirsch, NESC Principal Engineer, LaRC	5/5/11

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Technical Assessment Report

1.0 Notification and Authorization

In January 2007, the NASA Administrator and Associate Administrator for the Exploration Systems Mission Directorate (ESMD) chartered the NASA Engineering and Safety Center (NESC) to form an Agency team to design and build a Composite Crew Module (CCM) in 18 months to gain hands-on design, build, and test experience in anticipation that future exploration systems may be comprised of composite materials. The NESC Review Board (NRB) approved an assessment plan on May 3, 2007. Status briefings were presented at NESC face-to-face meetings in June 2006, May 2007, December 2007, March 2008, July 2008, January 2009, June 2009, and February 2010. The key stakeholders for this assessment are the ESMD and the Office of Chief Engineer.

The CCM project started in January 2007 and the technical work was completed with the final test to destruction in March 2010. Each discipline of the project achieved great success and developed extensive written results. Accordingly, the final CCM project report has been separated into one summary report with executive summaries from each of the six disciplines, and then one stand-alone report for each discipline. This results in some duplication between reports, but allows readers to limit their review to their particular discipline of interest in searching for lessons learned for future composite structure activities.

2.0 Signature Page

Submitted by:

Team Signature Page on File - 5/16/11

Mr. Michael T. Kirsch — Date
Team Lead

Team Leads:

Mr. Jeffrey W. Stewart — Date
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Mr. James W. Jeans — Date
Analysis Lead

Mr. Larry Pelham — Date
Manufacturing Lead

Mr. Kenneth L. Hodges — Date
Inspection Lead

Dr. Sotiris Kellas — Date
Test Lead

Signatories declare the findings and observations compiled in the report are factually based from data extracted from Program/Project documents, contractor reports, and open literature, and/or generated from independently conducted tests, analysis, and inspections.

3.0 Team List

Name	Discipline	Organization/Location
Core Team		
Michael Kirsch	Team Lead/NESC Principal Engineer	LaRC
Jeff Stewart	Deputy Team Lead/Design Lead	GSFC
Paul Roberts	Deputy Team Lead	LaRC
Jim Jeans	Analysis Lead	GSFC
Dan Polis	Materials Lead	GSFC
Larry Pelham	Manufacturing Lead	MSFC
Ken Hodges	Inspection Lead	JSC
Sotiris Kellas	Test Lead	LaRC
Pamela Throckmorton	Management and Technical Support Office	LaRC
Administrative Support Personnel		
Terri Derby	Project Coordinator	LaRC
Christina Williams	Technical Writer	LaRC

3.1 Acknowledgements

Appendix B provides a full list of team members that contributed to the CCM project.

4.0 Executive Summary

In January 2007, the NASA Administrator and Associate Administrator (AA) for the Exploration Systems Mission Directorate (ESMD) chartered the NASA Engineering and Safety Center (NESC) to design, build, and test a full-scale crew module primary structure, using carbon fiber reinforced epoxy based composite materials. The overall goal of the Composite Crew Module (CCM) project was to develop a team from the NASA family with hands-on experience in composite design, manufacturing, and testing in anticipation of future space exploration systems being made of composite materials. The CCM project was planned to run concurrently with the Orion Project's baseline metallic design within the Constellation Program (CxP) so that features could be compared and discussed without inducing risk to the overall Program.

This report discusses the project management aspects of the project including team organization, decision making, independent technical reviews, and cost and schedule management approach. This report also contains an analysis of the actual expenditures by civil servants, contractors, and project phases. There are six final reports associated with the project being released: Design, Analysis, Materials and Processes, Manufacturing, Test, and Non-Destructive Evaluation (NDE). Each of these reports contains a comprehensive discussion of the engineering behind the technical decisions within each discipline. Near the end of the manufacturing development phase, the team worked with experts from the Orion project to identify implementation issues associated with switching the Orion primary structure from their aluminum-lithium (Al-Li) baseline to the composite system. There were no mass or cost benefits identified to warrant the switch, and cost and schedule risk were increased for the Orion project, thus it was decided that Orion would remain with the Al-Li baseline.

5.0 Background

In January 2006, the NASA Administrator, Dr. Michael Griffin, and NASA AA for ESMD, Dr. Scott Horowitz, chartered the Crew Exploration Vehicle (CEV) "Smart Buyer Team (SBT)" Design project. The CEV SBT project's goal was to design a CEV to meet the requirements established in the Call for Improvements Request for Proposals released January 10, 2006, to better understand trade space, design drivers, and technical solutions.

During the CEV SBT activity, the structures team conducted a parametric analysis of polymeric composite materials for use on the crew module (CM) primary structure and pressure vessel. Following the CEV SBT outbrief, an NESC design team was chartered to develop a CM design optimized around the advantages of composites and to characterize the design drivers such as geometry, mass, manufacturability, inspectability, repairability, damage tolerance, crashworthiness, micro meteoroid orbital debris, and radiation shielding. The outcome of the NESC design team was that a CCM was feasible, but full-scale fabrication was suggested to quantify mass and manufacturability benefits. The NESC feasibility study was published in the NESC (RP-07-028) Composite Crew Final Report, Volumes I and II.

In January 2007, NASA chartered the NESC to form an Agency team to design and build a full-scale CCM to gain hands-on design, build, and test experience in anticipation that future exploration systems may be made of composite materials.

6.0 CCM Project

6.1 Project Objectives and Success Criteria

The primary objective of the CCM project was to provide members of the NASA family hands-on design, build, and test experience on a complex composite structure so that NASA would have the skills for future Exploration hardware projects (e.g., a lunar lander, Earth departure stage, or lunar habitat module). The effort was to be completed on a full-scale Orion CM primary structure in parallel, but not in competition with the baseline Orion Al-Li design. The intent was to perform a detailed design and fabrication of both an Al-Li design by the main line Orion project, and a composite design by the CCM team, so that details could be compared and contrasted.

The project's success criterion was defined as being able to predict both the as-built mass of the final assembly (using Preliminary Design Review (PDR) information) and the strain response of the structure as tested within 20 percent of the measured values.

While not considered success criteria, one of the project's goals was to deliver a full-scale structure for test, quickly; approximately 18 months from project kick-off to delivery. This goal emphasized rapid prototype management techniques, but from a geographically distributed team. This resulted in a project organization, communication plan, file management, and meeting approach that was not typical to most NASA projects.

6.2 Major Project Milestones

The overall project from the first kickoff meeting to the final hydrostatic test to failure spanned 36 months, as shown in Table 6.2-1. The first 12 months were spent in design and the second 5 months were spent developing manufacturing techniques. The project had a production stand down from May 2008 to October 2008 due to agency funding constraints and priorities. In October 2008, the project resumed and the test article was manufactured in approximately 9 months. It took 2 months to make final repairs and prepare for and conduct shipping. The test article arrived at Langley Research Center (LaRC) in September 2009. Testing was completed over 5 months, from October 2009 to January 2010, with the final destructive test completed about a month later on March 2, 2010. See Appendix A for the project milestone schedule.

Table 6.2-1. Itemized List of Reviews

Phase	Months Duration	Date	Event
Design	12	Jan-07	Project Kickoff: Kennedy Space Center (KSC) Beach House
		Mar-07	Conceptual Design Review
		Jun-07	Preliminary Design Review
		Dec-07	Critical Design Review
Development	5	Jan-08	Full Scale Tooling Delivered
		May-08	Manufacturing Plan Review
Manufacturing	9	Oct-08	Full Scale Test Article Started
		Jul-09	Full Scale Test Article Completed
Testing	5	Sep-09	Delivery of Test Article to LaRC
		Sep-09	Test Plan Review
		Jan-10	Baseline Full Scale Tests Completed
Failure	1	Mar-10	Hydrostatic Test to Failure

Although the 18-month goal was not achieved, the project still proceeded at a relatively rapid pace.

6.3 Project Organization

The team was staffed the way a traditional NESC team is formed, in that expertise was recruited Agency-wide. The team had participation from nine of the ten NASA field Centers including Ames Research Center, Dryden Flight Research Center , Goddard Space Flight Center (GSFC), Glenn Research Center , Johnson Space Center (JSC), Jet Propulsion Laboratory, KSC, LaRC, and Marshall Space Flight Center (MSFC). There were also participants from industry including Alcore, Alliant Techsystems (ATK) Aerospace Structures, Bally Ribbon Mills, Collier Industries, Genesis Engineering, Janicki Industries, Lockheed Martin, Northrop Grumman and Tayco Engineering. The team was managed as a collaborative effort; every person on the team was performing an in-line function for the project rather than mixing in-line work with civil servant oversight. This approach enabled individual contributions as a function of expertise, rather than NASA or company affiliation and resulted in increased innovation and a higher motivated team.

The team was organized into six groups; design, analysis, materials and processes, manufacturing, NDE, and test. A group lead provided focus for each discipline, but all project decisions were made in a consensus environment. Each discipline had multi-Center and industry participation, to ensure a broad decision space was considered.

6.4 Team Communications and Decision Making

Since the team included membership spanning all four time zones of the continental United States, actions were taken early on to build relationships amongst the different participants. The project began with 5 weeks of back-to-back collocations, starting with a kick-off meeting at KSC. The collocations were meetings where the team was physically present in one location. The objective of the first week of the first collocation was to define the project goals and objectives, expectations, and to understand concerns from individual team members. Following the week at KSC, the team travelled to Janicki Industries in Sedro Woolley, Washington, to participate in a hands-on build exercise of a complex curvature part. Again, the primary goal of the week was to begin forming the relationships between participants, but also to see firsthand how tooling complexity directly affects the manufacturability of a composite part.

The following 3 weeks were spent at GSFC in a high intensity extended duration conceptual design phase. During this time, many hours late into the evening and through the weekend resulted in trades between different structural concepts. The following 2 weeks, the team returned to their home-base work place, and operated virtually. During weeks 8 and 9 of the project, the team returned to GSFC to prepare for and conduct the first independent technical review of the conceptual trades considered and the proposed solution and path forward.

The first 9 weeks of the project were important to the spirit of the project. It provided an opportunity to assess the strengths and weaknesses of the different participants; it illustrated, for the participants, the pace and methodology for decision making on the project; and “drew a line in the sand" for the assumptions on loads and interfaces that would remain for the duration of the project.

The collocations were beneficial for the achievement of great results in a timely manner. However, given the likely duration of the total project, and the fact that team membership spanned the country, a secondary goal for the project was created to develop project management and system engineering techniques that would leverage the state-of-the-art in communication tools and to facilitate project management in a virtual environment. Emphasis was increased on decision making, conflict resolution, and problem solving, as if the participants were in the same room. In other words, when conflicts were encountered, the question was asked, "how would we solve this if we were in the same room?" This mindset led the team to more collaborative problem solving sessions and significantly increased the multi-location desktop sharing.

Traditional teleconferencing was used extensively, coupled with the use of Webex™ meetings. Overall project communication meetings occurred Mondays, Wednesdays, and Fridays late in the morning to allow east and west coast time zones to participate with minimal inconvenience. Additionally, design sessions were scheduled for Tuesday and Thursday afternoons, but occurred nearly daily to reinforce the need for participatory design decisions. Teleconferences were augmented with messaging services, such instant messaging. This instant messaging tool had the largest impact in terms of creating the environment simulating face-to-face participant interaction. An extension of the instant messenger tool is a desktop sharing function in a simple two-step process that connects two desktops virtually to allow a team member in one location to view and, if necessary, control an application at a different location as long as both team members are connected on the internet. This was the most powerful tool for simulating the virtual problem solving "as if in the same room."

Although, state-of-the-art tools enabled communication, they were still not as effective as a collocated team. Additionally, when team members were dispersed too long, old habits of "singular" decision making and other distractions would creep in. To keep the relationships and focus intact, 2 week collocations continued on the project about every 6 weeks for the first year, encompassing the full design phase.

During the project planning phase, the challenges of distributed teams were considered, particularly the challenge of team members being on travel for extended periods of time. There were two aspects of collocations that could be difficult for team members. The first, acknowledged early on, was the burden of team members having to travel to collocations and being away from home for extended periods of time. This was managed by establishing aggressive collocation goals that resulted in longer hours than normal. The second burden was the challenge of having the collocations at team member's respective home Center. While there may have been an expectation of regular work hours, the collocations required long daily hours and weekend work from every team member. This schedule often competed with the responsibilities at home and made the burden of collocations difficult for the local participants. This factor was not completely appreciated at the inception of the project.

After a year of design, the project transitioned into the manufacturing development phase. Routine project communication meetings continued to occur Mondays, Wednesdays, and Fridays, along with the Tuesday and Thursday afternoon design sessions. Additionally, a manufacturing tagup occurred on a daily basis each morning. The purpose of the manufacturing tagup was to discuss the plans for the day and the results from the previous day. These meetings were the primary communication tool between manufacturing and design, facilitating the "hand-off" from design to manufacturing, and discussing any issues that were identified. The daily virtual sessions were coupled with frequent visits to the manufacturing facility at ATK Aerospace Structures in Iuka, Mississippi. Since one of the project's primary objectives was to gain the hands-on experience, learning opportunities were accessible with design, analysis, materials, test, and project management personnel spending "time on the shop floor" participating in the handling, layup, bagging, curing, etc. This gave immediate feedback to team participants on the design and manufacturing details. The frequent trips to Iuka, and the daily manufacturing tagups continued throughout the 18-month manufacturing development, and manufacturing phase.

As the project evolved from manufacturing to test, the daily tagups continued, but moved to daily test goals and results discussions accordingly. During the test phase, the Monday, Wednesday, and Friday project management meetings were reduced to Mondays only.

6.5 Independent Review Process

Throughout the different phases of the project, numerous independent technical reviews were conducted to challenge assumptions and methodologies. The reviews were typically conducted during the second week of a 2 week collocation. The first week was dedicated to completing engineering tasks and preparation of review materials.

The review committee was formed by recruiting senior experts from NASA and Industry with the intent of maintaining participant continuity throughout the review process. The review team was generally about 15 to 20 multi-discipline experts, representing materials, analysis, manufacturing, systems engineering, or test expertise. The team did not use a closed loop required item disposition process; rather, the reviewers were asked to state or record their questions, comments, and concerns during the review. Their notes were then collected at the end of the day, copied, and returned. The team then reviewed the notes and developed internal team actions. These actions were delegated to the appropriate discipline on the team and tracked internally.

An independent review was conducted approximately 2 months into the project to review the conceptual designs and the down selects that occurred. Approximately 6 months into the project an independent review was conducted of the preliminary design and sizing results. The PDR was also the point that locked in the project interfaces, loads, environments, and final tool surface. Approximately 12 months into the project, an independent review was conducted of the critical design. This included review of the different computer models: analytical and computer-aided design (CAD). At 17 months into the project, an independent review was conducted on the manufacturing plan. This review discussed the manufacturing approach for the entire manufacturing phase including a discussion on the development work that had been done to date. Finally, at 33 months into the project, the team conducted the final independent review of the planned testing. At this review, the team presented the rationale comparing the design conditions to the planned test conditions and presented the analytical predictions based on the test conditions. Finally, the methods were presented for inducing the planned loads during test. An itemized list of reviews is contained in Table 6.2-1 above.

6.6 CCM Configuration Management

6.6.1 Data Management System

All data for the CCM project were maintained in the Integrated Collaborative Environment (ICE) Windchill data management system. Windchill is a product lifecycle management system commercially available from Parametric Technology Corporation® (PTC®), The Product Development Company®. Team members had access to the system by using their registered username and password through the URL http://ice.exploration.nasa.gov/windchill. Within the Windchill system, two repositories were used: a Windchill "project" and a Windchill "product."

Windchill Project

The CCM project repository was used for the creation and storage of design and manufacturing data not subject to revision control. Documents submitted to the project repository were maintained with a minor version history—a new minor version was created each time the document was "checked-in" to the project. Data was segregated into project sub-folders by discipline—"Design," "Materials," "Structural Analysis," and "Project Administration."

Windchill Product

The CCM product repository was used for the creation and management of design documentation subject to revision control and lifecycle state based access control, which formed the basis of the release and change management process for product data. Documents (reports, test plans, specifications, etc.) and all CAD data (mainly Pro/ENGINEER® (Pro-E®)) were controlled within the CCM product. "Part items" and bill of material data was also generated, though this capability was not exploited.

6.6.2 Numbering

To avoid future potential numbering conflicts within the ICE Windchill data management system, all data items checked into the CCM product were prefixed with a unique project designator. For all documents, the designator was "CCM-"; for CAD data, the designator was "CCM_".

Document Numbering
Document numbers were generated sequentially by document type. Table 6.6-1 lists the document types and corresponding document nomenclature.

Table 6.6-1. CCM Document (Object) Types

Document Type	Number Prefix
Analysis	CCM-ANYS-
Document (General)	CCM-DOC-
Plan	CCM-PLAN-
Procedure	CCM-PROC-
Report	CCM-RPT-
Statement of Work	CCM-SOW-
Specification	CCM-SPEC-
Standard	CCM-STD-

CAD/Drawing Numbering

Blocks of numbers were reserved from NASA LaRC. These CCM number ranges were 1247531 through 1247917 and 1247951 through 1248573. Assignment of numbers was maintained on a spreadsheet that was stored in the CCM project. All object numbers were prefixed with CCM_ but the prefixes were removed on the drawing title block and in the on-sheet parts lists.

6.6.3 Revisioning

Object revisions were designated using Military Standard (MIL-STD) convention. Pre-release CAD data was assigned numerical revisions (1,2,3..). All data was assigned Rev "-" (no revision) at initial release. MIL-STD alpha revisions were assigned to revised items.

6.6.4 Lifecycle States

Access controls and revisions of all data in the Windchill product were controlled by applying rules at different data maturity levels (lifecycle states). These rules are listed in Table 6.6-2.

Table 6.6-2. Lifecycle State Access Rules

Object Type	Lifecycle State	Revision Sequence	Access
Document	Development	"-"	Create / Modify
	Pending Approval / Under Review	"-"	Read Only
	Released	"-", A, B, C…	Read Only
	Production Change	A, B, C…	Create / Modify
CAD	Development	1, 2, 3	Create / Modify
	Pending Approval / Under Review	"-"	Read Only
	Released	"-", A, B, C…	Read Only
	Approved	"-", A, B, C…	Read Only
	Production Change	A, B, C…	Create / Modify

6.6.5 Electronic Approval

All data was released using an electronic approval process. All CAD data that were submitted for release were viewable using ProductView, the Windchill visualization client. ProductView enabled non-CAD users to view CAD data without requiring the native CAD system. Successful completion of the electronic approval advanced the lifecycle state-of-the-objects to be released. For CAD data, revision and lifecycle state values were reflected on the face of the drawing.

6.6.6 Change Management

Changes to released data were initiated using an engineering order (EO) for CAD data or a document change order (DCO) for documents. The EO or DCO was released as a document. Upon release of the EO or DCO, the prescribed changes were implemented as a revision to the affected items.

6.7 Cost and Schedule Management Approach

6.7.1 Schedule Management

The cost and schedule management approach for this project was critical path focused. The critical path of the project was reviewed and updated no less than weekly by most team leads. At the onset of the project, the critical path was fairly high level including milestones such as concept review, PDR, and critical design review. As the project progressed, detail was added to the schedule based on an understanding of the design. As the design was completed, the manufacturing schedule emerged in conjunction with the release of the drawing tree. Thus the manufacturing schedule had considerable more fidelity for managing major manufacturing operations. As manufacturing tasks were underway, a day-by-day, or even hour-by-hour schedule was developed for the following 2–4 weeks. Major manufacturing tasks beyond the immediate 4-week window were left vague with estimated durations at the parent task. As the detailed manufacturing tasks were completed and work progressed through the schedule, detail was added to tasks that entered the most current 4-week sliding window. This provided a lower maintenance mechanism for incorporating early lessons learned in later manufacturing operations. It also highlighted the effects of threats and opportunities since most views of the schedule including the 4-week detail could be viewed on a one page printout. To illustrate the concept, during the manufacturing phase, the test phase was one line in the schedule. This rolling 2–4 week list of critical path elements was used throughout the manufacturing phase into the test phase, until test completion. This made the schedule a valuable tool for managing priorities, exploiting opportunities, and minimizing the effects of identified risks. It also served as an effective communication tool for communicating information between team leads.

6.7.2 Cost Management

The CCM project's original cost estimate was considered an analogous estimate based on expert judgment, meaning labor costs were derived by multiplying a rough estimate of the size of the workforce by a generic hourly rate and then multiplied by the total duration of the project. Raw materials and other procurement costs were then added and estimated travel and other miscellaneous expenses.

Once the project was underway, the estimate at completion (EAC) was the primary tool for managing overall costs. EAC was calculated by looking at actual costs (AC) and adding an estimate to complete (ETC). The ETC was calculated by multiplying the estimating labor burn rate for the remainder of the work times the remaining project duration based on the critical path. Travel, major procurements, and onetime expenses were then added to the labor total to determine the total EAC. The burn rate was adjusted periodically using actual data, engineering judgment, and the project phase.

$$EAC = AC + (\text{estimated burn rate} \times \text{remaining schedule duration}) + \text{onetime expenses}$$

While the project was managed considering technical, schedule, and cost, strict earned value management (EVM) formulas, including the use of planned value (PV) and the earned value (EV) were not used on this project due to the high amount of uncertainty associated with rapid prototype projects. In that regard, the basis of estimate for individual tasks beyond 4 weeks in the future was too uncertain to accurately estimate traditional EVM. To roll the estimate up at a higher level would have resulted in maintaining two different schedule and cost estimates: one for managing earned value and one for prioritizing work. Alternatively, one schedule could have been used for tracking both EV and critical path management, but the project would have been rebaselining the PV schedule curve as the detailed schedule for future tasks became evident. Given the short term (2–4 weeks) rolling schedule detail, the project would also have to rebaseline the EV cost curves every time the 2-week rolling window shifted. This schedule uncertainty made the use of traditional EV tools too labor intensive and of limited value since the project would have rebaselined far too frequently to determine any proactive cost performance index or schedule performance index. In that regard, the project was managed using EVM constructs, considering schedule, costs, and technical content. However, it proved best to manage the costs based on current and future burn rates and compare anticipated versus actual cost and schedule deviations.

6.8 Project Cost Analysis

The CCM project total cost was $29.8M. The most significant contract contributors, as defined by resources expended, were ATK Aerospace Structures (design and test article fabrication), Northrop Grumman (test article design and manufacturing engineering), Janicki Industries (test article tooling fabrication), Genesis Engineering (design and analysis), and Collier Research (structural analysis). Contracted services and hardware represented some 79 percent ($23.5M) of total project cost, while civil service labor accounted for 19 percent ($5.6M) of the total project cost. Despite the significant use of collocations, and travel associated with much of the team participating in the manufacturing phase and the test phase, the overall civil servant travel expenditures were relatively low at 2 percent ($0.7M), well within the bounds of cost uncertainty on this development project. As a development project with extensive engineering, the project costs were large with respect to the hardware costs. This was driven by the need to maintain all engineering skill sets throughout the project lifecycle. The breakdown of total project costs among the full-cost categories of procurement (which includes work year equivalent (WYE) costs), civil service labor, and civil service travel is illustrated in Figure 6.8-1.

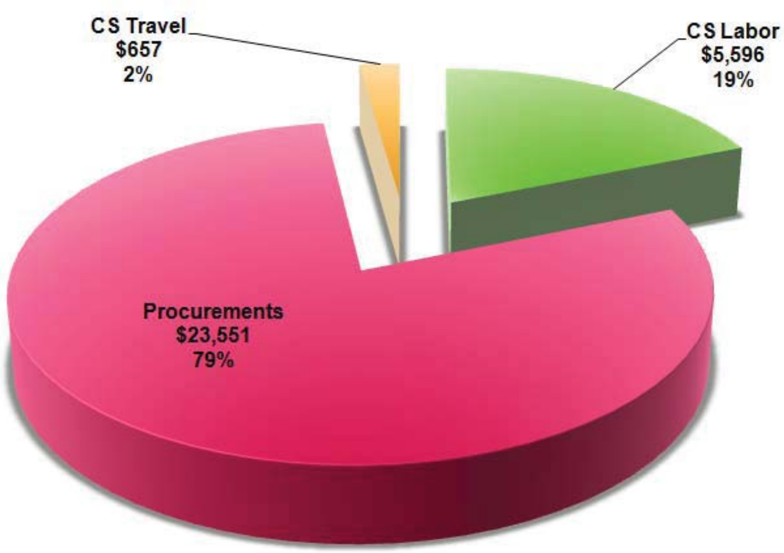


Figure 6.8-1. CCM Total Costs: $29.8M (FY07–FY10)

A breakdown of costs by project phase is depicted in Figure 6.8-2.

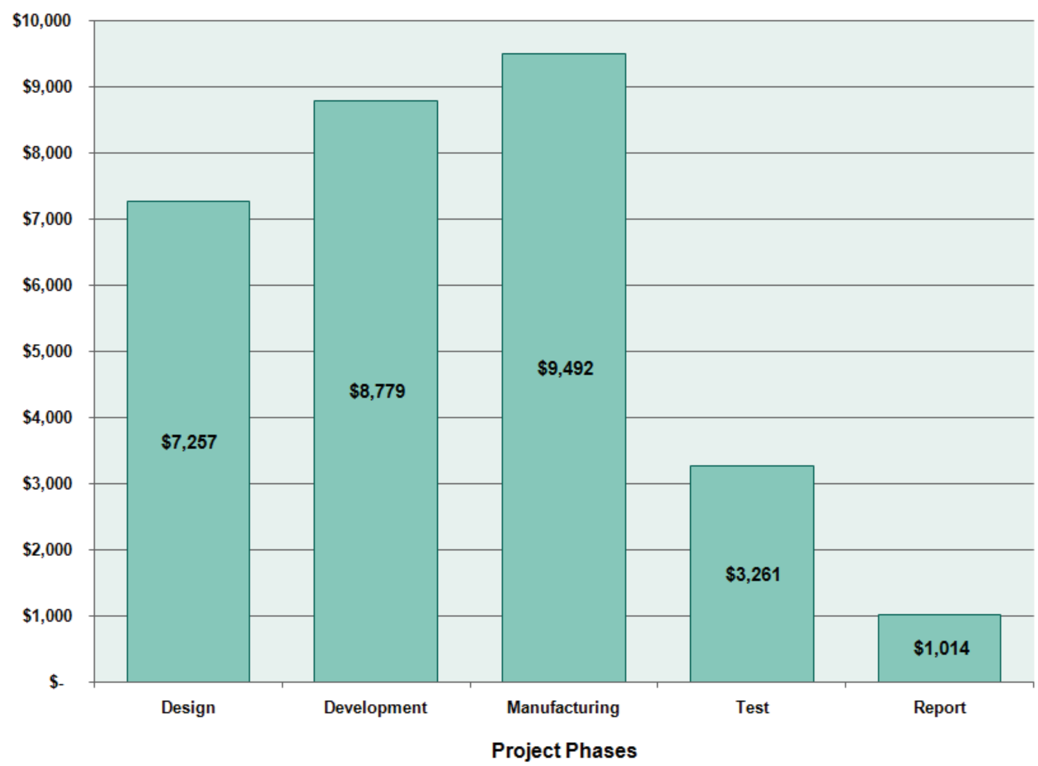


Figure 6.8-2. CCM Costs by Phase: Total $29.8M

6.8.1 Labor Analysis

Figure 6.8-3 depicts the total work effort expended in the execution of the CCM project. Over the lifecycle of the project, some 94 equivalent years of work effort were expended by the CCM civil service/contractor team—52 percent by civil servants and 48 percent by contractors. Figure 6.8-4 depicts the work effort between the civil servants and the contractor team by project phase. The design phase work was fairly equal between the groups, but the contractor group was slightly higher by percentage in manufacturing as expected, given the touch labor associated with manufacturing. The test phase had a high percentage of civil servants. This was driven by the civil servant labor pool at the LaRC combined loads test facility.

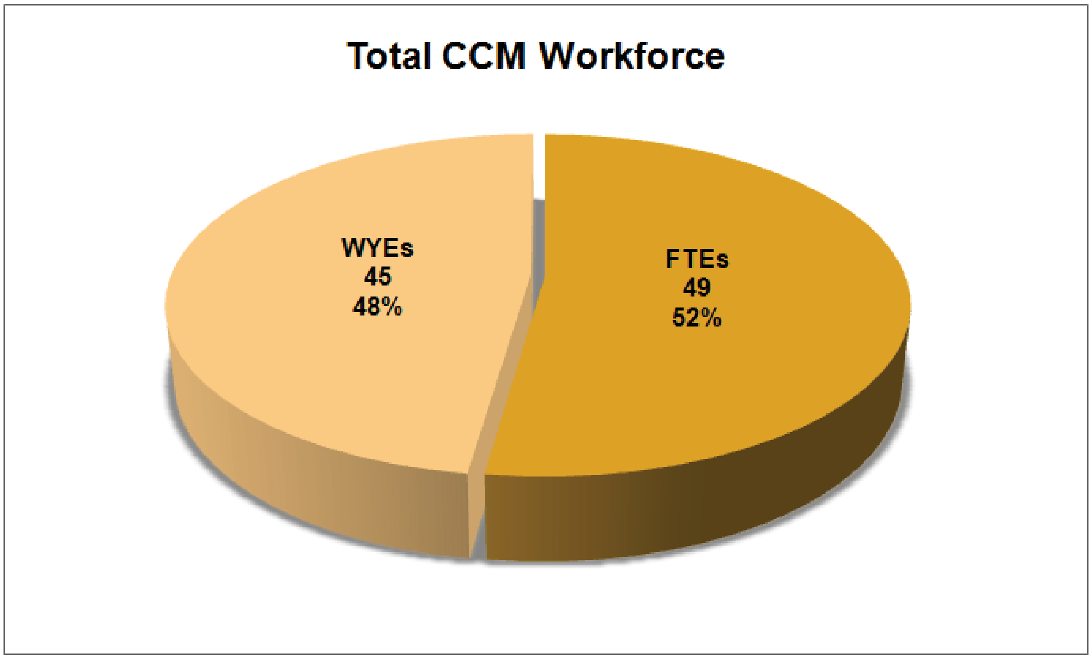


Figure 6.8-3. CCM Total Workforce – Full-Time Equivalent (FTE) and WYE

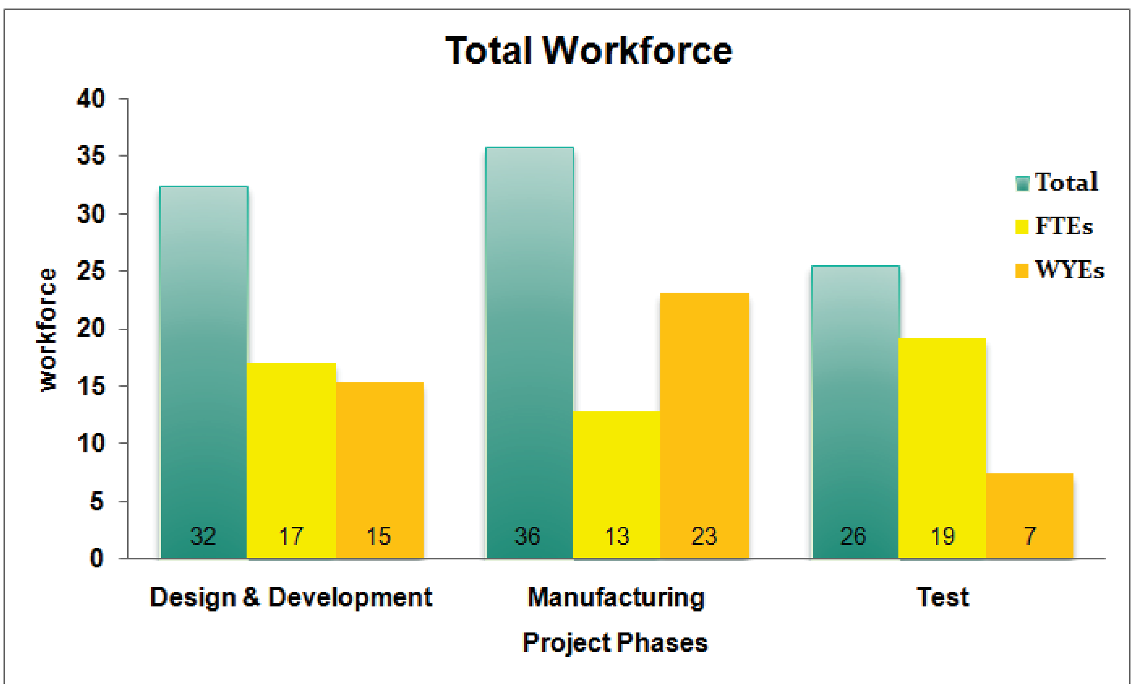


Figure 6.8-4. CCM Total Workforce – by Project Phase

6.8.2 Project Implementation Challenges

During the lifecycle of the CCM project, a number of finance-related circumstances presented significant challenges for the management of the project. First, a temporary limitation of available funding required a production slow-down in the pace of technical progress during the time period from June 2008 through September 2008. This circumstance, and other schedule extensions driven by funding limitations, resulted in increased levels of total project cost, due to requirements to maintain staffing levels over longer periods of time than initially planned. The project also experienced some unanticipated cost growth which resulted from a number of technical circumstances, such as:

- Metallic components were not included in original estimate.
- Support tooling and shop aids such as drill fixtures, router templates, etc., were not included in the original estimate.
- Transition from Pro-E®/NASTRAN® models to released drawing took 2–3 months longer than expected.
- Just in time engineering to manufacturing caused manufacturing inefficiencies and false starts.
- Overall layup was more complex than originally expected, specifically core application, including core forming, impression testing, and final bonding.
- Manufacturing estimate did not accommodate for multi-cure process that included inspection of the skin, and installation and cure of the core, and lastly installation and cure of the outer skin.
- Manufacturing estimate did not account for significant post cure assembly (e.g., 500 precision reamed holes for Service Module (SM) and Alternate Launch Abort System (ALAS) fittings).
- Overall project schedule growth caused design burn rate to be sustained through completion of testing.

7.0 Design Overview

The CCM baselined a set of loads and interfaces based on the Orion design in March of 2007. Beginning at the docking tunnel, the CCM used an aluminum ring to represent the docking system interface. This provided a generic interface that could easily be tailored to any of a number of docking system options. If the CCM had been a flight project, the ring would have been fabricated from titanium to alleviate thermal expansion mismatch between the metallic ring and the composite tunnel interface. A titanium ring could not be procured in time to meet the CCM critical path. The aluminum ring was sufficient to verify the design. The drogue chute interface from Orion is on one unique side of the docking system interface. For Orion, this interface was moved to coincide with a main chute interface. CCM did not incorporate this interface change.

The CCM has six gussets that align with six internal longerons. These include three metallic main parachute interface fittings on every other longeron. There are six metallic SM and launch abort system (LAS) interface fittings along each longeron. Although Orion had baselined an LAS interface that connected to the pressure shell primary structure near the main parachute fittings, a trade was underway in Orion that considered attachment at the major diameter near the SM interface hard points. The CCM project chose to adopt the interface at the major diameter, assuming Orion would also choose this path. However, Orion did not choose this interface and this represented one of the first points of divergence between CCM and Orion. The longerons are internal to the facesheets in the sandwich system and do not represent an additional part for assembly. See Figure 7.0-1 for locations of key features.

Figure 7.0-1. NESC CCM

The CCM included the major cutouts consistent with the Orion design: two side windows, two docking windows, and a main hatch. The cut outs are machined into the side of the pressure shell and fit with a matching aluminum ring. The composite structure was sized to carry all of the design loads, and the aluminum frames were installed to provide a sealing surface for the closeouts during test. Similar to the tunnel, a flight like design would incorporate either titanium frames, or would have the window frames incorporated directly into the layup. For CCM, both of these options were not incorporated due to schedule constraints.

The CCM was built as two halves, an upper and lower pressure shell as shown in Figures 7.0-2 and 7.0-3. It was manufactured on two different male tools: one for the upper and one for the lower. The two shells were joined using a double lap shear joint, with twelve different internal and external doublers; one for each longeron, and one for the acreage between longerons. The internal and external doublers were cured coincident with each other during 12 separate cures. The cures were done under vacuum bag pressure with a purpose built Kapton® heater. The motive for the design was that the spacecraft assembly and integration timeline could be shortened by allowing for parallel integration of labor intensive subsystems such as wiring, plumbing, etc., on each shell without the confined space constraints, and then the two halves could be joined outside the autoclave.

Figure 7.0-2. CCM Upper Shell

Figure 7.0-3. CCM Lower Shell

The majority of the construction was honeycomb sandwich with unvented aluminum honeycomb core. The unvented core was selected to provide double redundancy in pressure containment using the two skins of the sandwich. Given the mild temperature environment of the crewed pressure shell, unvented core was an acceptable selection since large thermal excursions would not be a concern. Some areas of solid laminate were used in the design, specifically the tunnel, the backbone cap, and the pan down regions where metallic fittings such as parachute fittings and SM interface fittings were bolted through the shell.

The CCM incorporated the backbone feature from the Orion design. The backbone was a grid-like structure in the lower shell used to manage packaging in the Orion solutions, see Figure 7.0-4. For Orion, it was originally a non structural feature but, for CCM, the design team chose to integrate the backbone into the primary load paths. Specifically, the backbone was extended and secured to the aft dome, see Figure 7.0-5. This allowed for the reduction of structure around the main diameter of the aft dome since the backbone could carry some of the bending loads in the aft dome. Connecting the aft dome to the backbone saved approximately 100 lbs of mass in the CCM baseline. In addition, by extending the backbone to the floor, a hard point pattern that the heat shield could bare up against on the exterior of the floor was provided. By load sharing between the SM interface and the backbone interface, the heat shield stiffness could be reduced, thus saving mass in the heat shield—an overall system advantage. Furthermore, the aft dome was allowed to take the desired membrane shape between the major beams of the backbone system. This created the “lobed” shape, a hallmark in the CCM design, and also reduced the mass of the aft dome by another 50 lbs, over the CCM baseline, see Figures 7.0-6 and 7.0-7. The exterior foot print for sharing heat shield loads was also preserved.

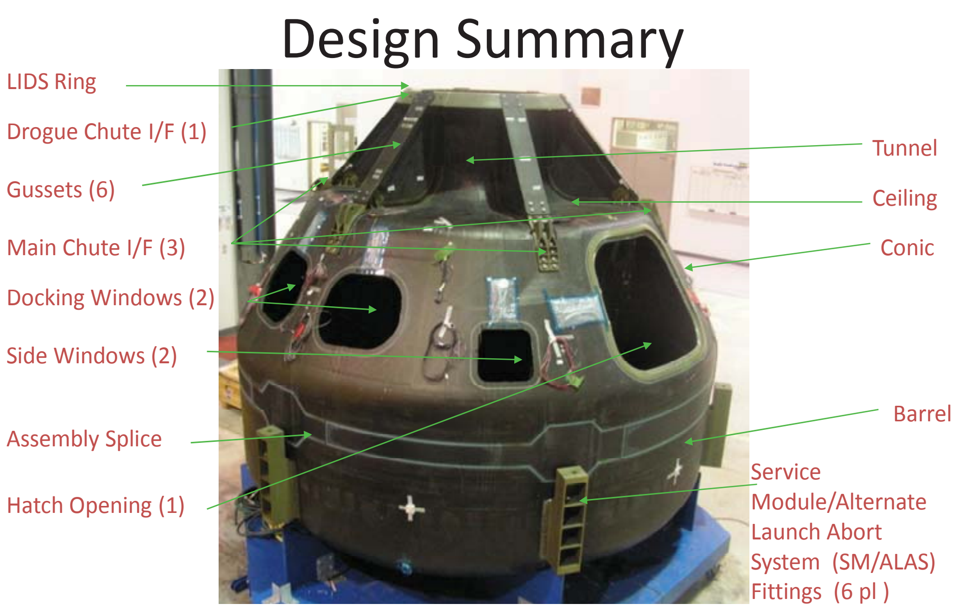


Figure 7.0-4. Final CCM Assembly

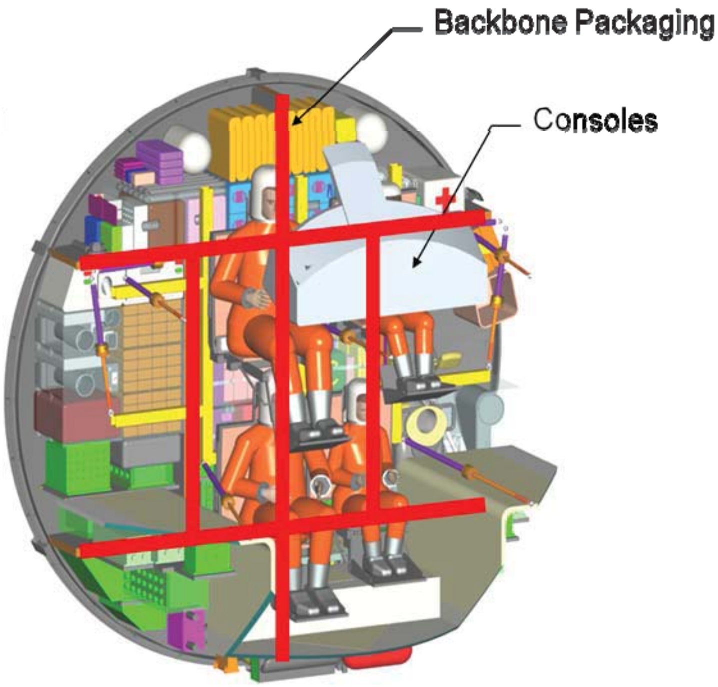


Figure 7.0-5. Illustration of Backbone Structure within Lower Shell

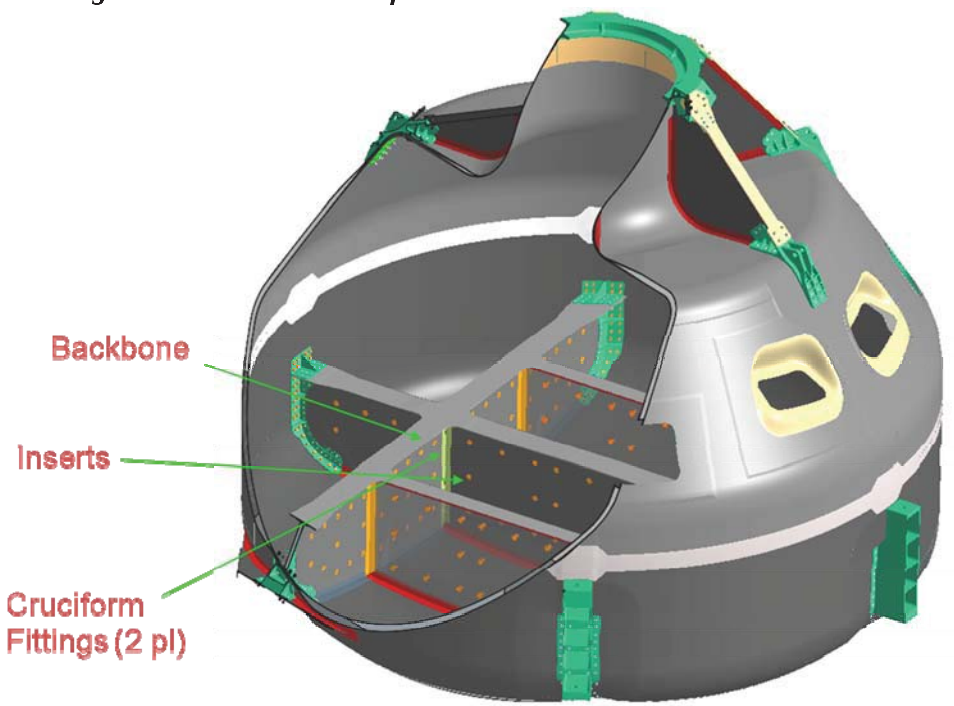


Figure 7.0-6. Backbone Structure in Lower Shell

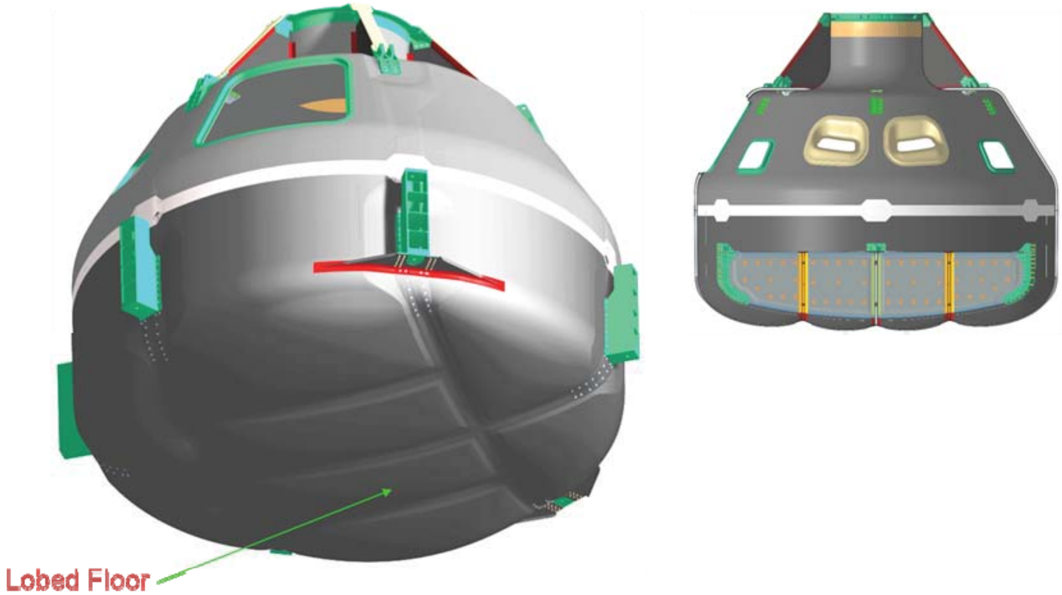


Figure 7.0-7. Lobed Floor on Lower Shell

One of the challenges in composite system design was the orthogonal joints. The team, collaborating with industry partners, adopted three dimensional (3D) woven Pi-preforms to facilitate orthogonal structural joints, particularly between panels of the backbone, between the backbone and the CCM floor and between the gussets and CCM tunnel, see Figure 7.0-8. These 3D woven preforms were key enablers in the composite design and represent a promising future for composites joints due to their robustness as possible design solutions.

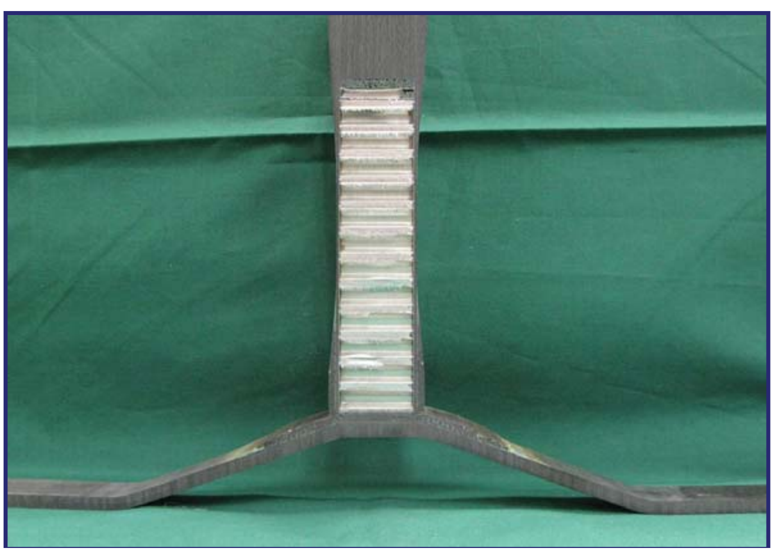


Figure 7.0-8. 3D Woven Preform Test Element

8.0 Materials and Processes Overview

The materials and process activities on the CCM project were prioritized based on a rapid prototype developmental model of the project. As such, the materials selection activity was driven as much by project constraints as performance optimization. Specifically, one of the primary selection criteria was that a sufficient amount of data was pre-existing, such that the design activity could proceed without an extensive lamina/laminate characterization program. Other examples include the fact that a single prepreg system (fiber and resin) was chosen for both autoclave shell construction and out-of-autoclave splice construction. Finally, an aluminum-docking ring was chosen over a titanium version, precluding the ability to co-cure the ring with the shell and driving out-of-autoclave and out-of-oven closeout bonds. While the team was able to successfully implement these solutions, they were responsible for several developmental anomalies. In addition, further optimization of materials selection could potentially reduce weight and/or improve performance.

Allowables and associated failure criteria were assembled from a compilation of literature sources with the intent of providing a flexible design tool that accounted for damage tolerance. This was accomplished by combining a lamina based failure criterion (Hoffman) with laminate damage tolerance considerations (open hole strain allowables) [ref. 1]. For the allowable defect sizes that were chosen, this approach is shown to be conservative, and may provide a fruitful avenue for weight savings at the expense of laminate-based testing.

By eliminating the traditional lamina and laminate building block level testing, the materials and process activities could focus on design details with greater risk and uncertainty, such as woven preform joints. The 3D woven preforms, specifically Pi-preforms, were used to join critical subassemblies together on the CCM. Because this technology was relatively immature compared to the rest of the materials technology on the CCM, considerable resources were focused on establishing process baselines, performance baselines, and design envelopes.

The Pi-preform joining technology proved to be an efficient design solution (~2 times stronger than composite L-clip design) and provided significant manufacturing advantages over such traditional joining technologies. One of these advantages was the ability to do all the Pi-preform joining using out-of-autoclave curing. In addition, the 3D woven technology was extended to a woven cruciform, capable of handling bi-directional joint tension to levels >3 times that of a Pi-preform (7,000 lbs/in versus 2,000 lbs/in pull-off).

Much of the process validation occurred during the full-scale manufacturing phase of the project. Witness testing was used to validate many of the engineering assumptions made during the design phase of the project, including elastic properties, strength distributions, thickness variation, and moisture effects.

Several process anomalies were encountered during the development of the CCM. They include a disbond of the inner skin-to-core, a splice re-design, and Pi-preform consolidation defects. While process development and associated building block testing were performed in each of these areas, the anomalies manifested themselves at the full-scale level due to interactions between process robustness and manufacturing scale-up. This highlights the importance of full-scale developmental work early in the development phase of a composite program.

A full-scale damage tolerance program was implemented to demonstrate that the CCM could meet the intent of current NASA requirements with minimal design changes. This included impacting the vehicle at 18 unique locations at 6 ft-lb, defined as the allowable threat level. Following these impacts, the test article was taken through two critical design ultimate load cases followed by life cycling. In addition, five design details were taken to critical threat levels (reliable detection or threshold energy of 26 ft-lb) and subsequently taken through life-cycling without detrimental defect growth. The full-scale impact testing did highlight the variability associated with the paste bond of the docking ring, which was a potential area for design improvement despite meeting requirements.

Leakage (consumable gas loss rate) remains one of the tipping points between accepting a composite replacement over a metallic solution. In this area, the team demonstrated how a simple polymeric film, loosely coupled to the facesheets using a viscoelastic adhesive, dramatically improved the leakage after impact behavior of the composite system. In addition, the team demonstrated that even the minimum gage skins were not appreciably permeable (below detection limits) under biaxial strains of greater than 4,000 μin/in.

A much more detailed discussion of the materials and process engineering for the CCM project is provided in the NESC 06-019 Composite Crew Module: Materials and Processes Report.

9.0 Analysis Overview

The CCM structure was designed and analyzed to support 115 separate load conditions, including launch, abort, pressure, trans-lunar insertion and landing cases. A “freebody” of the load magnitudes is shown in Figure 9.0-1.

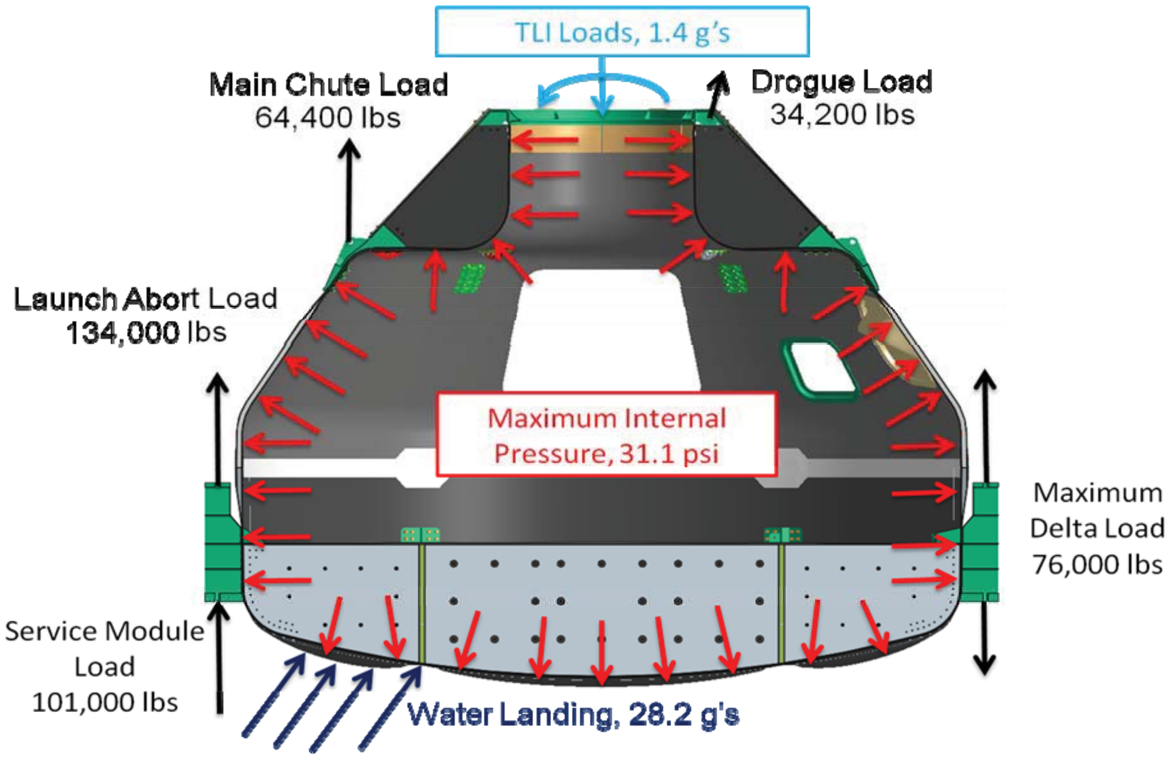


Figure 9.0-1.CCM Loads "Freebody"

CCM analysis was accomplished through the use of computer simulation using finite element modeling techniques backed up with hand analysis and engineering judgment.

Two NASTRAN® finite-element models were constructed of the CCM composite structure. The first was a fairly coarse grid model consisting of about 30,000 nodes and elements. Many of the design drawings were released for manufacturing based on this coarse grid model. This model was updated along with the design of the CCM as the design evolved. Once the design reached a stable level of maturity, a fine grid model was constructed. The fine grid model consisted of 215,000 nodes and elements. The fine grid model confirmed the sizing accomplished with the coarse model and was used to write final margins and predict strains.

A goal of the CCM project was to accurately predict the as-built mass at the PDR. To accomplish this, the coarse grid model was sized to achieve all positive margins using Hypersizer®, along with internally imposed constraints such as layup symmetry and similarity. This sizing was used to accurately predict the final mass of the CCM.

Hypersizer® was used throughout the CCM project. Hypersizer® was used in initial sizing to determine suitable layups for a given area. It was also used to track margins as the design evolved, ensuring that each area maintained sufficient margin when something changed. Additionally, Hypersizer® was used to perform trade studies to study the impact of a suggested change to the design.

The final sizing of the CCM yielded numerous low margins that are summarized in Table 9.0-1. Section reference in Table 9.0-1 refers to the section of the Analysis final report where the margins are described.

Table 9.0-1. Margins of Safety Summary

Location Description	Material	Section	Load Case	Failure Mode	FOS	MS
Longeron 1 Gusset Web	IM7/977-2	10.3.1.1	707	Hoffman	1.40	+0.05
Longeron 1 below hip radius	Al Core 5052	10.3.1.2	601	Core Shear	2.00	-0.07
Longeron 4 parachute fitting pandown	IM7/977-2	10.3.1.3	921	Hoffman	1.40	-0.07
Docking Window Edge	IM7/977-2	10.3.1.4	601	Hoffman	2.00	+0.09
Ceiling Core	Al Core 5052	10.3.1.5	601	Core Shear	2.00	+0.35
Area above SM/ALAS fitting	IM7/977-2	10.3.2.2	302	Hoffman	1.40	-0.16
Drogue Bracket to LIDS	A286	10.4.1.2	9917	Bolt Yield	1.25	+0.14
Gusset Cap to LIDS bolt	IM7/977-2	10.4.1.3	901	Bearing	1.40	+0.06
Gusset Cap to Parachute Fitting	IM7/977-2	10.4.1.4	703	Bearing	1.40	+0.05
Gusset Web to LIDS	A286	10.4.1.5	914	Bolt Yield	1.25	+0.31
Gusset Web to Parachute Fittings	A286	10.4.1.6	932	Bolt Yield	1.25	+0.33
Parachute Fitting to Ceiling	A286	10.4.1.7	706	Bolt Yield	1.25	+0.20
Parachute Fitting to Upper Conic	IM7/977-2	10.4.1.8	921	Bearing	1.40	-0.03
SM/ALAS to lower backbone fittings	A286	10.4.2.1	302	Bolt Yield	1.25	-0.16
Lower Backbone fitting to shell	A286	10.4.2.2	302	Bolt Yield	1.25	+0.23
SM/ALAS to Upper Backbone Fitting	A286	10.4.2.3	302	Bolt Yield	1.25	+0.03
Lower Backbone Fitting to Lower Backbone Fittings	A286	10.4.2.4	301	Bolt Yield	1.25	+0.09
Upper Backbone Fitting to Lower Backbone Fitting	A286	10.4.2.5	301	Bolt Yield	1.25	+0.08
Gusset Web Pi to Upper PV	Pi	10.5.1	601	Pi pull-off & shear	2.00	-0.34
Gusset Web Pi to Gusset Cap	Pi	10.5.1	723	Pi pull-off & shear	1.40	+0.30
Backbone Web to Backbone Cap Pi	Pi	10.5.2	302	Pi pull-off & shear	1.40	+0.01
Backbone Stub Keel Web to Lower Shell Pi	Pi	10.5.2	601	Pi pull-off & shear	2.00	+0.30
Backbone Cruciform	IM7/MTM-45	10.6	302	Cruciform Tension	1.40	+0.15
Acreage Splice	IM7/977-2	10.7	601	Hoffman	2.00	+0.46
SM/ALAS Fitting	7050	10.9.2	302	tension yield	1.25	+0.04
Backbone Fittings	7050	10.9.2	302	tension yield	1.25	+0.03

Another goal of the CCM project was to accurately predict strains during test. Using the fine grid model, strains for all critical channels were predicted well within the goal of 20 percent. In fact, most critical channels were predicted within 5 percent for each test condition.

A more detailed discussion of the CCM analysis activities is provided in the NESC 06-019 Composite Crew Module: Analysis Report.

10.0 Manufacturing Overview

The CCM manufacture, including pressure shell fabrication, composite component fabrication, and CCM assembly, employed a combination of existing manufacturing technologies and best industry practices in conjunction with processes designed around the data produced from the building block approach used in the rapid prototype model for the project. Additionally, a full-scale pathfinder upper pressure shell assembly was manufactured to qualify and, in many instances, revised key manufacturing processes and requirements.

Existing manufacturing technologies employed for composite fabrication included composite lay-up molds, hand lay-up using laser projection for ply placement, in and out-of-autoclave cure processes, machining processes, contact and through-transmission ultrasonic inspection and flash thermography. Special tooling was developed to accomplish pressure shell machining and assembly for both bonded composite and fastened metallic joints. Existing technologies were adapted for this unique application including the use of Pi-preforms from the aircraft industry to bond cured composite components to internal and external surfaces of the pressure shell. A new application of preform developed for the CCM was the "cruciform" used to assemble four cured composite panels in a single cured joint as part of the backbone assembly. The use of existing material and process technology was successfully applied to the splicing of two large composite structures to create a pressure shell, which was not previously applied to this application on the scale of the CCM. The precision manufacture of the lay-up molds combined with simple and effective assembly tooling enabled the manufacturing process to overcome alignment concerns that could have significantly impacted the test approach and overall project results. Numerous lessons learned were identified throughout the course of the manufacturing process, including the development and execution of several significant repair processes. These lessons learned are addressed in more detail in the NESC 06-019 Composite Crew Module: Manufacturing Report. The CCM Manufacturing Quality plan employed basic AS9100 processes and systems with reasonable exceptions needed to support the rapid prototype project. Success in real time changes to design and planning was made possible by the concurrent and on-site presence of key design, analysis, materials and processes, manufacturing and quality personnel. The resulting manufacturing flow for the CCM test article is shown in Figure 10.0-1.

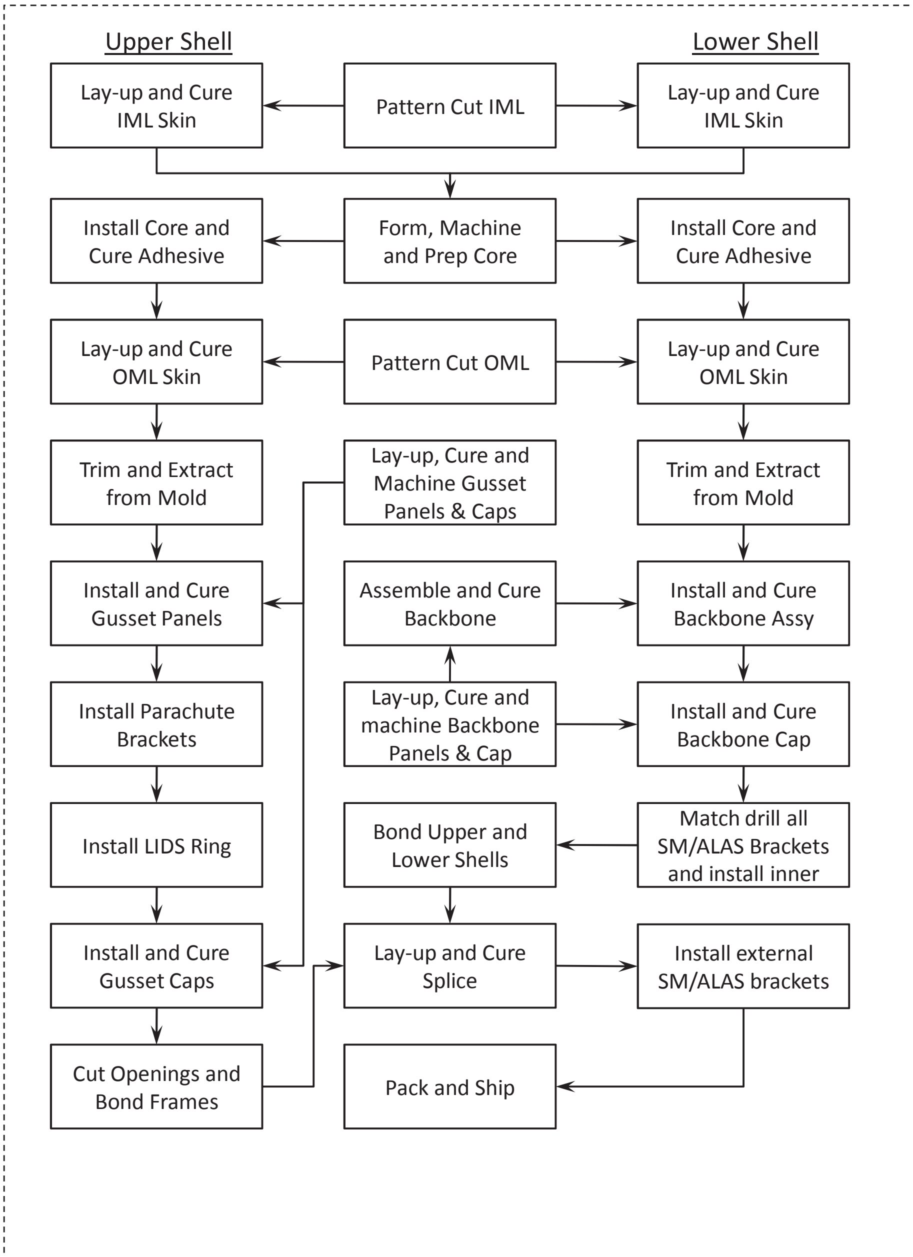


Figure 10.0-1. CCM Test Article Manufacturing Flow Chart

The CCM Manufacturing Development Team (MDT) worked side-by-side with Design, Materials and Processes, and NDE Engineering to support producibility and inspectibility of the CCM. Additionally, the MDT developed the planning and processes for the full-scale article fabrication, assembly and inspection as part of an overall concurrent engineering activity to drive the project in the shortest time possible. The MDT was led by NASA and chartered to concurrently develop baseline manufacturing planning in coordination with Design and Analysis, NDE, Quality, Test and CCM team leadership. The MDT was comprised of the key industry experts, each selected to ensure success of critical and challenging aspects of the project.

- Northrop Grumman – Composite manufacturing, assembly and inspection
- Lockheed Martin – Pi-preform process technology
- ATK Aerospace Structures – Composite and metal manufacturing, assembly, inspection and special tooling
- Janicki Industries – CCM special tooling and composite lay-up molds
- Alcore – Aluminum Honeycomb Core processing
- Tayco Engineering – Out-of-Autoclave cure processing

Manufacture of the CCM pathfinder and test article was conducted at the ATK Aerospace Structures manufacturing facility in Iuka. Building block, test panel and component manufacturing was supported by the National Center for Advanced Manufacturing at MSFC in Huntsville, Alabama.

11.0 NDE Overview

NDE is a noninvasive measurement science and, for CCM, was selected using several factors such as: measurement system maturity, hardware-specific flaw criteria (critical flaw size detectability), local part geometry, thickness, surface condition, and access to the inspection surface. Compound curvature and unique geometry part inspection required some tailored NDE techniques and specialized NDE/inspection tools, which are discussed further in the CCM NDE final report.

The following four NDE methods were approved for use on CCM. Figure 11.0-1 shows the primary NDE methods by component-type on the CCM structure:

1. Visual
2. Ultrasound
3. Thermography
4. Radiography

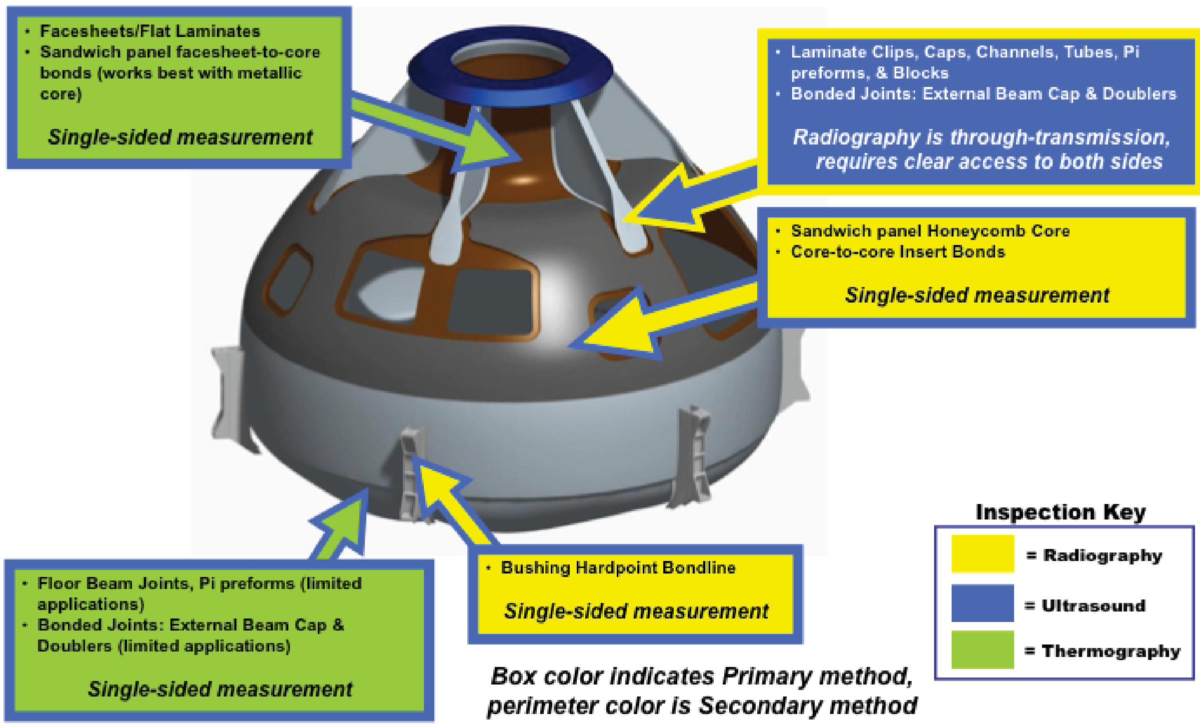


Figure 11.0-1. CCM Primary NDE Methods by Component Type

Composite manufacturing-induced defects such as voids and disbonds, and damage induced during manufacturing, processing and handling can lead to premature and/or unexpected failure of the hardware. Therefore it was essential to the CCM project that the appropriate NDE methods were carefully selected. Inspection methodologies such as ultrasound, infrared (IR) thermography, and radiography were chosen as the primary NDE methods because of their maturity, portability and field proven reliability.

Inspectability and damage tolerance were two of several key-driving requirements identified during the design process that influenced some of the project decisions during the early design trades. A comprehensive inspection goal was established during the early phase of the project that included the inspection of all piece-parts, primary and secondary structure. However, NDE was limited during certain phases of the build process by access restrictions after populating the cabin, geometric constraints, etc. The inspection and flaw detection capability was dependent on several factors such as the accessibility of the region of interest, the NDE system setup logistics and acquisition requirements, and the CCM part geometry, thickness, surface condition, etc.

The inspection feasibility for common defect types identified for the CCM project is shown in Table 11.0-1. Composite defects encountered on the CCM project included:

- Delaminations
- Debonds/unbonds (e.g., core-to-facesheet unbond, missing adhesive, fiber-to-matrix bond)

- Core discontinuities (e.g., tear, buckle, crush)
- Matrix porosity / cracking
- Excess/insufficient resin
- Fiber breaks
- Impact damage
- Inclusions (adhesive backing peel ply, moisture)
- Missing material

Table 11.0-1. NDE Methods for Common Composite Defect Types

NDE METHOD	COMMON DEFECT TYPES			
	Laminate-Interlaminar Delamination	Laminate-Interlaminar Voids/Porosity	Laminate-Inclusions	Sandwich/ Honeycomb Core Artifacts
Radiography	NOT FEASIBLE No through-thickness density change	POSSIBLE	POSSIBLE	POSSIBLE core splice & core fill anomalies
IR Thermography	POSSIBLE	POSSIBLE depends on part thickness/depth	POSSIBLE	POSSIBLE restricted to facesheet-core interface
Single-sided Ultrasound	POSSIBLE	POSSIBLE	POSSIBLE	POSSIBLE restricted to facesheet-core interface
Through-transmission Ultrasound	POSSIBLE	POSSIBLE	POSSIBLE	POSSIBLE

The NDE team recommended the use of multiple NDE methods (where applicable) for the first article production unit and subsequent test articles. All candidate commercial-off-the-shelf NDE systems met or exceeded the established minimum detectable flaw criteria that were established for the CCM project. The primary NDE methods are identified by component type in Table 11.0-2, and the advantages and disadvantages for the use of each NDE method are detailed in Section 5.2.

Table 11.0-2. NDE Methods Identified by Hardware / Component Type

NDE METHOD	HARDWARE/COMPONENT TYPE
IR Thermography	- Facesheet/flat laminates - Sandwich panels: Facesheet-to-core bonds - Bonded joints: joint bondline, caps and doublers
Ultrasound	- Facesheet/flat laminates - Sandwich panels: Facesheet-to-core bonds - Bonded joints: joint bondline, pi-preform bondlines, caps and doublers - Laminate: misc. piece-parts
Radiography	- Sandwich panels: Hoeycomb core or core-to-core bonds - Bushings/Inserts: Hardpoint bondline

All inspections were performed per CCM-SPEC-006, Rev A (which defines defect acceptance criteria) for the following configurations:

a. Facesheets / Flat Laminates (Laminate caps, Doublers)
   - Maximum defect width / diameter was < 0.250-inch
b. Sandwich Facesheet-to-Core Bonds
   - Maximum defect width / diameter was < 0.50-inch (2 x cell size minimum)
c. Pi-Preform-to-Laminate Bonds
   - The maximum permissible bondline defect width / diameter was < 0.125 inch
d. Core-to-Core Bonds
   - Foaming adhesive gaps not to exceed 0.06-inch in length (direction parallel to the splice)
e. Core-to-Insert Bonds
   - Defects or adhesive voids cannot span the entire thickness of the panel (i.e., inner mold line (IML) skin to outer mold line (OML) skin of a sandwich panel)

NDE was performed during three key phases in the project timeline: 1) test article fabrication and developmental testing, 2) full-scale manufacturing, and 3) full-scale testing. The final inspection series occurred after completion of full-scale testing to assess the final condition of the CCM test article.

Inspection data was presented to the team during regular team meetings or during special root cause/failure investigation meetings. The NDE team was a multi-center effort with specific expertise (i.e., ultrasound, thermography, etc.) usually residing at a particular center. Therefore, a standardized NDE reporting format was not adopted by the project. Each NDE organization was permitted to acquire post-process and present data and conclusions based on their center-specific best practice. However, NDE data was consistently presented in a manner that emphasized any critical conditions or features, such as defect-like anomalies, locations, depths, and sizes of pre-existing / known damages, and other pertinent data that would be required for an engineering review board disposition of a defect. Inspections performed by the CCM NDE team are archived in the ICE / Windchill CCM project folder.

A detailed discussion of the NDE for the CCM project is provided in the NESC 06-019 Composite Crew Module: NDE Report.

12.0 Test Overview

For the design and manufacturing of the CCM, the team adopted the building block approach where design and manufacturing risks were mitigated through manufacturing trials and structural testing at various levels of complexity. Because of time constraints, the team was required to execute the building block approach in a quasi-parallel.

The primary objectives of the test project were to:

(a) Reduce project risk through the building block approach.

(b) Provide data for analysis verification in areas of structural complexity (areas around fittings, core ramps, joints, and inserts).

(c) Demonstrate structural integrity under design limit and ultimate load conditions.

The CCM Test report contains information on all element, component, and full-scale level testing. For element and component level tests the analysis / test correlation is presented in the NESC 06-19 Composite Crew Module: Test Report. However, for the full-scale tests, the analysis and analysis / test correlation are presented in the Analysis report. Coupon level testing and element tests, which were associated with material development are presented in the NESC 06-019 Composite Crew Module: Materials and Processes Report.

Structural details that were selected for evaluation at the element level included joints (composite-to-composite and composite-to-metal), aluminum core taper, and metal inserts. At the component level a simplified version of a highly loaded fitting SM / ALAS was designed and tested. Element tests were useful in verifying both the fabrication processes and the analytical techniques. It was found that detailed pre-test analysis was crucial to the success of the element tests.

Full-scale tests included internal pressure, combination of pressure and mechanical load at specific hard points such as the SM / ALAS, main parachute fitting, and mechanical load application at the drogue chute fitting, and inserts.

Full-scale testing was accomplished through the design of a multifunction self-reacting test frame, which served as the backbone for all full-scale load applications. CCM testing was done in an upside down configuration so that installation of loading hardware could be done at the working level, and the risk of damage from dropped hardware was reduced. In addition, the test frame served as the skeleton of the shipping container. The test frame was built in Iuka and was delivered to NASA LaRC along with the full-scale CM for testing. Full-scale testing took place at LaRC's Combined Loads Test System (COLTS) facility. Figure 12.0-1 is an image of the CCM within the shipping and testing frame at the LaRC COLTS facility.

Figure 12.0-1. CCM in Upside Down Configuration within the Self Reacting Load Frame in LaRC's COLTS

A much more detailed discussion of the test activity for the CCM project is provided in the NESC 06-019 Composite Crew Module: Test Report.

13.0 Orion Comparative Study

In September 2008, the Orion Project Manager received an action from the NASA Administrator to evaluate the implications of incorporating the CCM primary structure into the Orion main line project as part of the CxP. A technical study ensued from September to November 2008 to characterize the implications.

13.1 Mass Differences between CCM and Orion

Since the CCM project had baselined loads and interfaces in March 2007, one of the biggest challenges in evaluating the implications of a CCM for Orion was the gap between the CCM configuration and the then current Orion configuration. CCM was at least two load cycles behind Orion; some load cases had increased, such as water landing loads, and some had decreased, such as parachute and drogue loads. In addition, CCM had baselined the LAS interface low on the cylindrical section of the pressure shell at the SM interface. Orion had baselined the LAS interface at the main parachute interface. A goal of the project was to obtain data as quickly as possible and did not allow for a design cycle on the CCM. Therefore, an accurate direct mass comparison was not possible.

However, first order materials comparisons were made that would suggest that mass between the CCM and the Al-Li Orion would be similar. The CCM was strength driven rather than stiffness driven primary structure. The majority of the structure was sized by multiaxial loads caused by internal pressure. The CCM will also be exposed to possible damage during spacecraft integration and during the mission, so damage tolerance knockdowns were used to accommodate for possible impact damage. These factors combined strength rather than stiffness, multiaxial loading, damage tolerant material properties, and limits the performance benefit a composite material system might traditionally offer to a design since strength per unit mass of damage tolerant, quasi isotropic composite materials systems are similar to Al-Li properties. Therefore, there were no expected significant mass differences between the CCM and the Orion Al-Li CM.

13.2 Manufacturability Differences between CCM and Orion

The CCM was built in two halves, an upper and lower, with system assembly performed on both halves before joining the upper to the lower. The major manufacturing operations of the CCM are:

1. CCM Upper
    - 1.1. Layup and cure IML skin
    - 1.2. Cure Honeycomb core to IML skin
    - 1.3. Layup and cure OML skin
    - 1.4. Install Docking Tunnel
    - 1.5. Install Gussets
    - 1.6. Install Gusset caps
    - 1.7. Install main parachute fittings
    - 1.8. Machine window and hatch cutouts
    - 1.9. Install window and hatch frames

2. CCM Lower
    2.1. Layup and cure IML skin
    2.2. Install and cure Honeycomb core
    2.3. Layup and cure OML skin
    2.4. Layup and cure backbone panels
    2.5. Assemble backbone panels
    2.6. Install and cure backbone to lower shell
    2.7. Layup and cure backbone cap
    2.8. Install backbone in lower shell assembly
    2.9. Install metallic interface fittings on Lower shell
3. CCM Assembly
    3.1. Splice longeron regions of assembly
    3.2. Splice acreage regions of assembly

The Orion design was especially different in operations. The lower barrel, aft dome, ceiling, and docking tunnel were each one piece components machined to final dimension in a computer controlled machining center. The Orion conic was fabricated from six segments with hatch, windows, and longerons integrally machined. The individual components were assembled using automated friction stir welding techniques with built in inspection.

The CCM approach could be improved through the use of automated fiber placement. However, this would only improve the layup and cure of the upper and lower sandwich systems, which represented only 2 months of the 9 month assembly process.

It was determined by both the Orion and CCM teams that manufacturability comparisons yielded no measureable benefit between the two different material systems.

One exception was the use of the assembly joint between the upper and lower pressure shell in the CCM. This joint was intended to offer potential benefits during subsystem integration as part of the overall spacecraft integration process. The Orion team developed a similar clam shell approach for their design, but it was later discarded as not being advantageous in the overall system integration flow.

13.3 Other Technology Gaps

In addition to the mass and manufacturing comparisons, there were numerous technology gaps identified by the Orion team with respect to adopting the CCM design. These technology gaps represented a risk to the Orion project. Given that CCM did not provide a quantifiable advantage, and represented numerous additional risks, the decision was made not to incorporate the CCM into the Orion baseline.

Since completion of the study in November 2008, some of the technology gaps have evolved and, in some cases, have been retired.

13.3.1 Damage Tolerance for Leak Integrity

The CCM leak integrity approach was to use predominantly sandwich systems with unvented core. The approach provided two barriers against through thickness permeability through the use of the IML skin and the OML skin. However, it was shown that exceedingly low impact damage, less than 2 ft/lb, could cause leakage and would not be detectable visibly or with NDE techniques. Given the extensive subsystem integration both on the inside and the outside of the CCM, there was a possibility of undetected damage coincident on the inside and outside that could provide an undetected leak path.

Some damage tolerant liners were studied during the CCM project and were shown to prevent leakage even after impact on biaxially loaded test coupons. However, this work was limited to coupon testing and was not demonstrated on the full-scale assembly. This work is discussed in more detail in the NESC 06-019 Composite Crew Module: Materials and Processes Report.

13.3.2 Damage Tolerance as Related to Structural Integrity

At the time of the Orion study, little if any damage tolerance work had been done on the CCM project except for the use of damage tolerant material allowable. However, the subsequent test project included numerous damage tolerant evaluation tests, including the effect of 6 ft/lb impacts at 18 different locations followed by inspection, testing to ultimate design levels, and then cyclic testing through four life times. Additional impact sites were impacted to 26 ft/lb and inspection, testing to ultimate design levels, and then cyclic testing through four life times and were repeated. In all cases, no detrimental growth of damage was shown.

13.3.3 Inspection of CCM Pressure Vessel

Inspections of the CCM pressure vessel were closely tied to the damage tolerance program for the structure. On CCM, impact damage was induced, measured visually, and then measured using different state-of-the-art NDE techniques. As mentioned earlier, in all cases, no detrimental growth of damage was shown.

On CCM, there are bonded joints in the primary load path that cannot be verified acceptable by inspection, particularly the docking tunnel interface ring and the main assembly splice joint. Since these joints are process-dependent, it was expected that some level of acceptance testing would be necessary for each assembly prior to flight. The team envisioned some level of proof test for the acceptance test, but did not finalize a position on this issue.

13.3.4 Splice Joint Feasibility

During the Orion study, the viability of the out-of-autoclave splice joint was in question because the operation had yet to be performed on the CCM project. There was particular concern about the manufacturing tolerance, leakage, structural integrity, and out-of-autoclave approach. As demonstrated by the final assembly and test results, the manufacturing tolerance, structural integrity, and out-of-autoclave technique were validated. The leakage, or more accurately, permeability in the out-of-autoclave material system, was managed by using a material system appropriate for out-of-autoclave curing, or by the use of a secondary barrier as discussed in Section 13.3.1.

13.3.5 Repair Techniques for Pressure Containment and Structural Integrity

CCM repair occurred numerous times during the development of the manufacturing process. Repair techniques were applied to correct for manufacturing anomalies such as tooling shift during cure of Pi-preforms, improper cure of splice doublers, excess void in docking tunnel doublers, and removal and replacement of tunnel gusset Pi joints following disbond from over constrained tooling. Additionally, repairs were made following impact damage caused by tool drop. These repairs are addressed more comprehensively in the NESC 06-019 Composite Crew Module: Materials and Processes Report

13.3.6 Verification and Certification

Verification and certification of composite primary structure for human spaceflight was not in the scope of the CCM project.

13.3.7 Material System Solution

Technology gaps associated with space environments and mission duration impacts and compatibility were cited as well as with the unvented core approach to leak protection versus the lunar mission requirements for leakage. These gaps are well within NASA's knowledge base and are not viewed as major risks for future composite spacecraft.

13.3.8 Penetrations to the Pressure Shell – Maintaining Leak Integrity

The CCM contains fastener penetrations through the pressure shell. The design baselined the use of polysulfide sealant, wet installed with the fasteners, as the method for managing leak integrity around the penetrations. The polysulfide passed many of NASA test Standard 6001 for compatibility, but represented an odor problem. It is believed that an alternative that preserves the advantages of polysulfide, but without the obnoxious odor, could be identified and demonstrated if a composite pressure shell was adopted for a human spaceflight program.

14.0 Findings and NESC Recommendations

14.1 Findings

The following findings were identified:

F-1. Many of the design, analysis, materials, and manufacturing lessons learned were not evident in the coupon, element, or subcomponent testing and only became evident when building the full-scale assembly.

F-2. Small agile teams—emphasizing "in-line" work—working in parallel with the flight project can achieve significant results through rapid decision making. These teams can exploit unforeseen opportunities and minimize consequence of risk with quick recovery to problems that occur.

F-3. Project collocations served as a valuable tool for developing relationships among team members and for achieving significant technical results quickly.

F-4. Frequent telecoms, WebEx™, instant messaging, and desktop sharing were critical tools enabling virtual project management when the team was not collocated.

F-5. Critical path project tools were the key method for managing overall project priorities, schedule performance, and cost performance.

F-6. Small, but focused, independent technical reviews with subject matter experts were effective for challenging team assumptions and technical decisions resulting in increased innovation and a higher motivated team.

F-7. Overall travel expenditures were insignificant expenses relative to the project value even though significant time was spent in team collocations throughout the design, development, manufacturing, and test phases.

F-8. Through thickness leakage or permeability, there remains an area for demonstrating solutions at the full-scale complex shape level, especially in applications exposed to possible impact damage.

14.2 NESC Recommendations

The following NESC recommendations were identified and directed towards the ESMD unless otherwise identified:

R-1. It is recommended that Programs/Projects consider implementing full-scale manufacturing development early in the conceptual design phase so that manufacturing lessons can be incorporated as the design evolves. ***(F-1)***

R-2. It is recommended that future Human Spaceflight Programs demonstrate permeability and leakage solutions on complex polymeric composite components such as the CCM. ***(F-8)***

15.0 Alternate Viewpoints

There were no alternate viewpoints identified during the course of this assessment by the NESC team or the NRB quorum.

16.0 Other Deliverables

No unique hardware, software, or data packages, outside those contained in this report, were disseminated to other parties outside this assessment.

17.0 Lessons Learned

LL-1. Small agile teams—emphasizing "in-line" work—working in parallel with, but outside the umbrella of a flight project can achieve significant results through rapid decision making. These teams can exploit unforeseen opportunities and minimize consequence of risk with quick recovery to problems that may occur.

LL-2. Engineering models predicted mass and structural response well.

LL-3. Engineering models did not always predict production challenges.

18.0 Definition of Terms

Corrective Actions: Changes to design processes, work instructions, workmanship practices, training, inspections, tests, procedures, specifications, drawings, tools, equipment, facilities, resources, or material that result in preventing, minimizing, or limiting the potential for recurrence of a problem.

Finding: A conclusion based on facts established by the investigating authority.

Lessons Learned: Knowledge or understanding gained by experience. The experience may be positive, as in a successful test or mission, or negative, as in a mishap or failure. A lesson must be significant in that it has real or assumed impact on operations; valid in that it is factually and technically correct; and applicable in that it identifies a specific design, process, or decision that reduces or limits the potential for failures and mishaps, or reinforces a positive result.

Observation: A factor, event, or circumstance identified during the assessment that did not contribute to the problem, but if left uncorrected has the potential to cause a mishap, injury, or increase the severity should a mishap occur. Alternatively, an observation could be a positive acknowledgement of a Center/Program/Project/Organization's operational structure, tools, and/or support provided.

Problem	The subject of the independent technical assessment.
Proximate Cause	The event(s) that occurred, including any condition(s) that existed immediately before the undesired outcome, directly resulted in its occurrence and, if eliminated or modified, would have prevented the undesired outcome.
Recommendation	An action identified by the NESC to correct a root cause or deficiency identified during the investigation. The recommendations may be used by the responsible Center/Program/Project/Organization in the preparation of a corrective action plan.
Root Cause	One of multiple factors (events, conditions, or organizational factors) that contributed to or created the proximate cause and subsequent undesired outcome and, if eliminated or modified, would have prevented the undesired outcome. Typically, multiple root causes contribute to an undesired outcome.

19.0 Acronyms List

3D	Three Dimensional
AA	Associate Administrator
AC	Actual Cost
ALAS	Alternate Launch Abort System
Al-Li	Aluminum Lithium
ATK	Alliant Techsystems, Inc.
CAD	Computer-Aided Design
CCM	Composite Crew Module
CEV	Crew Exploration Vehicle
CM	Crew Module
COLTS	Combined Loads Test System
CxP	Constellation Program
DCO	Document Change Order
EAC	Estimate to Complete
EO	Engineering Order
ESMD	Exploration Systems Mission Directorate
ETC	Estimate to Complete
EV	Earned Value
EVM	Earned Value Management
FTE	Full-Time Equivalent
GSFC	Goddard Space Flight Center
ICE	Integrated Collaborative Environment
IML	Inner Mold Line

IR	Infrared
ITAR	International Traffic In Arms Regulations
JSC	Johnson Space Center
KSC	Kennedy Space Center
LaRC	Langley Research Center
LAS	Launch Abort System
lbs	pounds
MDT	Manufacturing Development Team
MIL-STD	Military Standard
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NASTRAN®	NASA Structural Analysis System
NDE	Non-Destructive Evaluation
NESC	NASA Engineering and Safety Center
NRB	NESC Review Board
OML	Outer Mold Line
Pro-E®	Pro Engineering®
PTC	Parametric Technology Corporation
PV	Planned Value
SBT	Smart Buyer Team
SM	Service Module
WYE	Work Year Equivalent

20.0 References

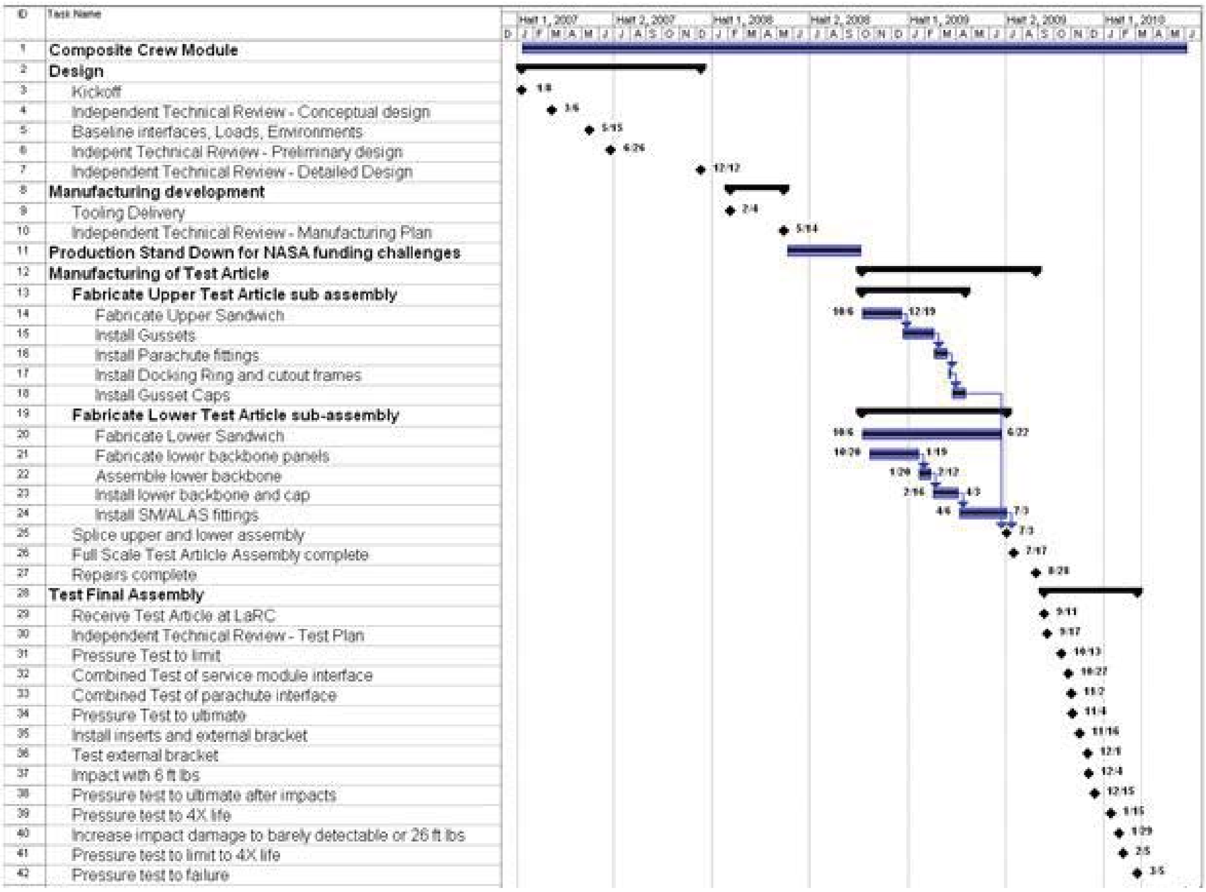
1. Oscar Hoffman, The Brittle Strength of Orthotropic Materials, Journal of Composite Materials, April 1967, pp 200-206.

21.0 Appendices

Appendix A. Major Project Milestones

Appendix B. CCM Team List

Appendix A. Major Project Milestones



Appendix B. CCM Team List

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14. ABSTRACT
In January 2007, the NASA Administrator and Associate Administrator for the Exploration Systems Mission Directorate chartered the NASA Engineering and Safety Center to design, build, and test a full-scale crew module primary structure, using carbon fiber reinforced epoxy based composite materials. The overall goal of the Composite Crew Module project was to develop a team from the NASA family with hands-on experience in composite design, manufacturing, and testing in anticipation of future space exploration systems being made of composite materials. The CCM project was planned to run concurrently with the Orion project's baseline metallic design within the Constellation Program so that features could be compared and discussed without inducing risk to the overall Program. This report discusses the project management aspects of the project including team organization, decision making, independent technical reviews, and cost and schedule management approach.

15. SUBJECT TERMS
Composite Crew Module; NASA Engineering and Safety Center; Alternate Launch Abort System; Exploration Systems Mission Directorate

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