

Project Management of the Capsule Parachute Assembly System (CPAS)

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Since the time of contract award of the Orion Crew Exploration Vehicle in 2006, NASA has spearheaded the design, development, test and evaluation of the Orion aerodynamic decelerator system through a Government Furnished Equipment project in the Engineering Directorate of the Johnson Space Center. This paper will describe the Project structure and organization, the interfaces to the major stakeholders, the processes applied, and a few major budget, schedule and technical challenges overcome.

I. Introduction

The Capsule Parachute Assembly System (CPAS) Project is a Government Furnished Equipment (GFE) project within the Johnson Space Center Engineering Directorate responsible for the design, development, certification, production, and delivery of the parachute system for the Orion Multi-Purpose Crew Vehicle (MPCV) Program and supports the Orion flight tests through the first human flight called Exploration Mission-2. The MPCV consists of a Crew Module, Service Module and Launch Abort System (Fig. 1). The Crew Module (CM) is the habitable volume of the Orion MPCV and functions as the command, control, communications, and navigation center for all in-space operations.

The CPAS consists of parachutes stowed and deployed from the forward bay of the Orion Crew Module after re-entry for a nominal mission or after a launch vehicle abort to support deceleration and landing. The system includes 3 mortar deployed Forward Bay Cover Parachutes (FBCPs) which assist in extraction and separation of the Forward Bay Cover, 2 mortar deployed drogue parachutes which provide initial CM stabilization and deceleration, 3 mortar deployed pilot parachutes to each deploy a main parachute, and 3 main parachutes to provide final stabilization, deceleration, and landing of the CM (Fig. 2). Each parachute is packed in its own deployment bag, and the main parachute includes a retention system. For the mortar deployed parachutes, the key external interface are the mortar assemblies provided by Lockheed Martin under the Orion contract, as well as the vehicle structure for interfacing the main and drogue parachute risers and main retention system. For each of the parachute sequences, the system is designed to meet vehicle requirements for a safe landing even if one of each parachute type failed to deploy.

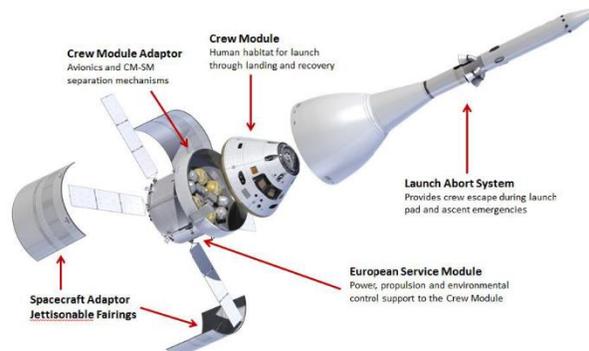


Fig. 1 Multi-Purpose Crew Vehicle Elements



Fig. 2 Capsule Parachute Assembly System (Deployed)

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II. Project Structure and Organization

The Project is supported by several organizations within the Johnson Space Center (JSC) as well as several external to JSC. A list of organizations is illustrated in, but is not limited to, Fig 3. In particular, this list does not include all the test facilities (e.g. structural/loads, avionics, vacuum/thermal chamber, vibration, wind tunnel, receiving chamber, inspection) or intermediate support (e.g. fabrication, photography/videography, academic research) that was utilized.

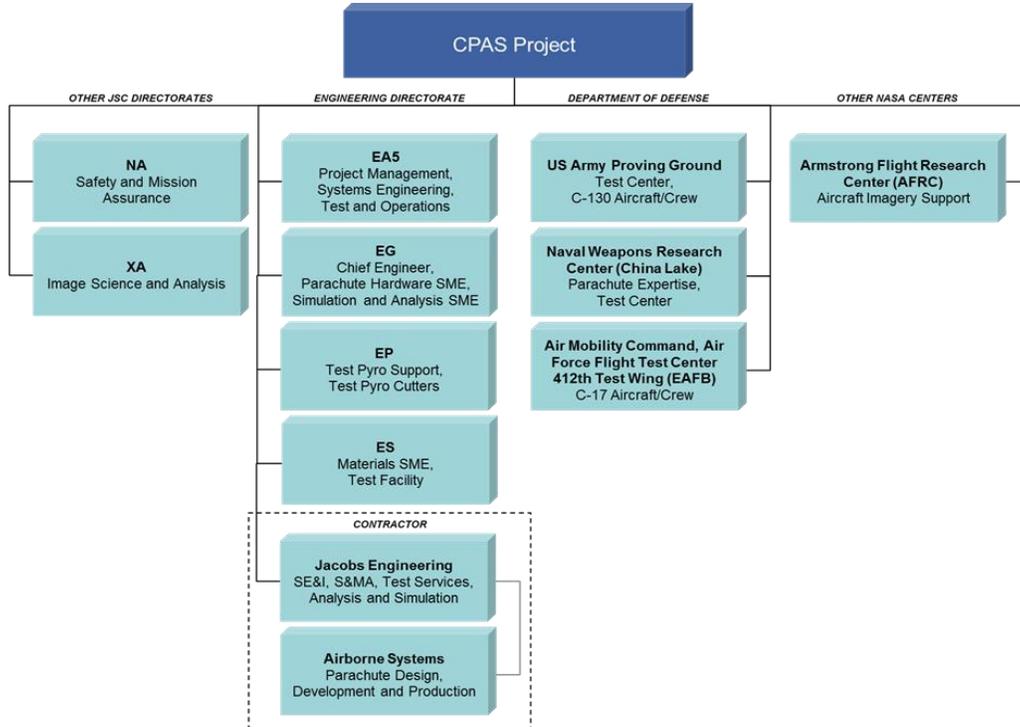


Fig 3. CPAS Project Support Organizations

NASA civil servants form the foundation of the project team with expertise in project management, parachute hardware development, systems engineering and integration, safety and mission assurance, simulation and analysis, and test and operations. The civil servant team is also the primary interface with the customer, the Orion Program, and associated stakeholders. Beyond the civil servant team, the Project utilizes the JSC Engineering, Technology and Science (JETS) contract with Jacobs Engineering for primary in-house engineering support, which also includes a sub-contract with Airborne Systems North America (a.k.a. Airborne) who is the supplier of the parachute hardware. This partnership serves as the fundamental workhorse of the Project.

Several Department of Defense (DoD) military branches are also utilized in the development and certification of the parachute hardware as well. The US Army Yuma Proving Ground (YPG) has the capability to test large scale parachute systems with proven capabilities such as aircraft, range, and imagery and acts as the primary test center support for parachute airdrop testing. The 412th Test Wing (412 TW) of the Air Force Flight Test Center (AFFTC) at Edwards Air Force Base, through the Air Mobility Command (AMC), operates the C-17 aircraft with the capability to extract large scale parachute payloads, and provides the C-17 aircraft to support parachute airdrop testing through a military branch sponsor (Army or Navy). In this situation, the Project is dependent on both test range and aircraft scheduling and availability from these DoD services. The Naval Weapons Research Center at China Lake is utilized for resident parachute hardware expertise and provides engineering support for the development and certification of the hardware. In addition China Lake provides test center support when required for parachute testing.

The Project management structure was set up discipline specific with Integrated Product Teams (IPTs) as depicted in Fig. 4. The Management IPT (M-IPT) consists of the Project Manager, Deputy Project Manager, two Technical Authority (TA) positions of a Project Chief Engineer and a Safety and Mission Assurance Lead, and the Team Manager from the other IPTs. Each IPT Team Manager and TA position is responsible for defining lines of communication within the team, defining splinter teams, defining distribution lists, distributing agendas and briefing charts, preparing meeting minutes, and managing key data storage in a centralized collaborative system. Each IPT is also responsible to ensure the full and complete visibility across the activities of the other teams.

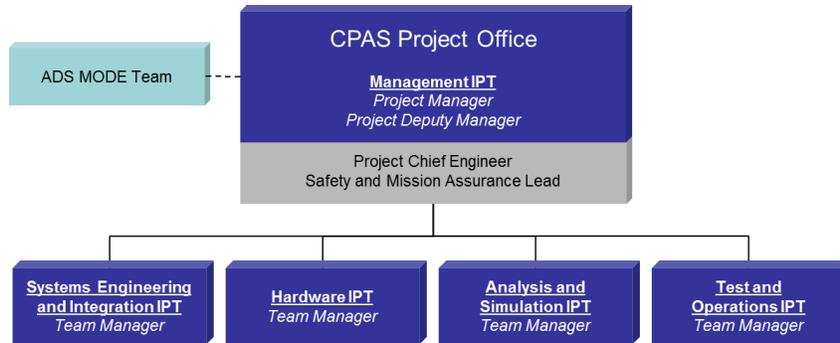


Fig. 4 CPAS Project Management Structure

A brief description of the primary responsibility of each IPT follows. The organization of the Jacobs Engineering and Airborne teams mirror this IPT structure and participate as primary members.

Management IPT

The management team is responsible for the overall integration and operation of the project team. It is the responsibility of the management team to ensure that the combined efforts of the team result in the most effective integrated product meeting customer expectations.

Project Chief Engineer

The primary role of the Project Chief Engineer is to serve as a Subject Matter Expert (SME) for the parachute hardware and testing, and to ensure that project cost and schedule pressures do not unduly affect the decision-making process and inadvertently compromise technical decisions necessary for a safe and functional system.

Safety and Mission Assurance Lead

The primary role of the S&MA Lead is to serve as a SME for the safety and quality products for the parachute system, and to ensure that project cost and schedule pressures do not unduly affect the decision-making process and inadvertently compromise technical decisions necessary for a safe and functional system.

Systems Engineering and Integration (SE&I) IPT

The SE&I Team is responsible for overseeing the requirements, verification, and external interfaces between the Project and the other vehicle systems. These interfaces include primary and secondary structures, mass and volume allocations, loads, trajectories and deployment envelopes, and model updates. This team manages product development and delivery activities for certification.

Hardware IPT

The Hardware Team is responsible for the development and certification of the CPAS hardware systems. This includes ensuring technical compatibility and integration of the components and subcomponents, managing the parachute hardware anomaly activities and resolution, and approving repair or design changes to the parachute hardware.

Analysis and Simulation IPT

The Analysis and Simulation Team is responsible for the development, validation, execution and maintenance of simulations and analyses in support of the parachute models which describe the hardware performance that are utilized in Orion Guidance, Navigation, and Control (GN&C) end-to-end simulations. The Simulation and Analysis Team is also responsible for the development, execution and maintenance of simulations and analyses to support test techniques and test execution.

Test and Operations IPT

The Test and Operations Team is responsible for the test definition, test planning, test execution, performing post-test inspections, and reporting of testing to support the design and certification of the CPAS system. This responsibility includes the design and implementation of the test support equipment.

III. Project Team Interfaces

The primary management interfaces for the Project are with the Orion Program, which includes the Prime Contractor and Technical Authority representatives, as well as the Engineering Directorate which serves as the home organization for the Project. The customer is defined as the Crew and Service Module Office within the Program, and

the hardware directly interfaces and integrates into the vehicle designed and produced by the Prime Contractor Lockheed Martin. Technical Authority personnel are those from the Chief Engineer's office and the Safety and Mission Assurance office and are embedded in the MPCV Program and interface the Project. The following meetings described are a sampling of the more significant Project management interfaces.

With the significant amount of collaboration necessary between the complex interfaces of the CPAS and the vehicle systems being designed by Lockheed Martin, the Prime Contractor for the Orion Multi-Purpose Crew Vehicle, an Aerodynamic Decelerator System (ADS) Multi-Organizational Development Engineering (MODE) team meeting (Fig. 4) is utilized as a direct line to the Project to communicate and coordinate the status of events and the resolution of technical issues between the CPAS Project and Lockheed Martin on a weekly basis. The ADS MODE team meeting is co-chaired by the CPAS Project Manager and the Lockheed Martin (LM) Landing and Recovery System (LRS) Certified Principle Engineer. Each CPAS IPT Team Manager, TA position, and LM LRS component manager forms the membership. This meeting is not decisional or binding, but can identify the appropriate board, panel or forum if a decision on a topic is needed.

The primary Orion Program board interface for the Project is the Government Equipment and Materials Control Board (GEMCB) which is within the Crew and Service Module office. In general the GEMCB manages decisions on Project product baseline changes, risk acceptance, and is the direct authority for providing Program direction to and receiving products from the Project. The GEMCB is on an as-needed basis.

A lower tier Program forum is the Descent and Landing Working Group that facilitates system success of the descent and landing phases by providing a venue to peer review interfacing products and for identifying and resolving issues between the Guidance, Navigation and Control (GN&C) system, the LRS, the CPAS, the Loads and Dynamics (L&D) group, and Aerosciences. This meeting is also on an as-needed basis.

Within the Engineering Directorate, the Project interacts with several forums under an existing governing structure such as the Engineering Staff Meeting, the Engineering Leadership Council (ELC), and the Engineering MPCV Technical Tag up. These are only on an as-needed basis. The Engineering Staff Meeting reviews topics or issues in work that the leadership team needs to understand and discusses the decisions/rationale being made. The ELC reviews, among other things, risks and strategic Project topics. The Engineering MPCV tag up consists of Engineering TA stakeholders and primarily reviews special topics going to Program or Project boards.

IV. Project Reviews and Management Processes

A. Budget and Schedule Management

The NASA Planning, Programing, Budget and Execution (PPBE) process sets the budget and dictates the schedule for the Project activities by fiscal year. This process is performed annually in support of the Program and Project costs are re-evaluated with the team and with the contractors. This results in negotiated content, including personnel and material resources, and associated milestones that fit within Program funding.

The annual budget is managed by the Project through monthly financial reviews with the contractor to monitor performance. Adjustments can be made to cover cost over-runs by finding internal Project opportunities which is the preferred method, or in more extreme cases by additional funding requests to the Program. Additionally, cost under-runs provide funding opportunities back to the Program to cover other cost liens. A Technical Cost Schedule Review (TCSR) is also performed on a periodic basis with the Program, which reviews the technical, cost and schedule performance of the Project, including risks and accomplishments.

The Project schedule performance is tracked on a bi-weekly basis by reviewing intermediate milestones that lead to major events. These milestones may include airdrop tests, significant ground tests, Prime Contractor mortar integration activities, parachute fabrication, key project reviews, and model memo product releases. A pictorial schedule including these intermediate and high-level key milestones for reference is maintained by the Project and used for general team awareness and Program reviews.

When schedule issues are highlighted during bi-weekly reviews, a deep dive with the team provides insight and accuracy. This allows for iterative decisions based on changing priorities, if required, to mitigate areas of schedule concern. A detailed integrated schedule is also maintained and demonstrates an understanding of the interdependencies. If changes to the key milestones or dates are required that affect external stakeholders or extend beyond the planned fiscal year, they are negotiated with the Program at the GEMCB.

B. Technical Reviews

The Project utilizes technical reviews to confirm the progress and completion of the life cycle phases. Per Engineering Directorate practices, the technical reviews applicable to the Project include the Systems Requirements Review (SRR), Preliminary Design Review (PDR), Critical Design Review (CDR) and System Acceptance Review

(SAR). Fig. 5 depicts the life cycle phases, technical reviews, and the completion dates for the Project for many of the reviews. As of the writing of this paper, the Project is in Phase D which includes production and certification as well as delivery and launch. The Project is planning to complete the SAR in September of 2019.

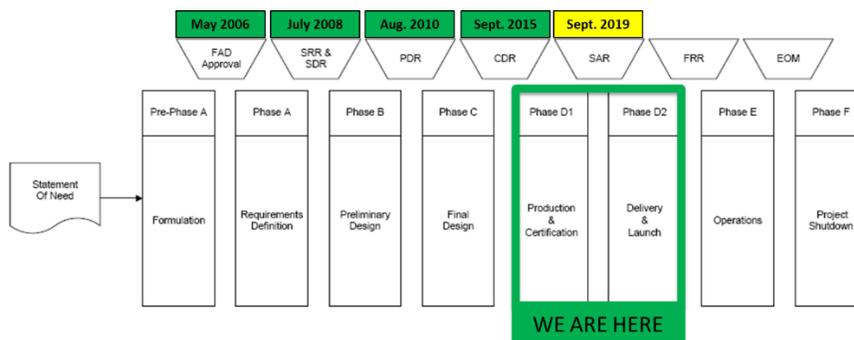


Fig. 5 CPAS Project Technical Reviews

Another set of technical reviews utilized more specifically to manage the delivery of a flight item, such as a parachute, include the Functional Configuration Audit (FCA), Physical Configuration Audit (PCA), and Hardware Acceptance Review (HAR). The primary purpose of the FCA is to review the design and drawings of a parachute, determine its acceptability to meet performance requirements, and provide authorization to proceed to fabrication of the parachute. The PCA is then performed prior to packing of a parachute to review the summary of inspections completed during fabrication, the readiness of the procedures to be utilized in the packing and assembly, and provide authorization to proceed with parachute packing. The HAR is the final review and examines the readiness of a parachute and documentation in support of delivery, and authorizes the delivery including transfer of ownership.

In support of Project testing, a Test Configuration Review (TCR) is utilized to review the planned test and hardware configuration(s) and analysis to verify it meets the planned test objectives, and to authorize proceeding with test hardware assembly. Additionally, a Test Readiness Review (TRR) assesses the final hardware configuration and readiness of the system to be tested, facility readiness, and provides authorization to proceed with testing.

C. Configuration Management

At each major technical review, products are developed to document the baseline of the technical configuration being reviewed and approved. When required, these technical baselines receive Program approval at the GEMCB.

In between the major technical reviews, technical configurations are managed by the Project IPTs as applicable through the use of both informal and formal documentation. One example of formal documentation the Project used is the Technical Guidance Document (TGD) which is implemented to capture the iterative hardware configuration during the development of the system leading to the CDR. This TGD includes key technical decisions and configurations applicable to the detailed design of the hardware not otherwise captured in other formal products, and important enough to be identified outside of an informal product (meeting minutes, etc).

In establishing the CDR baseline, approval for changes to products that define the design or process require a Change Request (CR) and approval at a Project Change Control Board (CCB) chaired by the Project Manager. The CCB includes the CPAS IPT managers, CPAS TA positions, and the contractor Project manager as standing members of the board. Ad-hoc members that include external Project stakeholders are requested to attend if the agenda item affects their area of responsibility. Additionally, for Project documentation that has Program signature or for hardware changes that effect external stakeholders or vehicle performance such as requirements compliance, interfaces, mass, or modeled performance, the Change Request (CR) is further reviewed and approved by the GEMB.

In addition to the CCB, a Material Review Board (MRB) was established by the Project shortly after CDR to review, disposition and record non-conformances to CPAS flight end items and associated products. Primary instances of non-conformances occurred at the contractor or vendor level since that is where the hardware was being produced, so the MRB process for the Project was developed in concert with their processes and ensured efficient collaboration on the disposition. The contractor had authority to return an item to print, return an item to a vendor, or scrap an item as long as there was no cost impact to the agreed budget or schedule impact to the agreed milestones. Dispositions that involved repairing an item, using an item as-is, or sorting a group of items to remove discrepant items required approval from the Project. Further, if the item involved hardware provided by the Program (including Lockheed Martin) or involved flight hardware to be delivered to the Program, the disposition required approval at the GEMCB.

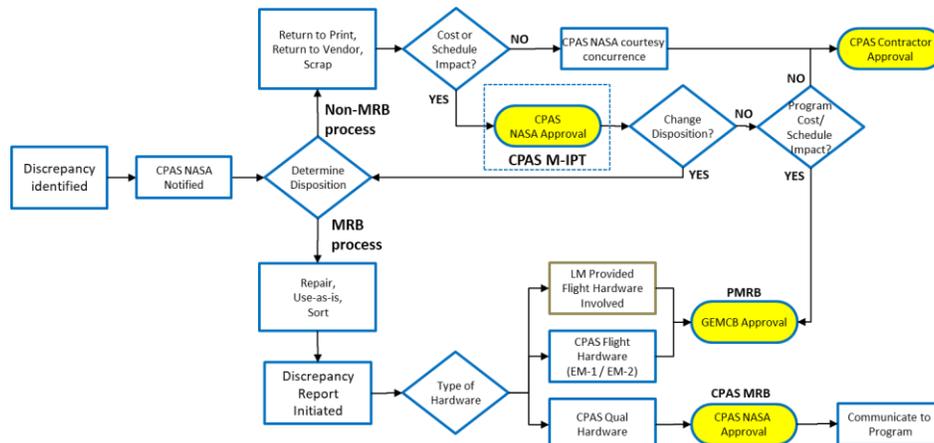


Fig. 6 CPAS Project Material Review Board Process

D. Risk Management

Risk management is used to identify activities or events that have some probability of adverse consequence on the performance, schedule, cost or safety of the project and/or system. The risk management process enables proactive task planning and risk informed decision making designed to ensure the success of the Project. The Project inherently follows a Risk-Informed Decision Making (RIDM) process and a Continuous Risk Management (CRM) process (Fig. 7) and manages 1) technical risks that may have a consequence of safety, performance, recovery cost and schedule and 2) cost threats and liens specific to Project and Program financial capabilities. Both are reviewed with the Program and home organization on a frequent basis to continually inform and sometimes execute decisions (e.g. risk acceptance or funding allocation change) when required.

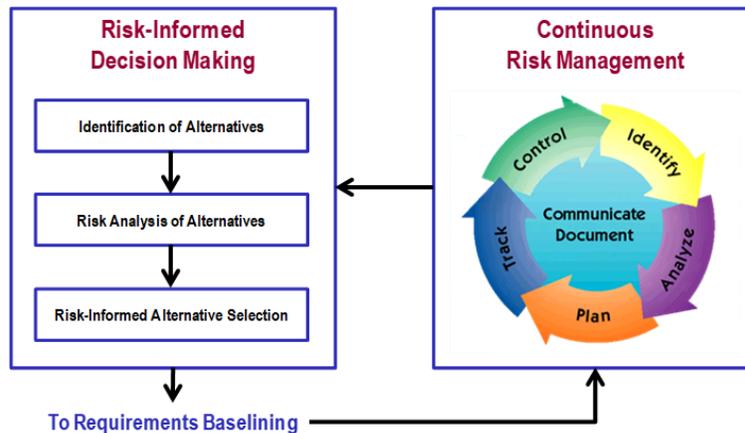


Fig. 7 Continuous Risk Management Process [1]

Technical Risks are assigned attributes of likelihood and consequence using definitions and scales defined by the Program. Likelihood ratings range from 1 (very unlikely to occur) to 5 (nearly certain to occur), and consequences are divided into subcategories of safety, performance, cost and schedule each with a range from 1 (low consequence) to 5 (very high consequence). While the assignment of attributes require judgement, it enables a debate and discussion among the team for a deeper understanding of the risk.

Cost threats and liens are costs not included in the baseline budget of the Project. Cost threats are defined as identified activities or events that if they occur will cause a cost impact to the Project. These can be inclusive and linked to technical risks that have a consequence of a recovery cost, but may also include stakeholder influences that have a causal effect of adding cost content to the Project. Cost liens are defined as identified activities or events that become part of the technical baseline but have not yet been incorporated into the cost baseline and therefore needs to be reconciled with either funding augmentation, prioritization, or off-sets such as affordability initiatives.

Specific to parachute airdrop testing which utilizes complex testing techniques, a test risk acceptance plan has been developed by the Project which calls for Program, Engineering Directorate and Safety and Mission Assurance review and approval of risks associated with the tests. This plan calls for a pre-declaration of hardware damage in order to preclude test failures being treated as mishaps. A risk level for each airdrop test is defined based on airdrop test complexity and test hardware replacement cost. The complexity of each test will be scored as low, medium, or high based on test vehicle complexity, aerodynamics and stability complexity, test sequence complexity, maturity of simulation and analysis capability, number of test chutes and complexity of rigging, and presence of mortars and mechanisms. The hardware replacement cost for each test will be scored as low, medium, or high where high is based on losing all hardware associated with the test configuration. The approval/acceptance process for the mishap preparedness includes a test risk briefing by the Project to define the risk level and review the test risks, mitigations, and residual risks. This briefing is followed by a written risk acceptance statement defining the residual risk for signature by the approvers.

V. Project Culture

Team culture is made up of values, beliefs, attitudes and behaviors and is often an inherent trait of a team. Team culture is cultivated by the team leadership to achieve a desired state, and takes buy-in from the organizations involved, including influences from the stakeholders and the customer (Program). One of the internal behaviors adopted by the CPAS project is that of a ‘badge-less team’ among the NASA civil servants, the Jacobs contractors, and the Airborne contractors. It isn’t always perfect, but the team behaves as if they belonged to the same organization while still recognizing contractual constraints that exist. This is heavily supported and influenced by the management in each organization, and the environment is grounded by the fact the entire team wants to execute the same objective – to develop and certify this system for deep space human flight – which we all believe is an exciting endeavor to do. Given this common ground, it is usually easy to re-focus to this objective to be on the same playing field together. The badge-less team environment is a critical component of the efficiency and success of the Project, and a testament to the quality of leadership from both Jacobs and Airborne.

The badge-less team environment is also supported by trust among team members which heavily influences the Project success. While the team is fortunate to have personnel with incredible expertise across the IPTs, it still takes trust both outside and inside of IPTs to enable greater flexibility in decision making on individual analysis, design, testing, and systems engineering tasks without significant overhead. Trust also enables inclusion where different viewpoints are welcome and ensures the team is looking at the problem and solution space from many angles to determine the forward plans.

Trust also plays a role in the relationship between the Project and the Program (customer). The Project has worked hard to maintain a good relationship with the Program which again affords greater flexibility in Project decision making without significant overhead. This comes with an understanding that if significant issues are identified and being worked, the Project will always communicate it with the Program or bring the topic to a GEMCB for discussion and decision. Similarly, a good relationship with the Lockheed Martin personnel who are the primary interfaces with the CPAS is key so that both teams recognize and support each other for the common objectives. This is one of goals behind the ADS MODE meeting described in Section III.

While motivation was never a significant concern within the Project, awards have been utilized to recognize the efforts of team members. The Project has a peer award that is distributed on a frequent basis and includes all contractors. Nominations of this award come from any team member to recognize individuals or groups of who has demonstrated some exemplary performance or enabled a noteworthy achievement that is above and beyond their normal duties in support of the Project. Nominations can also include (and are encouraged to include) those from supporting organizations that may not be a part of the Project but have played a critical role in the achievement of a Project task or milestone. The Project awards are not limited in count and are presented in front of peers by Project management.

Beyond the typical technical communication and coordination among the team, the Project holds an All-Hands meeting on an approximate quarterly basis. The All-Hands is used as an opportunity to pause and reflect on recent accomplishments (the past) and thank the team for their efforts, discuss current news (the present) regarding the Agency, Johnson Space Center or Program that influence Project decisions and strategy being made, and review at a high level the upcoming milestones (the future) and why they are so important to be executed in the timeframe planned. At each All-Hands a team member is also featured to learn more about each other. At times the All-Hands meeting is also combined with a pot-luck lunch or a fun activity giving team members more opportunity to socialize. In addition to the All-Hands, a newsletter is published with similar information but for wider distribution including all stakeholders.

VI. Project Challenges

E. Risk Management of Parachute Pendulum

Well into the airdrop test program of the Engineering Development Unit design of the CPAS, a well formed pendulum swinging motion of the test vehicle under two main parachutes was observed. This pendulum motion was further recognized as adverse to the structural integrity of the crew module for nominal landing conditions by imparting higher loads than designed from the increased angle of water at landing impact and increased crew module velocity dispersions. The physics behind the parachute stability, the root cause, was not well understood nor characterized in models, and this phenomena represented a significant risk to the spacecraft. Further exacerbating the problem, the Exploration Flight Test-1 (EFT-1) was launching in six months, and the Exploration Mission-1 (EM-1) spacecraft design was already in progress.

The pendulum issue was highly complex, spanning multiple spacecraft disciplines including aerodynamics and simulation for pendulum modeling development, Guidance, Navigation and Control (GN&C) for landing control authority under parachutes assessment, Loads & Dynamics, Landing and Recovery Systems, and Structures for structural capability assessment, systems reliability for vehicle risk assessment, and the CPAS for design mitigation assessment. The goal would be to iterate on options and mitigations in an effort to satisfactorily reduce the risk associated with a structural failure of the vehicle upon water landing, and this issue would end up being a good example of the risk management process.

For the CPAS Project, this issue would drive significant technical, schedule, cost and risk impacts to be addressed. A strategic plan was developed which would first identify feasible design alternatives to mitigate the pendulum phenomena. Next, targets for parachute performance would need to be defined with stakeholders to provide a success criteria for which to evaluate design alternatives. Methods to evaluate the risks and benefits of design and performance changes would need to be identified, which could include subject matter expertise, Computational Fluid Dynamics (CFD) and LS-Dyna analysis, wind tunnel testing, and airdrop testing. Finally, this plan would need to be iterated with the Program and stakeholders throughout the assessment. Inherently, this plan followed the process of Risk-Informed Decision Making [Reference].

Initial schedule estimates to complete this assessment was anywhere from a 6 month to a 2 year slip of the CPAS CDR and subsequent milestones depending on the potential design solution and evaluation activities required. This uncertainty made a cost for the mitigation activities hard to estimate. High level technical risks included design changes that could further impact interfaces, loads or mass; not receiving the targets by the integrated vehicle systems analysis for parachute performance in order to inform potential parachute design mitigations; and analysis or testing that may not sufficiently inform the updated performance and/or ultimately result in unintended consequences. Further, the plan was aggressive in schedule and still immature whereas further schedule or cost impacts were likely. But over a short period, the plan continued to be iterated and matured with cost estimates tied to tasks and received direction from the Program to move forward with implementing the strategy.

The strategic plan would continue to be matured and iterated with Program agreement along the way and resulted in overall assessment shown in Fig. 7 Continuous Risk Management Process [1]Fig. 7. The strategy utilized legacy knowledge along with CFD and LS-Dyna modeling to assess parachute design change options, an EDU airdrop test to assess a parachute modification, and subscale parachutes that would ultimately be tested in a wind tunnel and by airdrop to assess parachute modification options. Since the subscale testing approach had significant risks associated with it as well, several mitigations were performed prior to subscale testing to validate both the wind tunnel and airdrop approach, as well as evaluate the test technique for subscale airdrop testing.

The subscale wind tunnel test was to collect single-canopy static and dynamic data in a controlled environment to understand changes to canopy stability and drag performance, and to inform parachute aero models. This data would be used to down-select parachute modification options for pendulum mitigation that would proceed into the next sequence of subscale airdrop testing. There were significant challenges for this test including the technical challenges of implementing a 3-tether load cell system to the parachute vent coupled with axial measurements, and the aggressive schedule challenges of facility availability and procurement. Beyond the challenges, risks included receiving the test hardware in time that was in production, a constrained test matrix due to limited time in the tunnel, feasibility of using the wind tunnel as a performance indicator given the rigid body attachment, non-cluster effects and wind tunnel wall effects, and the effectiveness of utilizing the complex instrumentation data for modeling and parachute design option down-select. The test matrix was completed over a 10 day period and static data as well as observations were used to recommend two configurations for further evaluation in subscale airdrop testing.

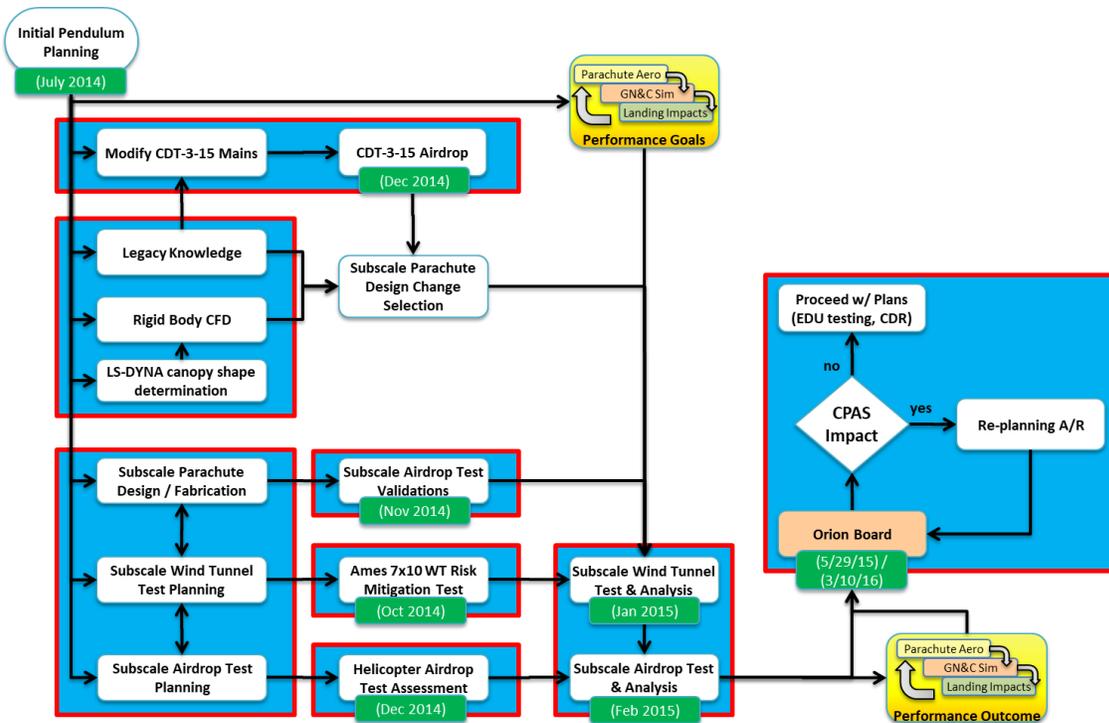


Fig. 8 – CPAS Project Pendulum Mitigation Strategic Plan

The subscale airdrop test would observe and quantify the behaviors of pendulum motion from the two wind tunnel selected main parachute systems using an instrumented payload with the goal to select one parachute configuration for a design change recommendation. The subscale parachutes would be tested in single parachute, 2-parachute cluster, and 3-parachute cluster configurations. The test data would be used for pendulum statistics and to validate static, dynamic and proximity parachute aerodynamics and computer models. The significant challenges for this testing would include the test hardware design, procurement and fabrication, and an aggressive schedule for testing.

Additional risks included test technique failures, reuse damage to the subscale parachutes, limited time during the execution of the test matrix to make informed decisions, transferability of the test data for modeling, insufficient performance improvement to mitigate the pendulum, and the transferability of the subscale performance to full scale performance expectations. The airdrop testing was completed after 54 successful airdrop tests over a 10 day period, and in the end two of the risks identified were unfortunately realized. The observations did not match the expectations of significant pendulum improvement, and analysis of the subscale data indicated that the canopy dynamic aero is shaped differently giving no confidence in using the subscale data to commit to a design without first collecting full-scale data.

By this time, the Program had been in parallel assessing the performance outcome of the crew module landing impact using an updated parachute aero model of a 2-parachute configuration. A better understanding of the landing impact risk and implementation of other vehicle design mitigations had resulted in an improvement in meeting positive vehicle structural margins. Additional improvements were still desired, which resulted in a decision for the CPAS Project to assess a different design modification on a full scale EDU airdrop test. An updated strategy was performed; again an iteration to the risk management process.

After the full scale EDU airdrop testing was completed with the alternate design modification, the results were discussed and shown to have a slight improvement in crew module structural margins for landing impact. On one side of the argument, there was an improvement, albeit small, and the implementation of the design change was seen to better preserve a robust fault tolerance in the parachute system. On the other side of the argument, the improvement was too minimal to counter the lack of test data and confidence in the full understanding of the parachute performance to make a design change decision this late in the parachute development. The final decision was to not incorporate a parachute design modification, and that the risk for structural failure had improved through other mitigations to a satisfactory level.

When reviewing the pendulum issue there are several takeaways regarding risk management. First of all, RIDM and CRM process is a natural way to manage complex risk. Throughout the process of the pendulum assessment, the Project identified, analyzed and made risk informed decisions followed by continuous re-evaluation(s). There are also scenarios of RIDM inside of the CRM process. Another takeaway is that effective communication and coordination is key for complex problems involving a range of stakeholders during the risk management process. And finally, accepting risk you can analyze and understand now vs. accepting risk that will take time to realize the benefit or consequence is a difficult situation to be in; especially when in a cost and schedule constrained Project. In fact, there are technical challenges when bounded by cost and schedule constraints that may not be solvable no matter how well your testing, analysis and engineering expertise is.

F. Critical Design Review & Production Schedule Management of Parachute Pendulum

While the implementation and execution of the pendulum mitigation strategy was in work, a schedule strategy that would keep the Project Critical Design Review (CDR) and subsequent parachute production for qualification and flight delivery on track was needed. This was also a priority for the Orion MPCV Program to limit these significant milestones from slipping.

The driving force behind the CDR date was the completion of the full scale EDU airdrop testing to review and set a design baseline from the testing results and subsequently produce the qualification parachute units to the updated design. The pendulum mitigation strategy tasks had slipped the schedule of the remaining EDU testing, which would waterfall to a slip in the CDR and parachute production. Further, some mitigation strategy options considered addition full scale tests which had the potential to slip CDR 2 years.

Schedule options were iterated as the pendulum mitigation strategy was in work, which included proceeding with an EDU airdrop test (with a modification for pendulum mitigation) since there were already key design updates in the test objectives that were important to complete to further inform the design in general. As the pendulum mitigation strategy matured, a risk trade evaluated the likelihood of major future design changes to be learned as a result of the remaining EDU tests against the cost and schedule implications for slipping the CDR and parachute production all under the assumption that subscale testing and subsequent modeling could inform a design change to mitigate pendulum to a reasonable level of confidence (if required). The Program agreed to a strategy to disconnect the EDU testing critical path from the CDR, putting the review before the completion of full scale EDU testing. This strategy would avoid costly schedule delays of the qualification test program and flight hardware delivery.

Near the end of the pendulum mitigation activities, it was determined that many of the design options being considered for pendulum mitigation could not be proven effective through subscale testing and analysis. But one more pendulum mitigation design option was still being pursued by stakeholders which had the potential to further impact the production schedule of qualification and flight parachute hardware. Additional schedule assessments became required to evaluate schedule impacts on when to incorporate the design option into the production. Each schedule assessment had varying levels of risk based on when the understanding of the performance of the design option would be realized.

As shown throughout the pendulum mitigation strategy, the schedule assessments were a critical tool to evaluate impacts to critical milestones that were synced to stakeholder milestones as well as lifecycle cost. The evaluation of the schedule were important in the evaluation and mitigation of technical risk and played a significant role in decision making during this iterative process.

Acknowledgments

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