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Design, Integration, Certification and Testing of the Orion Crew Module Propulsion System

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The Orion Crew Module Propulsion Reaction Control System is currently complete and ready for flight as part of the Orion program's first flight test, Exploration Flight Test One (EFT-1). As part of the first article design, build, test, and integration effort, several key lessons learned have been noted and are planned for incorporation into the next build of the system. This paper provides an overview of those lessons learned and a status on the Orion propulsion system progress to date.

I. Introduction

The Orion Multipurpose Crew Vehicle (MPCV) is NASA's next generation spacecraft for human exploration of deep space. Lockheed Martin is the prime contractor for the design, development, qualification and integration of the vehicle. The Orion vehicle is comprised of 3 major elements – a Crew Module, a Service Module, and a Launch Abort System (LAS). A key component of the Orion Crew Module (CM) is the Propulsion Reaction Control System (RCS), a high-flow hydrazine system used during re-entry to orient the vehicle for landing. The system consists of a completely redundant helium (GHe) pressurization system and hydrazine fuel system that supplies twelve 160 lbf monopropellant thrusters. The propulsion system has been designed, integrated, and qualification tested in support of the Orion program's first orbital flight test, Exploration Flight Test One, EFT-1, scheduled for 2014. A subset of the development challenges from this first flight test campaign will be discussed in this paper for consideration when designing future spacecraft propulsion systems.

The concept of operations (CONOPS) and human rating requirements of the CM propulsion system are unique when compared with a typical satellite propulsion reaction control system. The system requires a high maximum fuel flow rate. It must operate at both vacuum and sea level atmospheric pressure conditions. The system must meet stringent Orion human rating requirements.

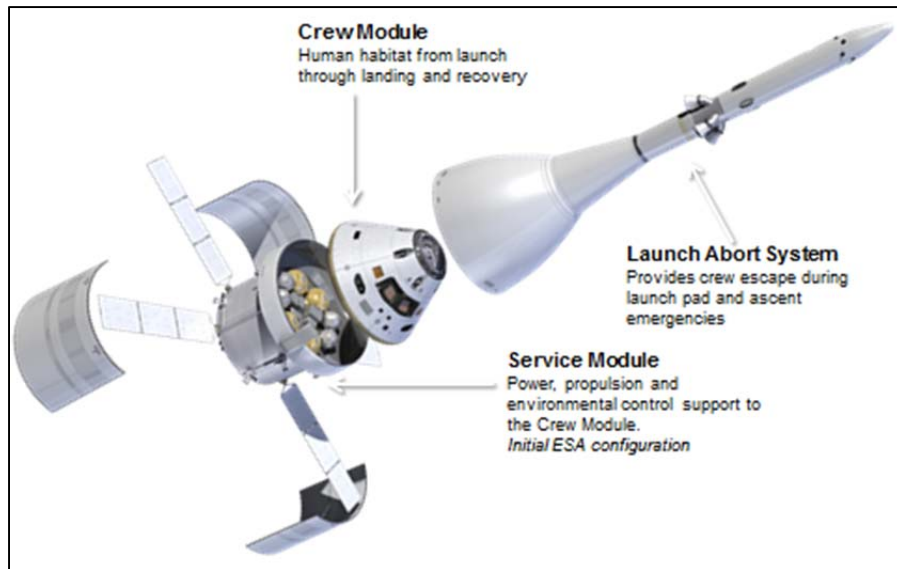


Figure 1: Orion MPCV Modules

II. System Design

A. Overview

There are many design challenges in the CM propulsion system. Key driving design requirements include the high flow rate, stressing flight loads and environments, mass limitations, packaging constraints, stringent thermal soak back requirements, redundant strings of the hydrazine propellant system and helium pressurization systems, and human rating the spacecraft. These requirements lead to a design with large diameter tubing, tight manufacturing and assembly tolerances, and complex secondary structure.

B. EFT-1 Integration and On-Vehicle Installation

The first time installation of the propulsion system on the CM for flight resulted in several lessons learned that can be applied to future integration and installation efforts.

In order to meet the compressed installation schedule to support the flight test campaign, the propulsion system was manufactured in stages at multiple locations across the country. This presented a unique set of communication difficulties that were successfully overcome. Obstacles included coordination of just-in-time parts procurement and delivery at multiple locations, different processes and procedures for manufacturing and installation across multiple locations, and reprioritizing work to meet next user need dates for on-vehicle installation.

In order to meet the integration schedule and launch date, the on-vehicle installation of the propulsion system was completed in parallel with the installation of multiple other subsystems, presenting a new set of challenges. Planning and re-planning of the installation work was required in order to make sure all components were accessible and met tight clearance requirements. Use of the Computer Aided Drawing (CAD) model in the clean room, in addition to the released drawings, was required in order to make sure tubes were installed and harnesses were routed appropriately to allow for the surrounding components to be installed at a later date.

Additionally, the clean room was a new design for this flight article build. Its unique operation, in combination with parallel work in the clean room resulted in propulsion system contamination challenges. Clean room modifications, heightened sensitivity to contamination, and revised processes/procedures were implemented to mitigate the issue.



Figure 3: Orion EFT-1 Crew Module During Assembly

C. EM-1 Improvements

There are several lessons learned from the EFT-1 vehicle that are being incorporated into the design of the CM for the follow-on vehicle, Exploration Mission-1 (EM-1). Mainly, weld head access and alignment problems led to welding challenges during on-vehicle integration.

During manufacturing of tubing assemblies, the trim to fit operations required added time to the operation and introduced unique fit up and installation challenges during clean room operations. These operations included tube trimming, facing, fit up and welding. Trimming operations during fit up were often asymmetric, resulting in tighter tolerances in some locations than others. As a result clearance issues within the propulsion system and between other subsystems required resolution as the build progressed.

Many saddle clamps were in locations that were difficult to access including behind tanks and pressure control assemblies. The saddle clamps were comprised of many individual parts, and required extra diligence to control many individual parts during installation activities, especially in inaccessible areas. On-vehicle closeout welds were often in locations that were difficult to align tube ends for welding. This led to additional challenges for non-destructive evaluation (NDE) and X-ray. The released engineering showed only a general routing of heater and temp sensor harnessing on EFT-1. Engineering on EM-1 will have better definition of heater and temp sensor harnessing to better determine tie down locations and avoid clearance issues.

The thruster pod design on EFT-1 consisted of struts attaching the pods to the primary structure. The struts took up volume shared with tube and harness routing raceways, and required heavier primary and secondary structure. The RCS thruster pods will be mounted to primary structure gussets on EM-1, increasing routing volume and reducing mass. The EFT-1 thrusters were designed without a nearby support location for the tubing attached at the thruster valve inlet and required the addition of brackets on the pods to support tubes. Additionally, in multiple locations, the on vehicle welding locations for thruster inlets were challenging to access.

D. Design for EM-1

The CM configuration for EM-1 has been updated and optimized to make the layout more efficient, with an improved design for manufacturability and producibility. The updated configuration allows for a simplified and more symmetric tubing design. The redundant strings of the hydrazine system are routed through the upper part of the aft bay and the lower part of the mid bay to provide the most effective routing path for the large diameter tubes. This also provides opportunities for the hydrazine lines to route to the thrusters in the forward bay and to the thrusters and crossover manifold located in the aft bay. The redundant strings of the helium system are routed through the lower part of the aft bay to more easily access the pressure control assemblies. The new configuration has service panels on each side of the vehicle to limit the number of service lines being routed from one side of the vehicle to the other. The wall thickness of some of the tubes has been increased to address water hammer concerns, improve tube bending, and eliminate tubing with common line diameters but different wall thicknesses.

The locations of the thrusters remain relatively unchanged, but the pointing direction is altered slightly to allow for more commonality in the design of the thruster pod housing and packaging in the aft bay. The thruster valve inlets have been adjusted to allow for greater welding access. The roll thruster pods have been split into individual pods and will be mounted, along with the other aft bay pods, to primary structure gussets. This opens up tubing and harness routing areas behind the thrusters and supports the thruster pods with greater mass efficiency. The welded-in nozzle inserts that were included in the EFT-1 roll thrusters to increase the sea-level thrust will be replaced with integrally machined dual-bell nozzles for EM-1.

The Pressure Control Assemblies (PCAs) and Crossover manifolds have undergone a significant redesign to improve packaging in the vehicle, manufacturability, and testability. The Crossover manifolds are centrally located to improve access and allow for more consistent and symmetric tubing in the system. There are two PCAs that contain the valves, regulators and pressure transducers used to control the helium to pressurize both the hydrazine propellant system and the ECLSS ammonia system. The updated PCAs are each designed to accommodate the same components in a nearly identical layout to simplify manufacturing and testing.

E. Additional Design Requirements for EM-1

In addition to challenges faced during the design of EFT-1, the design of the Propulsion system on EM-1 includes new obstacles. The addition of components and harnessing for other subsystems has made the routing of propulsion system tubing, packaging of RCS thrusters, and design of Pressure Control Assemblies exceedingly difficult. The limited volume and tubing support attach points in the vehicle requires shared routing areas with electrical harnessing and Emergency Crew and Life Support (ECLS) tubing. The environments the propulsion components will see during an abort event could necessitate vibration isolation or damping of the Pressure Control Assemblies and flex lines to allow the rigid tubing to absorb panel deflections.

The requirement to separate redundant systems and propulsion system tubing necessitates creative support structure and close coordination with other subsystems to utilize the limited volume and routing raceways available. To meet the separation requirement, tubing for String A of the hydrazine system is largely contained in the aft bay of the vehicle while the tubing for String B of the hydrazine system is largely contained in the mid bay. The hydrazine fill lines to tanks are routed in separate of the six sectors of the vehicle. The system valves are positioned to have a physical barrier between them. Redundant pressure transducers are mounted on separate brackets with appropriate spacing between the brackets. The individual strings of the Helium pressurization system are packaged in separate sectors of the aft bay.

III. EFT-1 Integrated Propulsion System Test

A. Overview

In support of the propulsion system qualification effort for EFT-1, a full scale test article was manufactured and hot fire tested with hydrazine propellant. The test article was manufactured using a full scale mock-up of the CM primary structure, and propellant tubing and components that were nearly identical to the flight configuration. Manufacturing and integration of the test article served as a pathfinder for the EFT-1 flight build, and the data gathered from test enabled validation of the propulsion system models and analytical predictions. These anchored

models will be used to predict performance on subsequent missions. Test sequences were completed to simulate the full breadth of system flight-operations and worst case fault scenarios to demonstrate system robustness over the range of anticipated flight conditions.

B. Test Configuration

The hot fire test article consisted of a mix of flight-like hardware and ground hardware, with 4 flight-like engine and 8 hydraulic simulators to replicate engine flow rate and pressure drop response. The Hot Fire Test Article (HFTA) also included two ASME-certified propellant tanks and all fluid and gas handling components, distribution lines, controls, and instrumentation required to control and monitor the HFTA test activities.

The system was instrumented with a number of strain gages, thermocouples, accelerometers, and pressure transducers which were used to measure system responses.

C. Objectives and Results

The Orion HFTA test series was a full-scale development test of the EFT-1 propulsion system design which demonstrated the performance of the integrated propulsion system over the range of operating pressure and GHe saturation conditions expected for EFT-1. The test article was designed to replicate the key elements of the EFT-1 propulsion system in order to characterize the expected performance of the EFT-1 propulsion system.

The key objectives were as follows:

- Verify satisfactory engine performance in the presence of feed system pressure transients in an integrated system.
- Examine feed system interactions under the worst case mission entry profile
- Demonstrate fault recovery configuration
- Validate models predicting steady state and transient fluid parameters
- Demonstrate propulsion operation using flight-like controls
- Verify stable pressurization system performance over the range of operating conditions

The hot fire test series successfully met the test objectives, and the results provided valuable insight into the EFT-1 system performance. However, there were two issues encountered during test that had to be resolved prior to requirements verification. During HFTA, the waterhammer pressures in the system exceeded predictions. Waterhammer occurs when high flowing fuel is rapidly stopped by a closing engine valve, resulting in a spike in system pressure. By performing additional stress analyses on the fuel manifold tubing and valves, it was determined that these waterhammer pressures were acceptable in the system. The second anomaly occurred when one of the engines emitted a cloud of white vapor during test. It was determined that the large cloud was fuel vapor from hydrazine that was not fully combusted when it flowed through the engine. After extensive investigation, the root cause of this anomaly was identified as poisoning of the catalyst with other potential contributing factors. The causes are primarily sea level ground test issues and not a significant risk for the EFT-1 flight.

A sample of the data collected during hot fire test is shown below in Figure 2. Analytical models predicting waterhammer pressure transients, pressurization performance, and material stresses were correlated with test data and will be used to make analytic predictions for future missions. The engines demonstrated performance margin above the maximum flight values, and the overall system robustness was confirmed over a range of stressing nominal and off-nominal conditions. The Orion HFTA met the objectives of test and provided valuable insight into the EFT-1 mission performance.

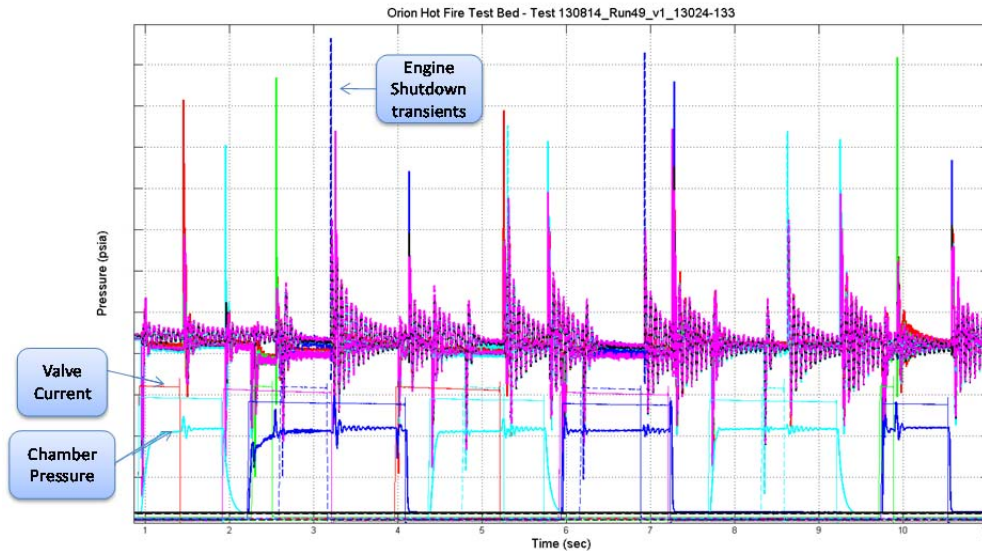


Figure 2: Representative Hot Fire Data Depicting Waterhammer, Engine Valve Current, and Engine Chamber Pressures

IV. Forward Work

At the time of this paper, qualification effort for EFT-1 is complete, and the flight propulsion system is fully installed and integrated on the CM. System level check out of the vehicle is nearly complete on the fully integrated CM. Integration of the CM, Service Module and LAS is in work for EFT-1. Lessons learned from the development challenges of this first flight test article are being applied to the next build. Design updates include a CM configuration optimized to make the layout more efficient, and improved design for manufacturability and producibility. Propulsion components are being modified to improve performance. System level testing results are being fed into the design to improve and optimize the design. The EFT-1 flight test will be completed in December 2014, simulating a deep space re-entry, and providing the ultimate test of the CM propulsion system performance and operation during flight.