Orion Heat Shield Manufacturing Producibility Improvements for the EM-1 Flight Test Program

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Abstract---This paper describes how the Orion program is incorporating improvements in the heat shield design and manufacturing processes reducing programmatic risk and ensuring crew safety in support of NASA's Exploration Missions. The Orion program successfully completed the EFT-1 flight test in 2014 and is currently developing the EM-1 spacecraft to meet the test objectives of an orbital mission to the moon and return to earth in 2019. Lessons learned from the EFT-1 manufacturing and flight test experience are being incorporated into a wide variety of vehicle systems and manufacturing processes to reduce risk to the Orion missions and flight crew. A critical contributor to crew safety is the heat shield that protects the crew capsule during re-entry through the earth's atmosphere for return from deep space. The first flight test vehicle, EFT-1, was manufactured and tested in the Neil Armstrong Operations and Checkout (O&C) facility at KSC to demonstrate early risk reduction including the functionality of the Thermal Protection Systems (TPS) for capsule safe return to earth. The approach for the EFT-1 heat shield utilized a low risk approach using Apollo heritage design and manufacturing processes using an Avcoat TPS ablator with a honeycomb substrate to provide a one piece heat shield to meet the mission re-entry heating environments. The manufacturing processes used honeycomb cell injection guns which were redeveloped from the Apollo Lunar Program processes to build the EFT-1 heat shield. The completed heat shield was transported across the country by aircraft to the O&C at KSC for installation onto the capsule. The EFT-1 heat shield successfully performed its mission and experienced ~80% of the re-entry velocity (50% heating rate) for a lunar return for an Exploration Mission. The second flight test vehicle is the EM-1 mission which will have additional flight systems installed to fly to the moon and return. Heat shield design and producibility improvements have been incorporated in the EM-1 vehicle to meet deep space mission and programmatic requirements.

The design continues to use the Avcoat material, but in a "block" configuration to enable improvements in the application processes as well as additional improvements in the carrier structure design and manufacturing operations. Incorporating flight test results and producibility improvements from EFT-1 for the heat shield system design and processes have improved the thermal protection capability, improved the producibility, and cost for EM-1 flight test.

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1. INTRODUCTION

The Orion program is developing a human rated spacecraft design, manufacturing and test capability to support the NASA exploration missions using an incremental approach with multiple flight test articles to retire program risk with qualification and flight tests. The Orion program continues to progress in providing a crew transportation vehicle for the NASA Exploration Systems Development (ESD) program to support missions beyond Low Earth Orbit (LEO). This paper describes how the Orion program is incorporating improvements in the heat shield design and manufacturing processes reducing programmatic risk and ensuring crew safety in support of NASA's Exploration Missions. The Orion program successfully completed the Exploration Flight Test – 1 (EFT-1) flight test in 2014 and is currently developing the Exploration Mission - 1 (EM-1) spacecraft to meet the test objectives of an unmanned orbital mission to the moon and return to earth in 2019. Lessons learned from the EFT-1 manufacturing and flight test experience are being incorporated in a wide variety of vehicle systems and manufacturing processes to continue to reduce risk to the Orion missions and flight crew. A critical contributor to crew safety is the heat shield that protects the crew capsule during re-entry through the earth's atmosphere for return from deep space.

A key contributor to a low risk manufacturing and test capability on the Orion program was the decision to locate the assembly and test operations adjacent to the launch site at the Kennedy Space Center (KSC). The Neil Armstrong Operations and Checkout Facility (O&C) is the location at KSC where the Orion manufacturing and test operations are performed to assemble and test the spacecraft. The O&C facility was originally established for the Apollo program in the 1960’s to support the checkout and integration of the various spacecraft to be integrated on the Saturn V launch vehicle. In 2006 NASA started Orion as part of the Constellation program and initiated the refurbishment of the O&C facility for spacecraft assembly, integration, and test. The O&C was selected because as an existing facility it provided a lower cost and more affordable approach versus having to build a new facility. Additionally, its location at KSC eliminated the transportation and checkout risks that would be realized if the spacecraft were manufactured at other locations across the country.

The first Orion flight test article processed in the O&C was the EFT-1 vehicle, which underwent a 27-month production and test operation ending with the flight test in December 2014. This was the first vehicle to exercise the O&C manufacturing and test capabilities and was integrated onto the Delta IV heavy launch vehicle at the Cape Canaveral Air Force Station (CCAFS). The EFT-1 flight test was a four-hour mission that successfully performed the ascent staging of Orion fairings and adapters, the jettison of the Launch Abort System (LAS) and flew two high altitude orbits achieving ~80% of the lunar return velocity requirements resulting in 50% of lunar return heating rates and safely landed where recovery operations were performed to retrieve the capsule.

The EM-1 flight test spacecraft is currently in design and production to meet the flight test objectives of an unmanned orbital mission to the moon and return to earth in 2019. The spacecraft configuration is summarized in Figure 1 where the Crew Module (CM), Spacecraft Adapter Jettisoned (SAJ), and LAS are derived from the EFT-1 design.

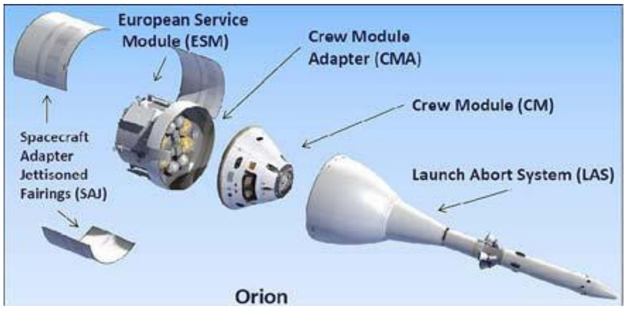

Figure 1 Orion EM-1 Configuration Overview

EM-1 will require a new propulsion system module which is provided by the European Space Agency (ESA). A European Service Module (ESM) propulsion system will be integrated into the Crew Module Adapter (CMA) to provide the functionality of a Service Module (SM) for the EM-1 spacecraft.

Orion utilized the heritage of the Apollo heat shield design and fabrication processes for the EFT-1 first flight test. A significant departure from Apollo is the increased size of the spacecraft from 12.8 ft. (154 in) to 16.5 ft. (198 in) in diameter as shown in Figure 2. Orion baselined the Apollo heat shield design for the EFT-1 mission to support an early flight test of the overall vehicle by utilizing existing and proven heat shield design and processes. With the successful flight test of EFT-1, considerable lessons learned were established that led to the redesign and manufacturing improvements of the heat shield for EM-1 and subsequent deep space missions.

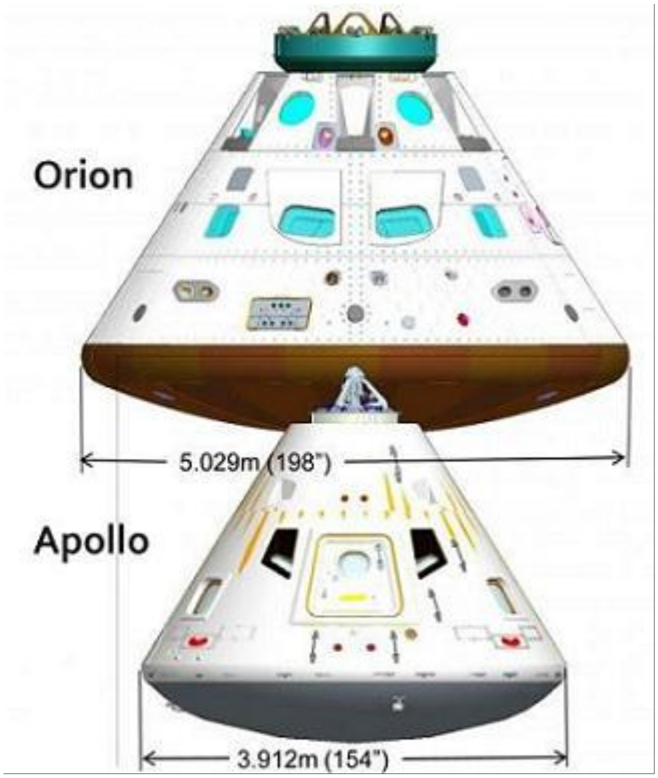

Figure 2 Apollo to Orion Crew Module Comparison

The EM-1 flight test will fly to the moon and return demonstrating the spacecraft capability to fly beyond LEO, operate autonomously and safely return to earth. The EM-2 spacecraft will be the first crewed vehicle and will complete the certification of the Orion program for human rated flight. The EM-1 spacecraft will be launched on the new NASA Space Launch System (SLS) vehicle currently under development. This heavy lift launch vehicle is the next generation launch system that will deliver NASA Exploration Mission spacecraft beyond LEO to support the deep space missions as shown in Figure 3. The SLS launch vehicle configuration for the EM-1 mission will use the Block 1 version of SLS containing an Interim Cryogenic Propulsion Stage (ICPS) which will assist Orion to lunar transfer orbit.

Figure 3 EM-1 Launch on SLS and Trans-Lunar Configuration

The EM-1 flight test is unmanned and will demonstrate a deep space mission beyond Low Earth Orbit (LEO) with a lunar orbit trajectory and return to earth. The return trajectory to earth is a TEI (Trans Earth Injection) which will require the CM to enter the earth's atmosphere at ~36,000 feet per second as shown in Figure 4. This trajectory provides about a 20% higher entry velocity than the velocity for EFT-1 mission.

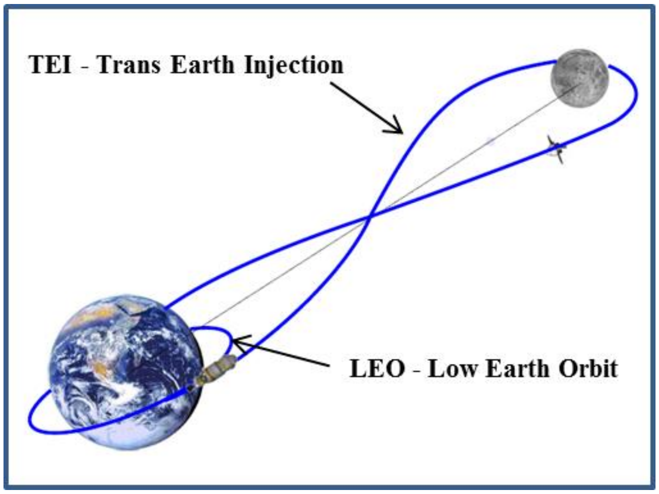

Figure 4 EM-1 Lunar Mission Profile

The Orion EM-1 heat shield configuration at 16.5 feet in diameter will be the largest heat shield developed for human rated missions. This heat shield design contains a carrier structure which interfaces with the CM and supports the ablation thermal protection system to protect the CM from the re-entry environments as shown in Figure 5. The carrier structure contains a metallic titanium "skeleton" structure combined with a composite skin to interface to the CM at 4 compression pad locations. The ablation system uses a new form of the Apollo based ablative material (Avcoat) in a tile or "block" form bonded to the composite skin. The EFT-1 heat shield design was Apollo based using Avcoat injected into a honeycomb substrate. The improvements in the EM-1 heat shield design and manufacturing processes will satisfy the lunar re-entry mission thermal protection capability while incorporating producibility improvements in fabrication and assembly processes. The producibility improvements will provide cost and schedule savings and a reduction in overall heat shield weight.

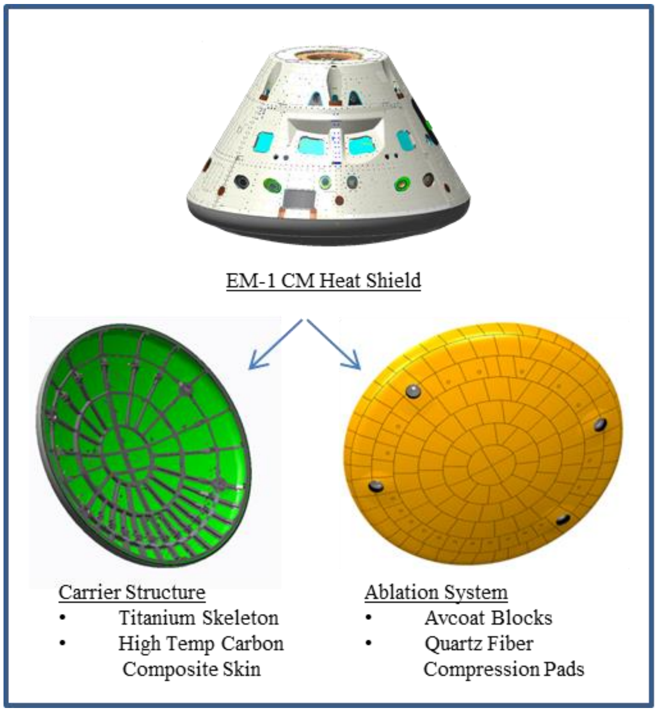

Figure 5 EM-1 Heat Shield Configuration Elements

2. EFT-1 LESSONS LEARNED

The EFT-1 flight test program was very successful in completing the launch, on-orbit maneuvers and re-entry phases of the mission as shown in Figure 6. A significant benefit of the returned CM is the ability to conduct post flight assessment of the hardware. This effort compliments the Development Flight Instrumentation (DFI) with inspection, analysis and testing of the returned heat shield to validate the performance of the design and processes.

Figure 6 Orion EFT-1 Launch and Re-Entry Flight

Post flight analysis of EFT-1 determined that all of the critical test objectives were met including the performance of the heat shield. The heat shield performed within expectations and was removed from the returned CM capsule for further evaluation as shown in Figure 7. Post flight assessment of the EFT-1 heat shield was performed by NASA and results were provided to the EM-1 heat shield team to support margin and capability evaluations for design improvements to meet the deep space mission re-entry requirements.

Figure 7 EFT-1 Heat Shield in Post Flight Evaluation

The EFT-1 flight test objectives for the heat shield contained three goals including TPS thermal-structural performance during re-entry environments, TPS thermal-structural performance during the launch and on-orbit environments, and structural performance during splash down loads. The heat shield was in good shape overall after the mission and responded as expected for nominal re-entry and landing conditions. During the manufacturing of the EFT-1 heat shield, before the flight test, two manufacturing defects were realized and were assessed as acceptable for the flight test. The first defect was cracking of the Avcoat heat shield in the gore seams after post cure processing and the second defect was witness panel mechanical strengths lower than the design allowables. Pre-flight root cause analysis did not determine a definite cause for either of the defects and the EFT-1 heat shield was determined to have adequate margins for the flight test. Producibility trades were conducted on the fabrication and installation processes of the Apollo heritage heat shield approach indicating significant benefits of weight and cost reduction opportunities. The program determined the EFT-1 heat shield design would be updated using an Avcoat Block configuration bonded to a carbon skin / titanium skeleton structure for EM missions.

A comparison of the flight environments of the EFT-1 and EM-1 heat shield is summarized in Table 1 indicating the EM-1 will experience an increase in the re-entry velocity by ~20% due to the change in re-entry trajectory to a lunar return. This will result in higher re-entry heating rates and will also provide colder on-orbit temperatures due to the deep space mission trajectories. This increase in re-entry velocity has a significant impact to the heat rates experienced by the EM-1 heat shield by as much as a two-fold increase which impacts the ablator and support structure design.

Table 1 Orion Heat Shield Environments Comparison

Flight Environments	EFT-1	EM-1
Re-Entry Velocity (fps)	30,000	36,000
Heat Rate (BTU/ft2/sec)	Baseline	~2X
On-Orbit Temperature (F)	>55	>0

In addition to the increase in thermal flight environments for EM-1, lessons learned assessments were conducted on the EFT-1 heat shield design configuration to include producibility improvements to the design and manufacturing operations/processes shown in Table 2.

Table 2 EFT-1 Lessons Learned Summary

Lessons learned EFT-1	**Improvements for EM-1**
Avcoat Application Process with Manual Injection Process Exhibits Limited Inspection in Honeycomb	Avcoat Blocks Fabricated in Standard Billets, Machined, Inspected and Bonded Using Process Controls
Avcoat Cracks in Gore Seams were Observed Post Cure	Avcoat Blocks Eliminate Cracks in Final Layup
Avcoat Low Material Properties	Avcoat Billets Acceptance Testing before Bonding
Heat Shield Edges Exhibit Exposed Partial Open Cells	Avcoat Blocks Eliminate Open Cell Configuration
High Tolerance/Complexity in Design and Tooling	Simplified Structural Design and Tooling Approach
High Part Count in Structure Assembly and Installations	Reduce Number of Spars, Rings, Fasteners & Pads
Composite Skins use Low Temp Carbon with Machining	High Temp Composite Skins w Laser Layup & Butt Joints
Transport Risk with Heat Shield Shipped to KSC	Carrier Structure Delivered to KSC Without TPS
No CM to Heat Shield Prefit without TPS installed	Added Flexibility for a Heat Shield Prefit Before TPS Installation
Heat Shield Assembly Performed at Vendor location	Heat Shield Assembly Performed at O&C Facility

Table 2 summarizes the lessons learned which addresses the application issues of the EFT-1 Avcoat material as well as improvements in design tolerances, part count, simplification of interfaces and risk mitigation operations.

Three improvements in the operational approach to heat shield assembly have been incorporated into the EM-1 installation plans. Separating the carrier structure and delivering it without the ablation TPS enables the flexibility of a pre-fit of the carrier structure to the CM if necessary and eliminates transportation risk of a completed heat shield assembly to KSC. Additionally, installing the Avcoat ablator at the O&C enables consolidation of installation operations with other TPS systems (i.e. CM Back Shell panels and Forward Bay Cover) providing synergy of touch labor staffing, training, and installation processes as well as facility floor space utilization. Incorporating the EFT-1 experience into the EM-1 design and manufacturing operations and processes provides a heat shield that meets the EM mission requirements and simplifies the design with producibility improvements.

3. HEAT SHIELD CARRIER STRUCTURE

The EM-1 carrier structure provides the surface to bond the ablator system and to interface the heat shield to the CM. The carrier structure has been updated to accommodate the Avcoat blocks with a carbon skin layup that will accommodate bonding requirements for ablator blocks attachment. A titanium skeleton structure is attached to the skin layup to provide structural support of the composite skin to support local compression pad loads and support the skin structure.

The titanium skeleton structure has incorporated several lessons learned from EFT-1 and has been redesigned to simplify the configuration as shown in Figure 8.

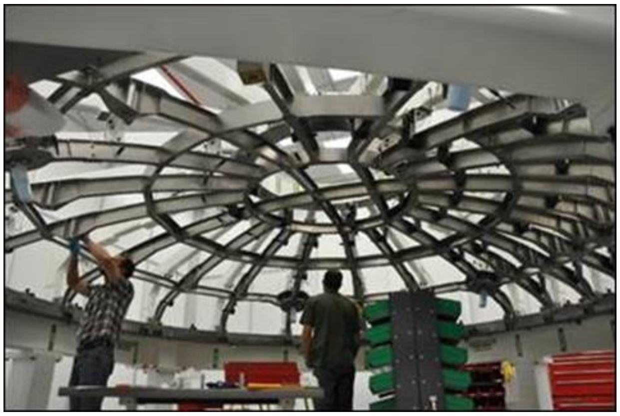

Figure 8 – EM-1 Carrier Structure Configuration

The EM-1 carbon composite skin is a new design incorporating producibility improvements in layup processes as shown in Figure 9. Skin layup processes were improved using laser imaging to aid in layup operations and included butt joints versus overlapping joints used on EFT-1. Increased precision of panel layup eliminated mold line machining requirements. Skin attachment fasteners were optimized to reduce the fastener size and count which reduced overall drill time.

Design changes include eliminating an intermediate ring frame, redesigning the spars and rings, reducing the CM interface fastener number from 104 to 20, and reducing the number of compression pads from 6 to 4. With the EM-1 thermal environments increasing, the compression pad material was changed from carbon phenolic to a quartz fiber design.

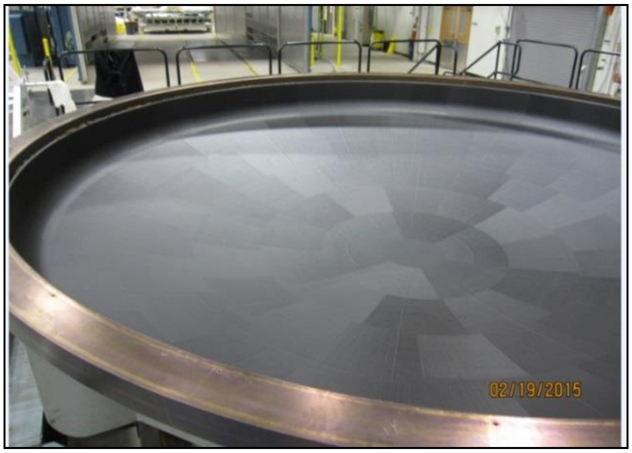

Figure 9 EM-1 Carrier Structure Composite Skin

Improvements in the carrier structure design and manufacturing processes provides a heat shield support structure that meets the thermal environments for EM-1 and reduced layup and machining time while reducing fastener and part count quantities resulting in a reduction of the overall heat shield weight.

4. HEAT SHIELD AVCOAT BLOCKS

The ablator system used on the EFT-1 heat shield was based on Apollo experience which was a monolithic honeycomb Avcoat design with injection of the Avcoat ablative into the honeycomb cells. Based on the producibility improvements of the EFT-1 heat shield Avcoat monolithic design, an Avcoat block design was established for the EM-1 heat shield. The Avcoat block heat shield configuration is dependent on the block size and thickness, number of unique block size configurations, total number of blocks required, gap filler material selection and the block orientation or pattern on the heat shield. Avcoat material billets are fabricated using standard billet sizes and are machined into unique blocks for installation.

Configuration trades were performed to optimize the design to minimize the number of billets required to fabricate the blocks to minimize the number of blocks on the heat shield which impacted thermal performance, weight impacts, and cost. Three standard Avcoat billet configurations are used to minimize forming costs and the billets are machined to meet the specific block dimensions for installation. The resulting block configurations are based on large and thick rectangular billets and curved billets. The machined blocks are uniquely sized and tapered in thickness based on location on the heat shield. Typical block configurations are shown in Figure 10.

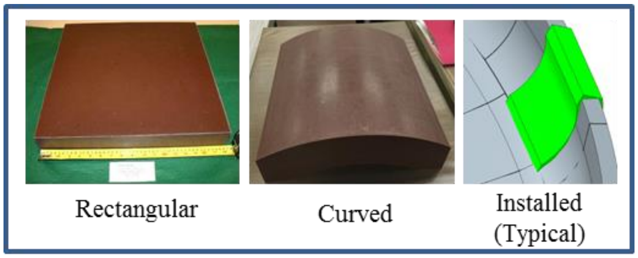

Figure 10 EM-1 Avcoat Billet Standard Sizes

Layout patterns were selected to minimize the flow streamline angles to the block seams and to minimize the number of block seams located on the spars of the carrier structure. Gap filler options were evaluated trading structural stiffness with thermal performance. An industry standard adhesive was selected combined with standard gap filler material satisfying the block sealing requirements. Extensive material development testing was completed establishing the EM-1 Avcoat block heat shield configuration as shown in Figure 11.

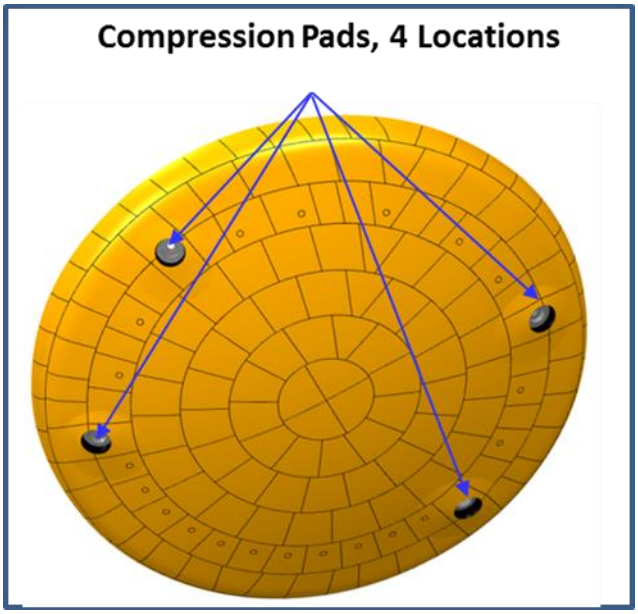

Figure 11 EM-1 Heat Shield Block Configuration

The EM-1 heat shield configuration satisfies the deep space re-entry and colder on-orbit environments required for the EM missions to the moon and beyond. The increased thermal environments increased the Avcoat ablation weight over the EFT-1 design, but the redesign of the carrier structure offset this weight increase resulting in a net weight reduction for the entire heat shield system.

5. MANUFACTURING DEVELOPMENT UNIT

EM-1 heat shield development plans included an Engineering/Manufacturing Development Unit (MDU) risk reduction effort addressing the implementation of the heat shield design and manufacturing processes using a full-sized flight-like article. The MDU effort has been completed in support of the EM-1 heat shield production operations beginning in 2017. The MDU's objective was to retire risk on a full-scale heat shield configuration offline to the EM-1 flight article design, build, and verification operations.

The engineering objectives for the MDU were to perform test and analysis for the heat shield system for mechanical, thermal, and combined mechanical/thermal flight conditions. This data was used to verify that the heat shield elements respond according to engineering predictions.

The manufacturing objectives for the MDU were to demonstrate that all critical processes are acceptable for the heat shield assembly and inspection requirements. These include methods to achieve step and gap tolerances in the block installations, evaluate skin to block spring-back, test various Avcoat plug configurations, demonstrate skin surface preparation processes, prove out block bond Non-Destructive Evaluation (NDE) methods, determine optimum adhesive batch management methods, demonstrate tooling designs and operations, and to demonstrate repair techniques. Figure 12 shows the MDU configuration with bonded rectangular and curved blocks installed in critical locations on the carrier structure. The MDU configuration was full scale in

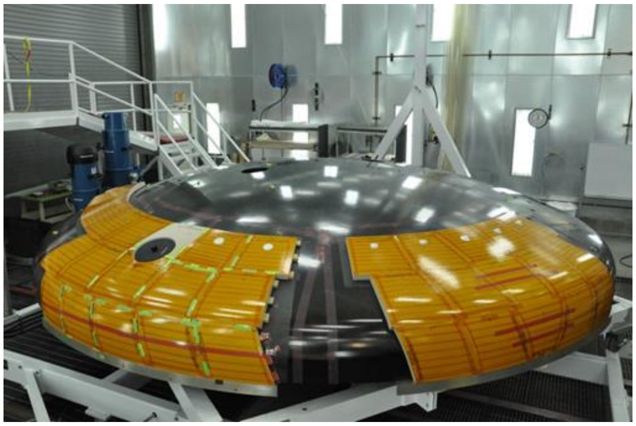

Figure 12 EM-1 Manufacturing Development Unit

geometry and represents flight characteristics for critical features and processes, but is simplified where appropriate. The skeleton structure used steel spars in a “T” extrusion design in selected areas and the composite skin design was a constant thickness configuration. Selected Avcoat blocks were installed to demonstrate the block bonding and inspection processes and additional foam blocks were used to simulate pattern match up conditions.

A significant product of the MDU process development was the validation the Avcoat block bonding verification process. This approach is derived from other aerospace re-entry programs including the Space Shuttle Transportation System (STS) tile bonding operations. The Avcoat block bonding verification process comprises three elements which include process controls, NDE, and thermal cycle proof testing as shown in Figure 13.

The process control approach addresses all critical processes of Avcoat block fabrication and installations including block properties, skin surface preparation, inspection of block mismatch conditions, adhesive mixing, witness panels for offline testing, and process monitoring. Statistical Process Control (SPC) methods are employed to ensure each process outcome is within acceptable parameters and limits.

The NDE approach utilizes proven and certified inspection processes for block bond adhesion to carrier skin panels and block to block gap filler sealing. Terahertz imaging is used for void detection with 100% inspection. Ultrasonic inspection is used to identify any bond delamination and kissing bond defects with 100% detection. X-ray inspection is used to identify any voids in the block to block gap filler material with 100% inspection. These NDE process are also under SPC control to determine the limits of acceptable indications.

The final verification process is the heat shield thermal cycle proof test performed on the flight heat shield article to provide acceptance data of the Avcoat bonds and gap filler in the final as built flight configuration. This test is conducted in the Thermal Cycle Chamber located in the O&C facility. Post-test NDE is performed to identify any unacceptable defects or defect changes from the pre-test conditions. Any post-test anomalies can be readily addressed at the O&C where the heat shield is fabricated, assembled and inspected.

Test results from each EM heat shield will form the basis of acceptable bond process criteria and is used to adjust the process controls for future bonding operations. Each heat shield contains ~180 blocks which provides the opportunity for a significant database of bond measurements for the EM heat shields in the future. Successful implementation of the Avcoat block bonding verification process ensures each heat shield will meet all design and manufacturing processing requirements ensuring crew safety for the EM missions.

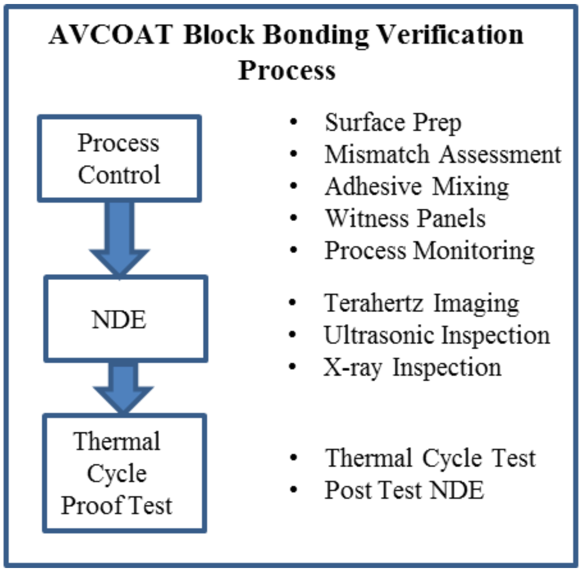

Figure 13 Avcoat Bonding Verification Process

6. SUMMARY

The Orion program is incorporating improvements in the heat shield design and manufacturing processes for the next launch in 2019 for EM-1 where earth re-entry will be from a lunar trajectory as depicted in Figure 14. Incorporating flight test results from the EFT-1 flight in 2014 and improvements in design and manufacturing producibility has enabled the EM-1 heat shield to meet the increased thermal environments while reducing program cost in support of NASA’s Exploration Missions.

Figure 14 EM-1 Re-Entry from Lunar Trajectory

BIOGRAPHY

***William Koenig** received a B.S. in Marine Transportation from the United States Merchant Marine Academy in 1979 and A M.S. in Industrial Engineering from the University of Central Florida in 1996. He worked 20 years with United Space Alliance supporting the Space Shuttle Program in numerous managerial positions. For the last 10 years he has been working for NASA as the Orion Program lead for Production Operations. He is responsible for the fabrication, assembly, test and checkout of the Orion spacecraft at Kennedy Space Center. From the NASA standpoint, he was responsible for the successful renovation and modernization of the KSC Operations and Checkout Building for the Orion program.*

***Mike Stewart** received a B.S. in Engineering from the University of Central Florida in 1990 and is a Project Management Professional (PMP). He has worked for 30 years in the aerospace industry for Lockheed Martin and United Space Alliance spending most of his career supporting the Space Shuttle Program, Space Station Program and Orion Programs. Mike has been supporting Orion since contract award and is currently the lead manufacturing engineer, responsible for assembly and integration of the Orion Crew Module Aeroshell subsystem at Kennedy Space Center. Products under his responsibility include Heat Shield, Back Shell Panels, Thermal Barriers and Multilayer Insulation (MLI) Blankets.*

***Richard Harris** received an M.S. in Aeronautics and Astronautics from Massachusetts Institute of Technology in 1975 and completed 35 years with Lockheed Martin Space System Company. He was the Orion Deputy Program Manager for Production Operations and was responsible for the fabrication, assembly, test and checkout of the Orion spacecraft at Kennedy Space Center. He was responsible for Lockheed Martin's renovation and modernization of the KSC Operations and Checkout Building for the Orion program.*