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Materials, Processes and Manufacturing in Ares I – Upper Stage: Integration with Systems Design and Development

By

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Abstract

Ares I Crew Launch Vehicle Upper Stage is designed and developed based on sound systems engineering principles. Systems Engineering starts with Concept of Operations and Mission requirements, which in turn determine the launch system architecture and its performance requirements. The Ares I-Upper Stage is designed and developed to meet these requirements. Designers depend on the support from materials, processes and manufacturing during the design, development and verification of subsystems and components. The requirements relative to reliability, safety, operability and availability are also dependent on materials availability, characterization, process maturation and vendor support. This paper discusses the roles and responsibilities of materials and manufacturing engineering during the various phases of Ares I-US development, including design and analysis, hardware development, test and verification. Emphasis is placed how materials, processes and manufacturing support is integrated over the Upper Stage Project, both horizontally and vertically. In addition, the paper describes the approach used to ensure compliance with materials, processes, and manufacturing requirements during the project cycle, with focus on hardware systems design and development.

Introduction

NASA's Ares I Upper Stage (US) is designed and built based on sound systems engineering principles to ensure compliance with requirements such that the system performs as expected and meets customers' and stakeholders' needs. At first it would appear that the materials, processes and manufacturing do not enter the picture until the design is complete and the hardware is ready to be manufactured. But appearances can be deceptive. It is important to note that all systems are built from combinations of materials using various manufacturing processes. Materials and processes selection is of utmost importance from the beginning. They offer opportunities for making the design robust, affordable and producible. At the same time materials can also be design constraints, i.e., they can be limiting in what designers want out of them. Hence it is very important that designers work closely with materials and manufacturing engineers during system design and development. It is the materials and manufacturing engineers who make the designers dream design come true. This paper attempts to show how the materials and manufacturing are integrated with design and analysis cycles, hardware development, testing and verification in Ares I – US project.

Ares I –US Description

A preliminary configuration of CLV stack, Figure 1, shows the Crew Exploration Vehicle (CEV or Orion), Upper Stage (US) and the First Stage. Figure 2 shows an expanded view of US architecture, showing various subsystems and components. A brief description of the US hardware components is given below.

Instrument Unit (IU)

The IU provides the mechanical and electrical interfaces between the ORION and the ARES I system.

Liquid Hydrogen (LH2) Tank

The LH2 tank is a welded assembly consisting of a forward ellipsoidal dome, Y-Ring flange, and three cylindrical barrel sections. A Common Bulkhead is located at the aft end of the tank. The tank is manufactured entirely from 2195 aluminum-lithium (Al-Li) alloy and friction stir welding is used for all weld joints.

Common Bulkhead (CB)

The Common Bulkhead is an internal partition that physically divides the fuel from the oxidizer. It is designed as a composite sandwich structure, which consists of two face sheets from spun formed 2014 aluminum domes and a bonded phenolic honeycomb core**.** The domes are friction stir welded to 2219 aluminum Y-rings.

Liquid Oxygen (LOX) Tank

The liquid oxygen (LOX) tank is an Al-Li 2195 structure. The tank is a friction-stir-welded assembly consisting of a Common Bulkhead at the upper end, four bump formed isogrid barrel panels, an aft Y-Ring forging, eight stretch formed hemispherical aft dome panels, an aft manhole cap, an array of slosh baffles, an anti-vortex baffle assembly, a Thrust Cone attach ring, and a sump assembly.

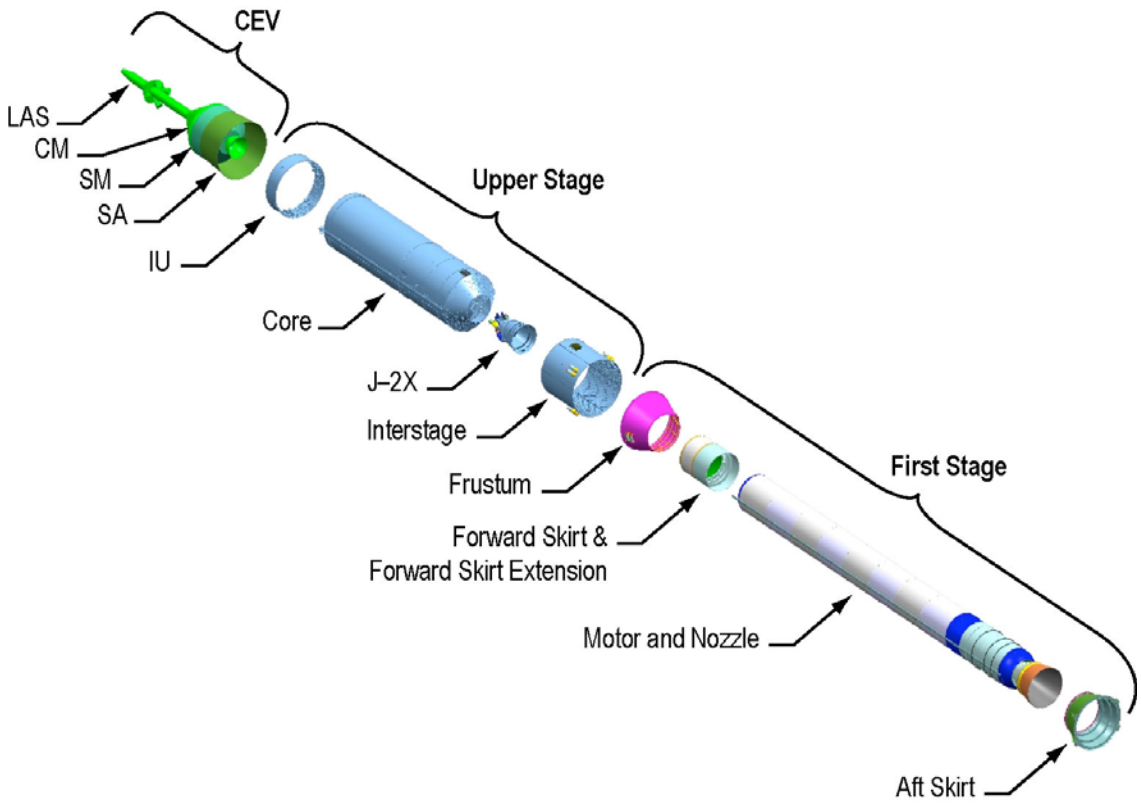


Figure 1: Ares I Integrated Stack – Expanded view

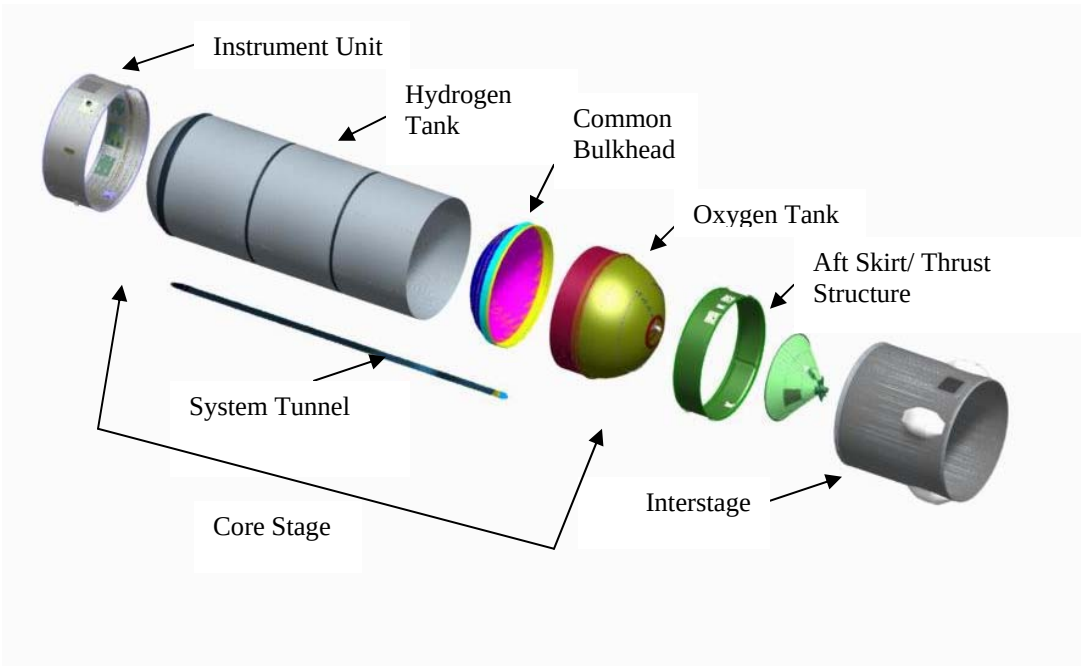


Figure 2: Upper Stage – Expanded View showing Components

Thrust Cone

The Thrust Cone serves as the structural interface between the Core Stage and the J-2X engine. It is a fastened structure made up of four Al-Li 2195 cone panels with integrally machined stringers, two intermediate ring frames, a forward interface ring frame, and an Aluminum engine gimbal mount casting. The J2-X engine is mounted on a fitting at the bottom of the thrust cone, which also provides support for the TVC actuators and MPS propellant inlet ducts.

Aft Skirt

The Aft Skirt provides the structural interface between the Core Stage and the Inter stage. It is a welded structure made up of four machined Al-Li orthogrid panels and top and bottom flanges. The Aft Skirt provides feed-throughs for the LH2 feed line and fill/drain line, a bulkhead feed-through for the systems tunnel, and penetrations for the propellant tank pressurization/ recirculation lines. Two umbilical panels are mounted on the aft skirt for ground services, purge, LOX tank fill/drain and LH2 tank fill/drain. RCS thruster pods and ullage/settling motors are mounted on the outside of the Aft Skirt. The inside of the Aft Skirt supports RCS feed lines, a purge system manifold, hazardous gas detection system tubing, cameras, and avionics as required.

Upper Stage Design Approach

Ares I - US is designed and developed based on sound systems engineering principles as outlined in NPR 7120.5, NASA Program and Projects Management Processes and Requirements. Ares I is an element of NASA's Constellation Program (CxP - Level II). Figure 3 shows the document tree for Constellation. It shows the relationship between various levels of requirement documents. Requirements are allocated from higher level to lower level. CLV is Level III and Upper Stage Element is Level IV. It also shows the interfaces between levels and among different projects at the same level. US requirements are documented in US ERD (USO-CLV-SE-25710) and are allocated to subsystems. The US design is accomplished through a number of Integrated Product Teams (IPT), viz., Systems Engineering and Integration (SEI), Main Propulsion System (MPS), Structures and Thermal (S&T), Manufacturing and Assembly (M&A), Test, Avionics, Thrust Vector Control (TVC), Reaction Control System (RCS), Logistics and Small Solids. SEI IPT has the overall responsibility for integrating the work of all other IPTs. There is significant interaction among the IPTs, whose works/products are integrated both horizontally and vertically.

Ares I systems engineering engine incorporates a rigorous, top down procedure involving three basic steps:
1. System requirements are derived from stakeholder needs,
2. Designs are realized from system requirements
3. Products are realized and transitioned following design implementation.

Figure 4 depicts this procedure from left to right. System requirements and control are implemented from top down and products are realized and verified from the bottom up. Technical management processes are integral to the development of systems and products. The processes are generally iterative and recursive. US Systems Engineering Management

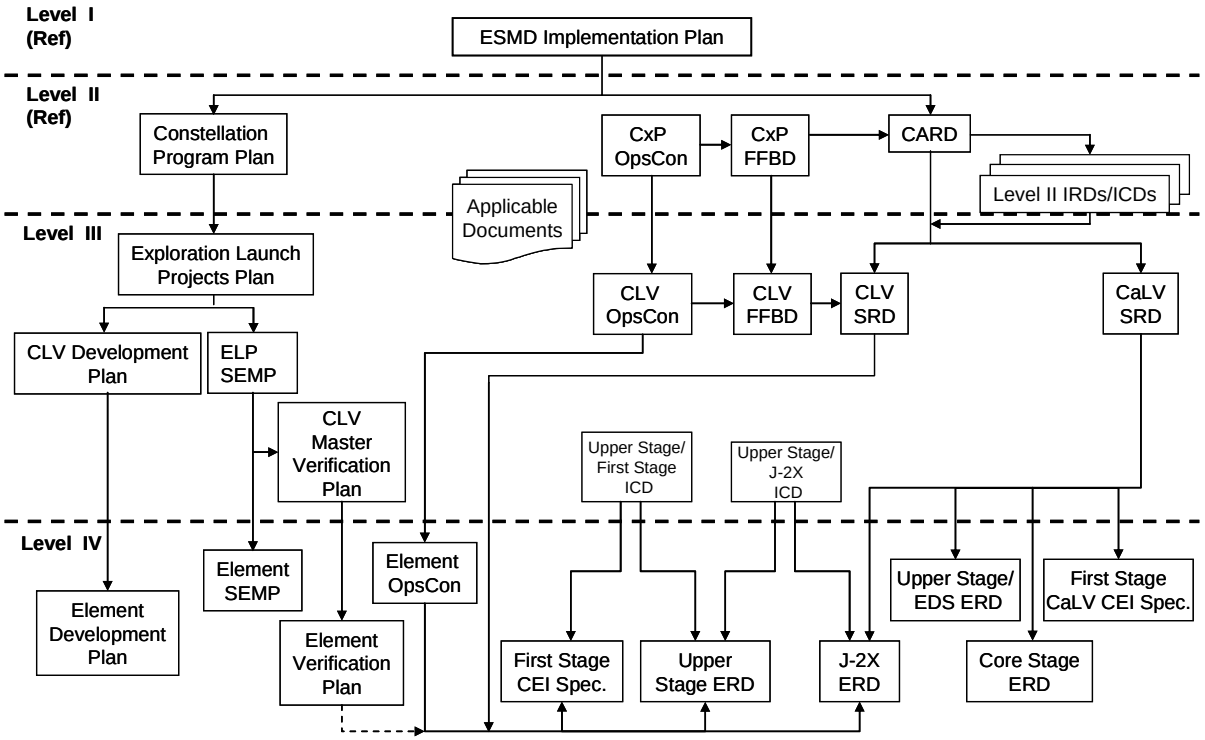


Figure 3: Constellation Document Tree showing Requirements Flow down

Plan (SEMP) describes how the requirements will be met through design solutions that are matured through a series of design and analysis cycles or DAC (Figure 5). System design processes constitute the early stages of the SE engine. They include formation of requirements from user/stakeholder needs and will be evolved into more clear, coherent and complete statements for design realization and product transition. The President's vision for Space Exploration, the Constellation Design Reference Missions (CxP 70002) and the Constellation Architecture

Requirements Document (CARD – CxP 70000) provides the primary stakeholder requirements for Ares I. The system requirements flow down into system technical requirements and derived technical requirements. Requirements are allocated and decomposed from the CARD and associated IRDs. Definition of technical requirements will involve converting NASA needs, goals and objectives to technical requirements in order to capture constraints and conduct requirements analysis and traceability. Requirements analysis is the process of determining what the system "must do", "how well it has to do it", and under what conditions and in what environment the mission must be performed. Requirements validation will ensures that each requirement is properly defined via the following characteristics: Specific, Verifiable, Achievable, Agreed to and Realistic. Analysis is done to assess the ability of the DAC to meet the requirements within the technical and programmatic constraints.

Requirement allocation could be either direct allocation, or apportionment or derivation. This approach provides integrated project and technical responsibility for requirement inclusion and

corresponding validation. It ensures that every requirement is validated by a product, and that every product supports a requirement. The allocation and decomposition stage flows according to the document diagram (Figure 3). Program requirements flow down to the Project and then to the Elements. Requirements and Verification team performs requirements decomposition to the Element level (Level IV) based on operations concepts and functional flows to ensure design completeness, define each subsystem and control the interfaces.

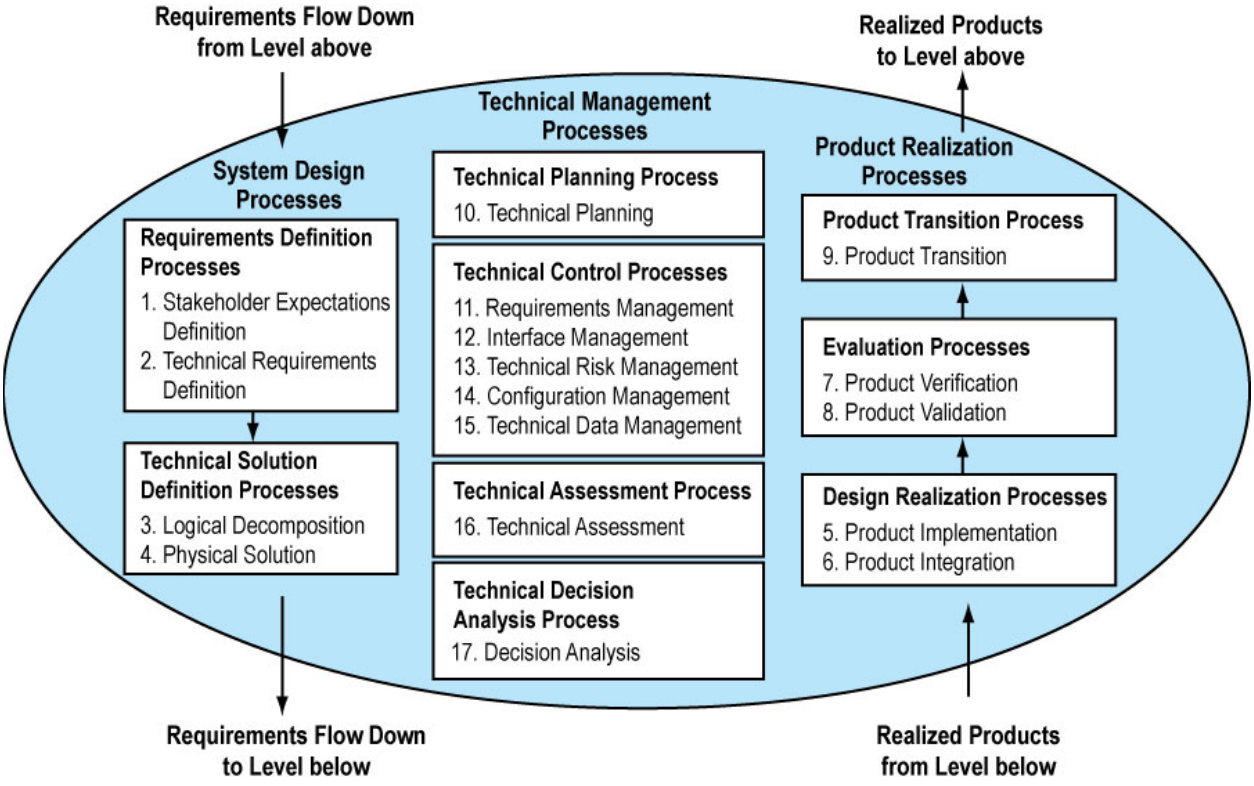


Figure 4: NASA Systems Engineering Technical Process Model

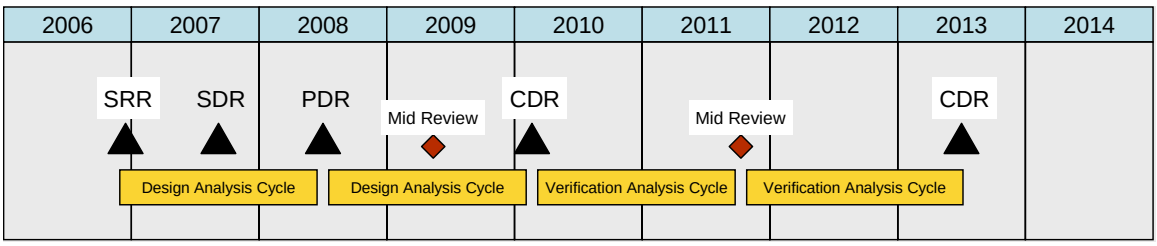


Figure 5: Integrated Design and Analysis Events for Ares I

Design solutions are how the system requirements are met. This is done through a number of Design and Analysis Cycles or DAC. Figure 5 shows the top level analysis cycle road map. Each DAC may have one or more cycles within it, e.g., DAC 1-A, DAC1-B. After the Critical Design Review (CDR) they are verification analysis cycles.

Risk Management (RM) is an important aspect of Systems Engineering. RM identifies circumstances or issues that could threaten the success of Ares I Project, and provides plans to avoid the risk, or to reduce the impact to acceptable levels (mitigation strategies). Common risks include the following:

1. Risks from critical unverified programmatic and technical assumptions
2. Risks from shortfalls or gaps in the underlying technical capability needed to define, design, integrate, validate, fabricate, verify and operate Ares I and its Elements.
3. Independent validation of achievability of requirements and of Technology Readiness levels (TRL) by the designers

Risk information is integrated all across the whole project. Any new technology insertion carries an unknown risk which must be mitigated. Many of these risks in category 2 above fall in the M&P area. Examples: incomplete or outdated databases, NDE technique not available for certain hardware, unverified fabrication processes, and shortfalls in verification capability.

The next sections will discuss how Materials, Processes and Manufacturing (MPM) are integrated with Systems Engineering, specifically with Design and Analysis, Risk Mitigation and Design Verification.

Materials, Processes and Manufacturing: Integration with Design and Analysis

As mentioned before, US design is carried out through a number of IPTs. MPM work is book kept under Manufacturing and Assembly (M&A) IPT, which has generated a detailed Work Breakdown Structure (WBS) showing the areas where M&P support is required. Four major categories are:

1. Design IPT support --- materials data, consultation
2. Development support --- process specifications, process development, design maturation
3. Deliverables --- various development and test articles, M&P documents
4. Integrated M&A --- Various MPM planning documents, materials properties data book (for flight)

Ares I is designed to meet the requirements of the CARD and CLV SRD (CxP 720137) while the Upper Stage is designed to meet the requirements of US ERD. Even during the conceptual design phase it is important to make sure the design is realistic and not a fantasy. Systems Requirements Review (SRR) is held to make sure that the requirements are realistic and can be met through the conceptual design. By realistic it is meant that the vehicle can actually be built as designed with a high degree of confidence. Its performance characteristics are only predicted at this point through analysis using models that are anchored through limited testing of subscale hardware with proper outer mold line (OML). Mass properties are an important metric for design. Mass properties are governed by the materials used in the design and their properties. So during the design phase MPM engineers provide the designers with important data on materials,

processes and manufacturing. They offer consultation on whether the hardware can be manufactured as designed. MPM considerations include the following:

- Are the selected materials well characterized in the environment they are going to be used? How good is the data base? Is there a need to generate additional properties?
- Are the materials available in the time frame of the project? Can they be procured on time to support schedule? Are the suppliers reliable?
- How much vendor support is needed? Do we need multiple sources or a single source will do?
- Manufacturing processes – are they proven? If not, can they be matured in a timely fashion (need TRL of 6 by CDR)
- Facility considerations—where is the hardware going to be built? Is the facility available? Is a new facility needed to meet new requirements?
- Tools and equipment considerations – Does this project require unique equipment that needs to be specially designed and built? This may entail a long lead time.
- Cost of new facilities and equipment.
- Availability of experienced personnel to operate the facility and equipment.

Trade Studies

In addition to supporting the DAC, MPM engineers support trade studies involving alternate design concepts. One such example is the use of common bulkhead (CB) for the LH2 and LOX tanks (the current design) versus using separate tanks (initial conceptual design). Use of CB helps to reduce the mass of the US significantly—the primary reason for selecting that design. However, CB is more complex and difficult to manufacture compared to manufacturing separate tanks and stacking them. Hence CB poses an added risk to the project in terms of cost and schedule. Project has accepted that risk, putting confidence in MPM capability to deliver the CB on time and within budget.

Similar considerations apply to selecting materials for various components. Al-Li alloys are materials of choice since they are lightweight and high strength. Further, there is an experience base of using it in Shuttle's External Tank. However, they are available in limited thicknesses and sizes. They are not as ductile as 2219 and 2014. Cryogenic fracture toughness is a major consideration. Hence materials selection must be made with care. Interstage material selection is another example. Composite interstage is lighter weight structure than the metallic inter stage and hence is a logical choice. However, metallic construction is a more mature technology with a larger experience base. Composites cost more and cost is always an important consideration, especially under budget constraints. It should be noted that pay off due to weight reduction is much higher for the US than the FS, usually by a factor of 10:1. Since the interstage is discarded after the FS flight the impact of mass savings are not as significant as in the CB case. Final selection will be based on the need for payload capability and mass requirements of Orion.

Design and Construction Standards

US ERD requires that building standards used for US are in compliance with applicable design and construction standards for space hardware. Some of the applicable documents and standards are listed below:

NASA-STD-5006: General Fusion Welding of Aerospace Materials used in Flight Hardware
NASA-STD-5007: General Fracture Control Requirements for Manned Space Flight Systems
NASA-STD-5009: Standard NDE Guidelines and Requirements for Fracture Control Programs
NASA-STD-5012: Strength and Life Assessments of Liquid Fueled Space Propulsion Systems
NASA-STD-6016: Standard Manned Spacecraft Requirements for Materials and Processes
CxP 70145: Constellation Program Contamination Control Plan
CLV-USO-MP-25500: Upper Stage Manufacturing and Assembly Plan
CLV-USO-MP-25505: Upper Stage Contamination Control Plan
MSFC-SPEC-164: Specification for Cleanliness of components for Use in Oxygen, Fuel and Pneumatic Systems
MSFC-STD-2594: Fastener Management and Control Practice Requirements
MSFC-STD-3029: Selection of Metallic Materials for Stress Corrosion Cracking Resistance in Sodium Chloride Environments
MSFC-STD-486B: Torquing of Threaded Fasteners
ANSI/AIAA G-095-2004: Guide to Safety of Hydrogen and Hydrogen Systems
ASTM MANL 36: Safe use of Oxygen and Oxygen Systems

MPM engineers are responsible for making sure that the project is in compliance with the requirements stated in the above standards and specifications. As mentioned before (Figure 3) the NASA standards are applicable at the highest level (Level I) and flow down to lower levels. However, many MPM standards do not enter into the picture until Level V, the subsystem level, or Level VI, the component level. At these levels the standards have to be tailored to each subsystem/component and they are usually written as specifications. Further, these standards apply to flight hardware and not necessarily to development/test hardware. There are no firm MPM requirements for the latter; they are determined on a case basis. However, it behooves us use these standards during development/test to reduce the risk to flight hardware.

There are many requirements relative to performance and physical characteristics that US must meet for mission success (see US ERD). While these are not MPM requirements per se, MPM have a huge influence on them. For instance, material properties (mechanical and physical properties) will determine the US mass, which is a key driving requirement. Therefore MPM support is required for the design maturation (development) and success of various integrated products. Similarly, MPM support is required for design verification through analysis, test or demonstration. US Development Plan (USO-CLV-MA-25001) gives the details of how the design will be matured through development and test programs. A number of Level IV and Level V plans are generated to show how the project is going to meet the requirements as stated in the Design and Construction Standards. The MPM related plans are listed below:

- Upper Stage Element Manufacturing and Assembly Plan (Ares-USO-MP-25500)
- Materials, Processes Selection, Control and Implementation Plan
- Materials Usage Agreements
- Materials Identification and Usage List
- Contamination Control Plans, including Foreign Object Debris/Damage (FOD)
- Non-destructive Evaluation Plan
- Fracture Control Plan

- Electric, Electronic, and Electromechanical (EEE) Parts Control Plan
- Limited Life Items List

M&A Plan calls for manufacturing and assembly of flight hardware to be done at Michoud Assembly Facility (MAF) in New Orleans, Louisiana, by Boeing, the US Production Contractor. Early development work is done at Marshall, including welding, tooling and fixtures and assembly procedures.

Developing MPM Specifications

MPM requirements are met through the use of a number of specifications that are either existing or developed especially for the US. The purpose of these specifications is to make sure that all the materials and processes used to manufacture the US hardware meet the NASA construction standards. They also help to define the quality control procedures that go in the drawings. Manufacturing Requirements Sheets (MRS) are prepared for components and assemblies. These sheets show the additional features required in the design drawings that enable manufacturing, such as excess material required for machining, handling or welding. They also list the specifications to be used for manufacturing specific components, including materials, processes to be used, heat treatment, NDE specs, etc. In this way all manufacturing requirements are captured during the design phase. Ultimately all the manufacturing requirements will be captured in a document, and kept under configuration control. Selected MPM specifications being developed by Marshall for the US are listed below in Table 1.

Table 1: **MPM Specifications to Support Upper Stage**

- Aluminum-Lithium 2195 Ingot, Alloy Plate and Extruded Rod
- Aluminum Thrust Cone Casting specification
- Honeycomb Core, Phenolic Reinforced
- Honeycomb Core, splice adhesive
- Cryogenic Insulation materials and Processes
- Stretch Forming and Aging of 2195 Aluminum Gore Panels for Liquid Hydrogen (LH2) and Liquid Oxygen Cryogenic Tanks
- Forming and Aging of Aluminum 2195 Barrel Panels
- Spin Forming of 2219, 2014, 2195 and 7075 Alloys
- Roll Ring Forging of 2195, 2219 Ingots
- Fiction Stir Welding
- Bump Forming and Aging of Common Bulkhead Bolting Ring
- Machining of Honeycomb Core
- Structural Bonding of Common Bulkhead
- Surface Preparation for Adhesive Bonding and Sealing
- Adhesive Bonding and Sealing
- Lifting and Handling Requirements Specification for Common Bulkhead
- Standard Repair Procedures (for various situations)
- Prof Test Requirements for Common Bulkhead and Cryogenic tanks
- US TPS Materials and Processes Control Plan
- Cleaning Processes for US Components

Technology Readiness for Upper Stage

MPM engineers must make sure that the technologies used in the program are sufficiently mature and do not pose a significant technical risk to the project. NPR 7120.5 requires that all technologies used in the program be at TRL 6 or higher at CDR. Figure 6 shows the TRL chart for NASA programs. Figure 7 and Figure 8 show the corresponding Capability Readiness Levels (CRL) for Materials and Processes, respectively. The CRL levels should be at least at 6 or higher by CDR; anything less than that poses a risk to the project.

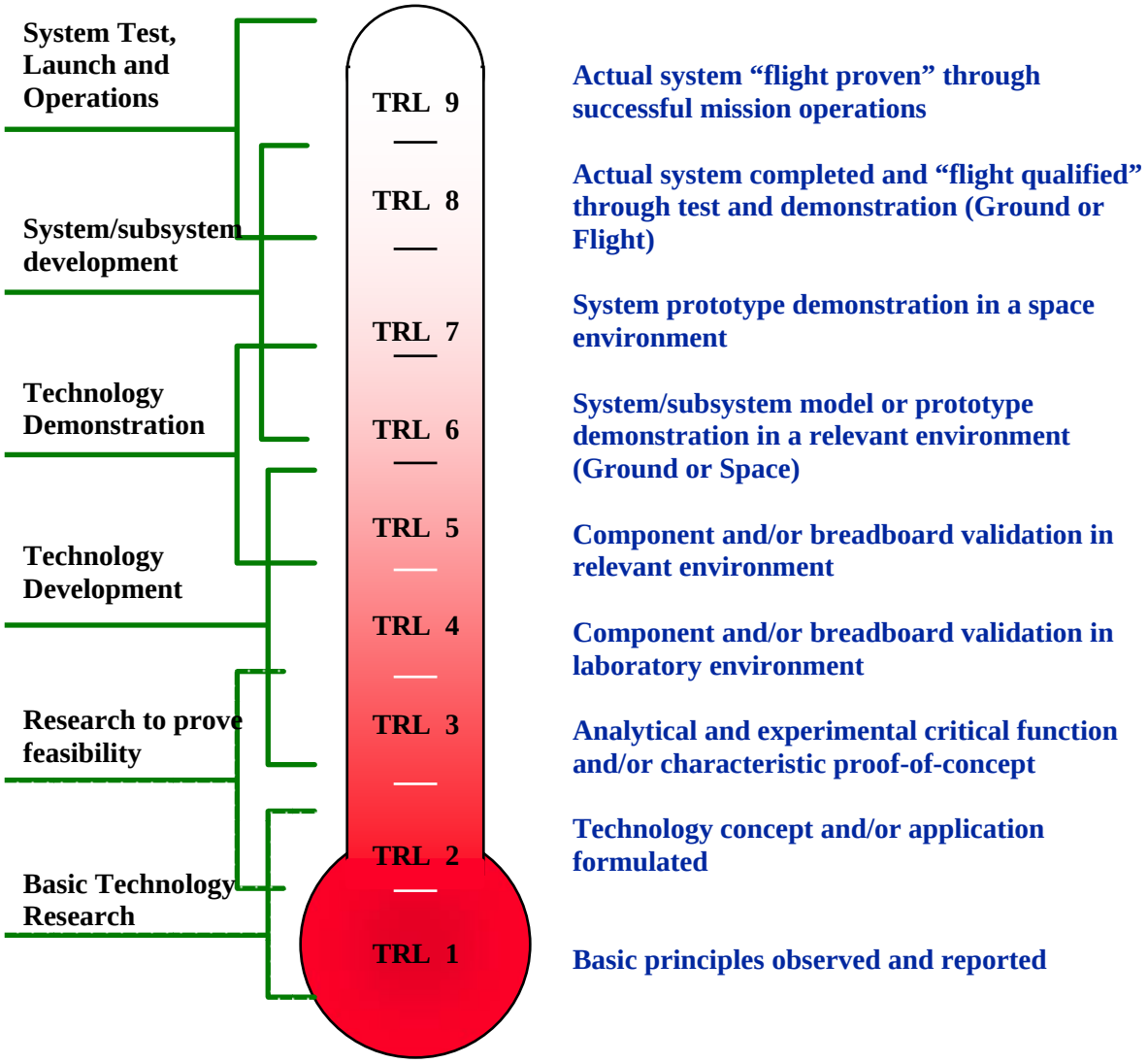


Figure 6: Space Technology Maturation Process: Technology Readiness Levels (TRLs)

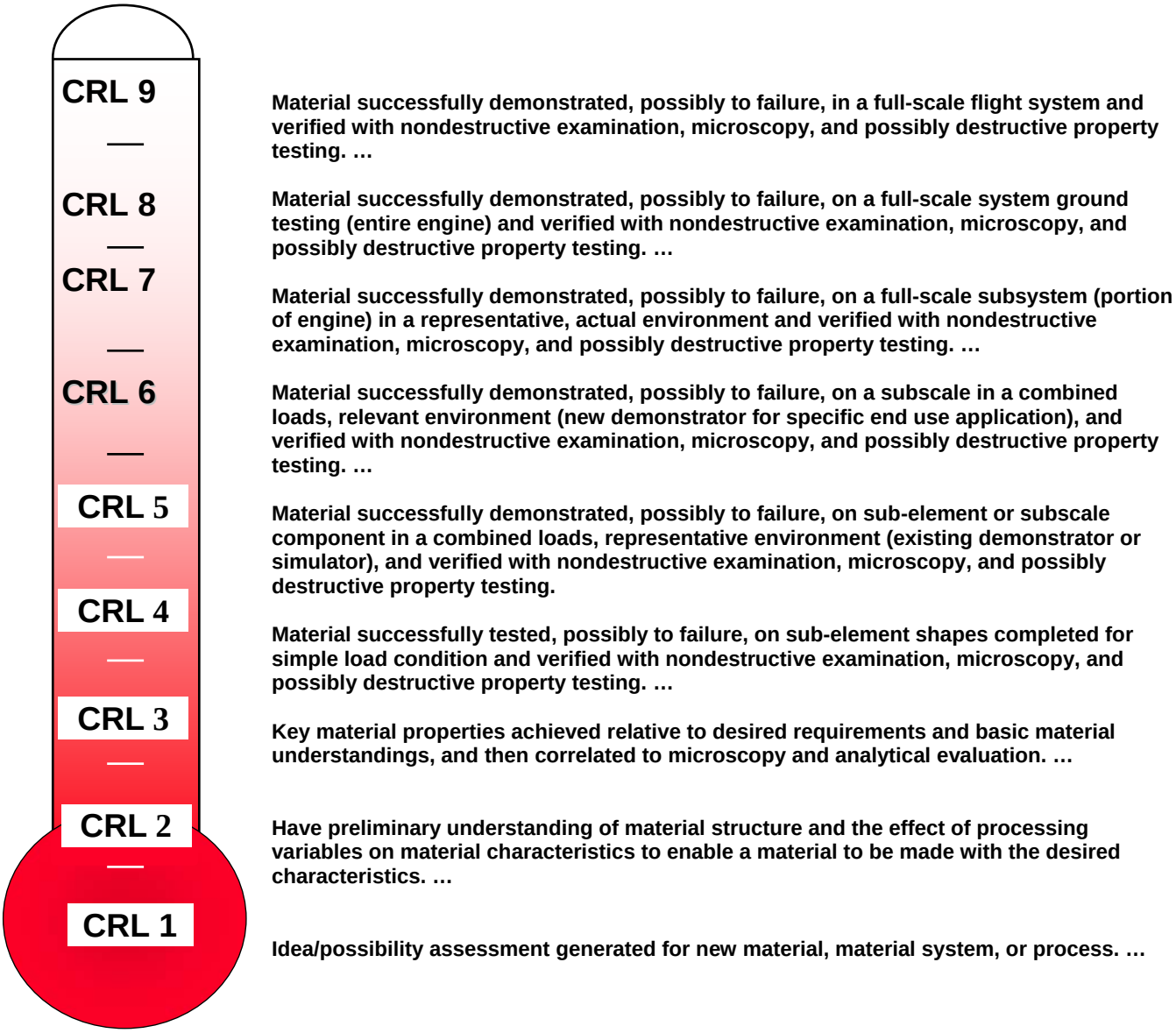
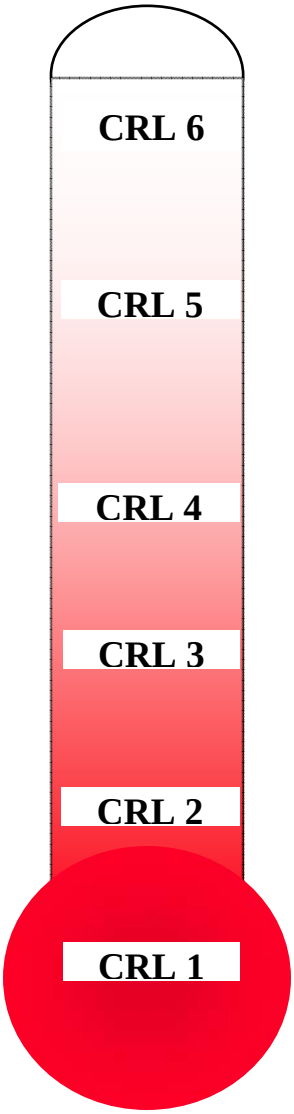


Figure 7: Materials Technologies Maturation Process: Capability Readiness Levels (CRL)



Note: Example cut off at CRL 6; scale goes to CRL 9

Process applied to object has produced defect free components; process parameter ranges identified

Process has been applied to shapes of the size and type of the objective component

Process has been modified to apply to objective shape

Process produces desired physical and mechanical properties

Process has been applied to simple test coupons

General classes of possible processes identified

Figure 8: Processing Technologies Maturation Process: Capability Readiness Levels (CRL)

Approach to Risk Management

Risks and associated mitigation plans are first developed internally within the M&A and evaluated with the M&A IPT. Risks which are wholly controlled within M&A resources stay internal to M&A and are managed by the M&A IPT. Risks which require outside resources to accomplish mitigation plans are forwarded the US Risk Management Team (RMT). The US RMT will disposition the risk and associated mitigation plan by accepting or rejecting the risk. The US RMT may also direct M&A participation in parent or child risks or in a joint risk with another IPT. For example, the US RMT directed the M&A IPT to provide a mitigation plan for a risk entitled "Lack of 2195 Fracture Data," which was generated by the S&T IPT. The US RMT direction to the M&A IPT was appropriate since M&A IPT has test facilities to test the 2195

aluminum alloy as required. In all cases, both M&A internal risks, M&A US risks, and US RMT directed risks conform to US risk management procedures.

It should be noted that risk identification and mitigation an integral part of the definition, design and verification processes. The key element in risk management is risk identification. Only the engineering and project "doers" can accomplish this effectively. It is the job of MPM engineers to identify all risks relative to MPM. They are responsible for identifying the risks and mitigating them on a continuous basis. Risks are often categorized into technical, programmatic (cost and schedule) and safety. MPM engineers have the primary responsibility for the technical risks in materials, processes and manufacturing areas, but they do influence on the other two. Table 1 shows some of the MPM risks for the US. They are being mitigated and the mitigation approach is shown in the last column.

Table 1: MPM Risks in US and Mitigation

Category	Risk	Mitigation Approach
Materials	Lack of materials characterization—lack of fracture data for Al-Li alloys	Generate necessary data for fracture control
	Hexavalent Chrome Material Obsolescence – currently used for conversion coating	Develop alternate surface treatment approaches
	HCFC-141b blowing agent material obsolescence – currently used on Shuttle, but not available for Ares	Develop alternate materials as blowing agents
	Lack of qualified vendors for Al-Li 2195 alloy; loss of supply base for Al-Li 2195	Qualify new vendors – e.g., Alcan
Processes	Friction stir welding technology for gores, barrels and CB not fully developed	Manufacturing demonstration Articles (MDA)
	Friction plug welding not fully developed	MDA
Manufacturing	Manufacturing CB – proposed technology is not proven	MDA and SDTA
	Long lead items – procurement takes too much time- having to release drawings before design is mature	Speed up procurement (has limitations)

Manufacturing Demonstration Articles (MDA)

The Manufacturing Demonstration Articles (MDA) are the technology demonstrators that M&A have assessed the hardware material properties and manufacturability to a high enough level for design confidence to proceed at the Critical Design Review level. Several MDA's are planned to provide the initial framework and cornerstone for all future Upper Stage metallic and composite material development by accomplishing the following objectives: 1. Full-scale demonstration to a Technology Readiness Level (TRL) 6 of all major components required to manufacture and assemble an Upper Stage tank (i.e. forward hydrogen bulkhead, tank barrel sections, and a Common Bulkhead), 2. Full-scale demonstration to a TRL 6 of all major assembly steps.

The following basic components of the US are being manufactured in-house to demonstrate feasibility:
1. Barrel Panels: 2195 Aluminum ingots will be rolled into plates, machined, brake formed into final shape
2. Dome Gores: 2195 Aluminum ingots will be rolled into plates, stretch formed into dome gores
3. Dome Fittings: 2195 Plates are machined to form dome fittings
4. Y-rings: machined out of rolled ring forgings, both 2195 and 2219 aluminum.
5. Dome caps: Both spin formed and stretch formed 2195 Al dome caps will be manufactured

The following assemblies will be manufactured to demonstrate feasibility:
1. Barrel Assembly: One full length friction stir welded barrel assembly
2. Dome Assembly: One FSW dome assembly

The following two separate demonstrators will be built:
1. A dome-and-barrel assembly representative of the Upper Stage Hydrogen Forward Dome (shown in Figure 9) to develop Aluminum-Lithium 2195 component forming and friction stir welding practices. FSW process will be demonstrated on newly designed weld tool and will be matured to CRL 6.

Figure 9: 2195 Manufacturing Demonstration Article—Barrel and Dome Assembly

2. A Common Bulkhead Assembly and will develop Aluminum 2014 to Aluminum-Lithium 2195 welding practices, complex honeycomb bonding and curing, and overall manufacturing and assembly processes (shown schematically in Figure 10). This development involves several process developments:

- Machining development for metallic domes and honeycomb core,
- Welding development for CB welds self-reacting weld for thin material
- Properties of adhesives cured at lower temperatures
- Deformation of thin walled material during curing cycle.
- NDE of thin walled material

- Coupon level honeycomb testing
- Cryogenic effects on bond strength
- Damage tolerance capability of thin walled weld lands and domes
- Eddy current testing of threaded holes and fasteners
- Repair processes for de-bonds

A detailed manufacturing flow and sequence for each component, sub-assembly, and article have been developed and are presented in the Manufacturing Demonstration Article Development Plan, USO-CLV-MP25501.

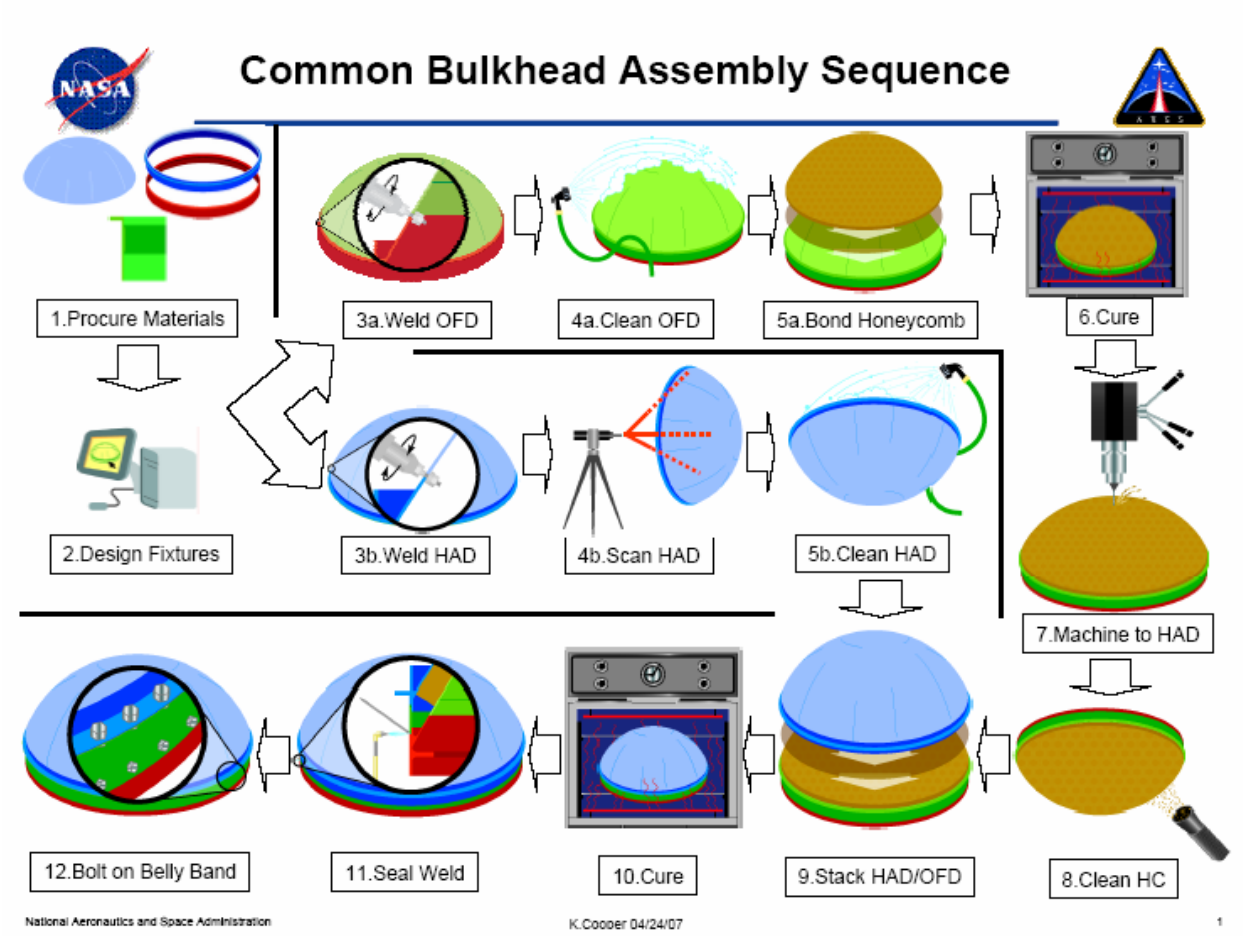


Figure 10: Simplified Schematic of the Common Bulkhead Assembly Process

MSFC has the primary responsibility to show that the Upper Stage can actually be built as designed. After successful demonstration the processing and manufacturing technologies will be transferred to MAF.

Corrosion Resistance Development Efforts

The products currently used for cleaning and conversion coating for corrosion protection of Shuttle External Tanks contain hexavalent chromium (Cr+6) salts. Cr+6 has been identified as a carcinogen and there are more and more stringent national and international regulations to lower its human exposure limits. There is a possibility that the Cr+6 products will become obsolescent, and there will be no replacements available that can meet the anticipated metal surface preparation and corrosion protection requirements for the Upper Stage fuel and oxidizer tanks, and various other exposed metallic surfaces. Therefore a risk mitigation task was developed to find alternatives to Cr+6 products. This task identifies a number of candidate replacement products, and procedures to qualify them for application in the US. So far tests have been run to screen a number of potential replacement candidate conversion coating products that do not contain Cr+6. Tests were also run to evaluate relative merits of using anodization as opposed to conversion coating to provide required corrosion protection.

The risk mitigation plan is implemented in four phases:

Phase I: Screening of cleaning solutions and materials combinations and down selection of promising combinations

Phase II: Testing of dissimilar alloy welding junctions; extending cryo-strain testing to LH2 and LOX temperatures; development of large scale spraying technology for selected conversion coats; Continue anodization evaluation if judged to be viable.

Phase III: Development of optimum surface treatment and parameters; scale-up; testing of large panels and curve surfaces; development of materials and processes specifications.

Phase IV: System level qualification testing and certification of selected coatings and/or processes

This task is expected to be completed by April, 2011. The current process is base lined for Ares I US, and the new processes will be used when ready.

Design Verification: Structural Development Test Articles

Following the Upper Stage MDA's, the Structural Development Test Articles (SDTA) are the second major step to verify the hardware designs for the Ares I US prior to Critical Design Review. Major, full-scale hardware tests are imperative to ensure that the design and materials used in the aerospace hardware are verified and validated. Table 2 lists the planned SDTA's. These are major demonstration efforts, encompassing and ranging from small panel compression tests, through full-scale pressurized tests-to-failure, to large Interstage composite panel tests. The structural test data acquired through the SDTA's must be satisfactorily completed to proceed at the Critical Design Review level to ensure that a re-design is not required. SDTA data will thus be generated early enough to allow for design iterations while there is still time to make changes. The SDTA data will feed into the last MSFC-built article, the Main Propulsion Test

Article (MPTA) development activities, which will be then followed by the Ground Vibration Test Article (GVTA), the first major article to be built at the Michoud Assembly Facility.

Table 2: **Structural Development Test Articles**

SDTA	Title	Purpose
SD02	Wide Panel Compression Test Article	Characterize compression behavior
SD03	CB Development Test Article	Characterize CB acreage and Y-ring design, LH2 forward and LOX aft Y-ring designs
SD05	LOX Tank Aft Dome/Thrust Structure Development Test	Characterize response of LOX tank aft dome design under flight-like loading
SD06	Wide Composite Panel Compression Testing Article	Characterize compression behavior of the composite Interstage panels
SD07	Bolted Ring Joint Strength Testing Article	Characterize the strength and stiffness the Interstage near the bolted flange.
SD08	Curved Panel with Access Door Testing Article	Characterize the stability of the Interstage around the access door
SD15	Thrust Cone Engine Mount Gimbal Test Article	Characterize the response of the Engine Mount Gimbal design under flight-like loading.
SD17	Second Stage Separation Joint Development Test	Understand the tensile and compressive strength of the separation joint and the bending stress induced by load path eccentricity
SD18	Avionics Rack Mounting System (ARMS) Development Test	Characterize the structural integrity, locking features, heat transfer, and functionality of the ARMS design
SD19	Development Test of the CB (follow-on to SD03)	Characterize the growth of known damage in CB

MPM engineers work closely with S&T IPT to help develop and manufacture the SDTAs, which can be tested to verify that the design actually works and meets the expectations of the designers. At the same time these tests prove that the materials, processes and manufacturing technologies used in the project have indeed done their job. Manufacturing engineers work very closely with structural engineers to make sure that the structural test articles can be manufactured as designed. The materials engineers provide the allowables that help to define the margins and safety factors in these tests. MSFC Handbook – 3513 is being developed to compile all materials properties data needed for the US Project, including fatigue and fracture data, which support these tests. An Ali-Li material test plan has been generated to provide material properties information for the parent alloy and for the primary components thicknesses and shapes. This plan will also characterize the properties for friction stir welding, self-reacting friction stir welding, and the corresponding weld repair techniques for the various component geometries and material thicknesses. The test plan will further evolve to satisfy the design requirements for the Ares I US components.

Acronyms/Definitions

Al-Li - Aluminum-Lithium
ARMS - Avionics Rack Mounting System
CARD - Constellation Architecture Requirements Document
CaLV - Cargo Launch Vehicle
CB - Common Bulkhead
CDR - Critical Design Review
CEI - Contractor's End Item
CEV - Crew Exploration Vehicle (Orion)
CLV - Crew Launch Vehicle (Ares I)
CM - Command Module
CxP - Constellation Program
DAC - Design and Analysis Cycle
EDS - Earth Departure Stage
ESMD - Exploration Systems Mission Directorate
ERD - Element Requirements Document
FFBD - Functional Flow Black Diagram
FSW - Friction Stir Welding
FOD - Foreign Object Debris/age
GVTA - Ground Vibration Test Article
ICD - Interface Control Document
IPT - Integrated Product Team
IRD - Interface Requirements Document
IU - Instrument Unit
LAS - Launch Abort System
LH2 - Liquid Hydrogen
LOX - Liquid Oxygen
M&A - Manufacturing and Assembly
MAF - Michoud Assembly Facility
MDA - Manufacturing Demonstration Articles
MPM - Materials, Processes and manufacturing
MPS - Main propulsion System
MPTA - Main Propulsion Test Article
MRS - Manufacturing Requirements Sheet
NASA - National Aeronautics and Space Administration
OML - Outer Mold Line
PDR - Preliminary Design Review
RCS - Reaction Control System
RM - Risk Management
RMT - Risk Management Team
SA - Spacecraft Adapter
S&T - Structures and Thermal
SDR - System Definition review
SDTA - Structural Development Test Articles
SEI - Systems Engineering and Integration

SEMP - Systems Engineering Management Plan
SM - Service Module
SRD - System Requirements Document
SRR - System Requirements Review
TRL - Technology Readiness Level
TVC - Thrust Vector Control
US - Upper Stage
WBS - Work Breakdown Structure

References

NPR 7120.5: NASA Program and Projects Management Processes and Requirements
USO-CLV-SE-25710: Upper Stage (US) Element Requirements Document (ERD), 2007
USO-CLV-SE-25707: Ares Upper Stage Systems Engineering Management Plan (SEMP), 2007
USO-CLV-MA-25001: Ares I Upper Stage (US) Development Plan
Ares-USO-MP-25500: Upper Stage Element Manufacturing and Assembly Plan
USO-CLV-MP25501: Manufacturing Demonstration Article Development Plan,
CxP 70000: Constellation Architecture Requirements Document (CARD)
CxP-7002: Constellation Design Reference Missions
CxP 72034 "CLV System Requirements Document (SRD)" May 7, 2007, Baseline Version

National Aeronautics and Space Administration

Materials, Processes and Manufacturing in Ares I – Upper Stage

Biliyar Bhat

NASA-MSFC

NSMMS- June 25, 2008

Materials, Processes and Manufacturing in Ares I – Upper Stage:

Integration with Systems Design and Development

Overview

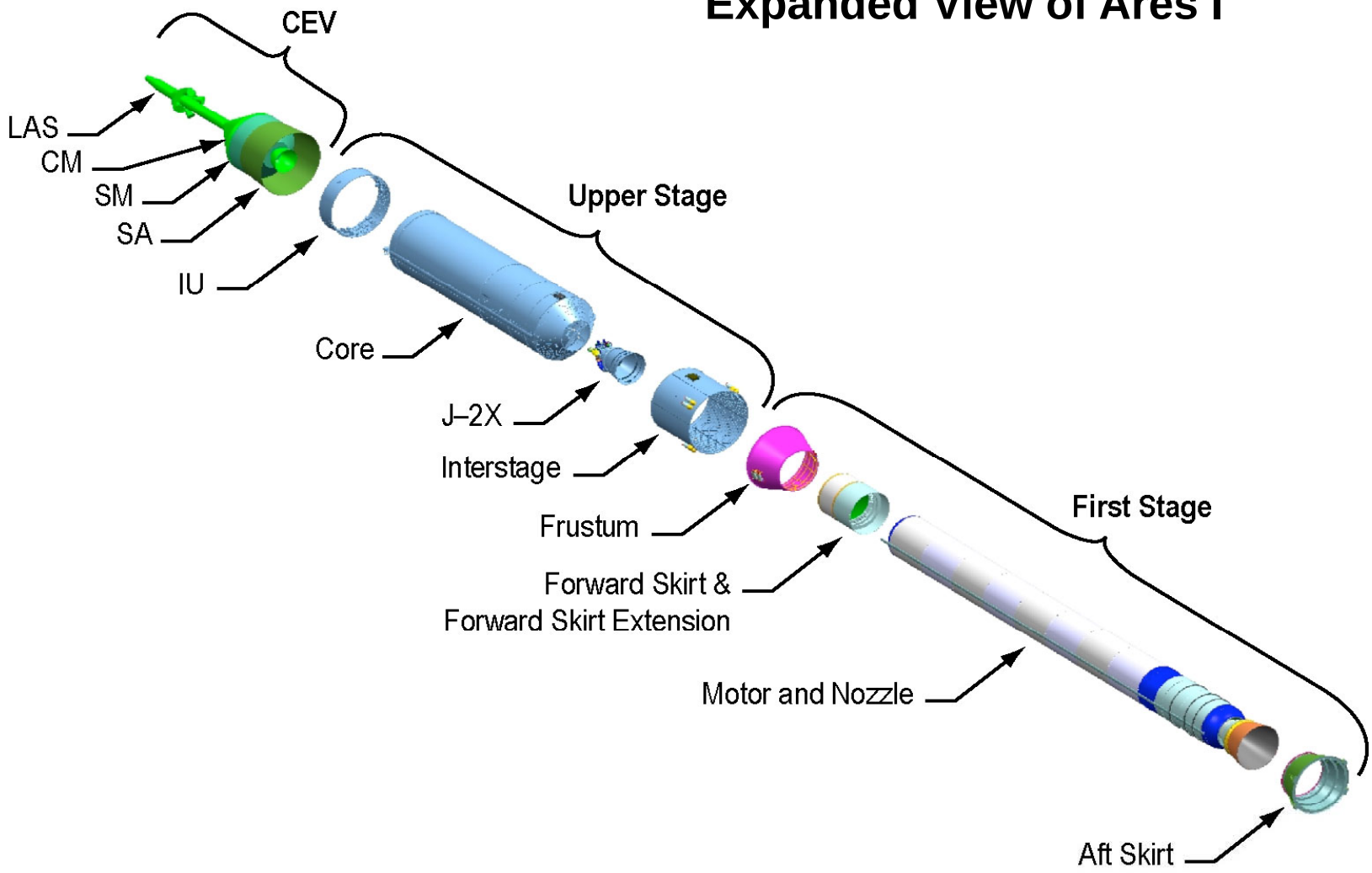
- Introduction
- Ares I: Crew Launch Vehicle
- Ares I - Uppers Stage
- Upper Stage Design – Systems Engineering
- Integrated Design and Analysis
- Integrated Product Teams
- MPM Integration with US Design and Development
- US Construction
- US Construction Standards
- MPM Plans & Specifications
- Technology Readiness and Maturation
- Risk Mitigation
- Manufacturing Demonstration Articles
- Structural Development Test Articles
- Summary

Introduction

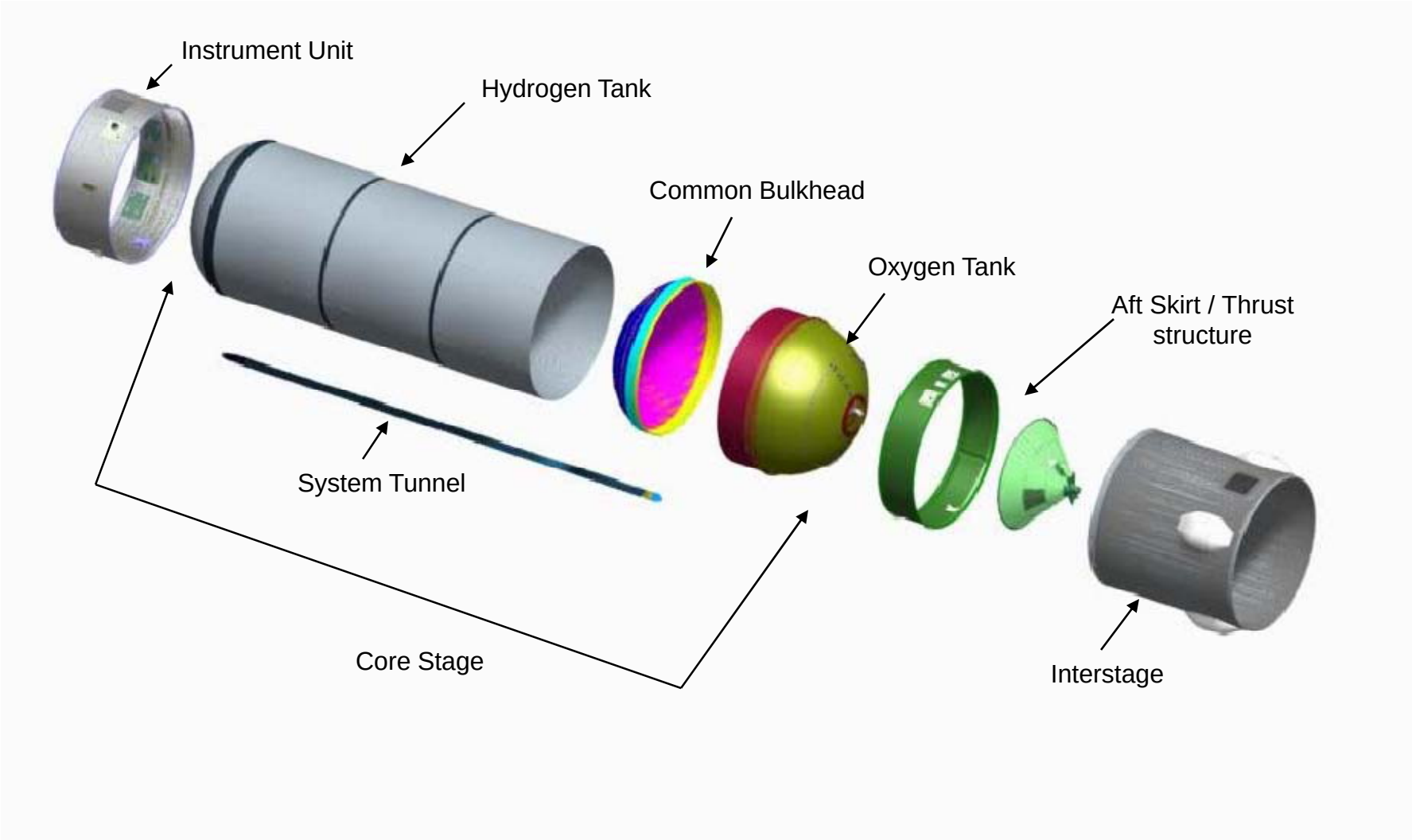
- Ares I Upper stage is designed and built based on sound Systems Engineering principles
  - Compliance with requirements
  - Meeting performance goals
  - Meeting stakeholders' expectations
- Materials and Processes are important throughout the design and development of Ares I
  - All systems are built from materials
  - Many different processes and manufacturing techniques are used
  - Materials and Processes are enablers for design and development
- Materials, Processes and Manufacturing (MPM) Engineers must work closely with Design and Analysis Teams during Ares I systems design and development
  - To ensure robust design
  - To make sure that the system is producible and affordable

Ares I – Crew Launch Vehicle

Expanded View of Ares I

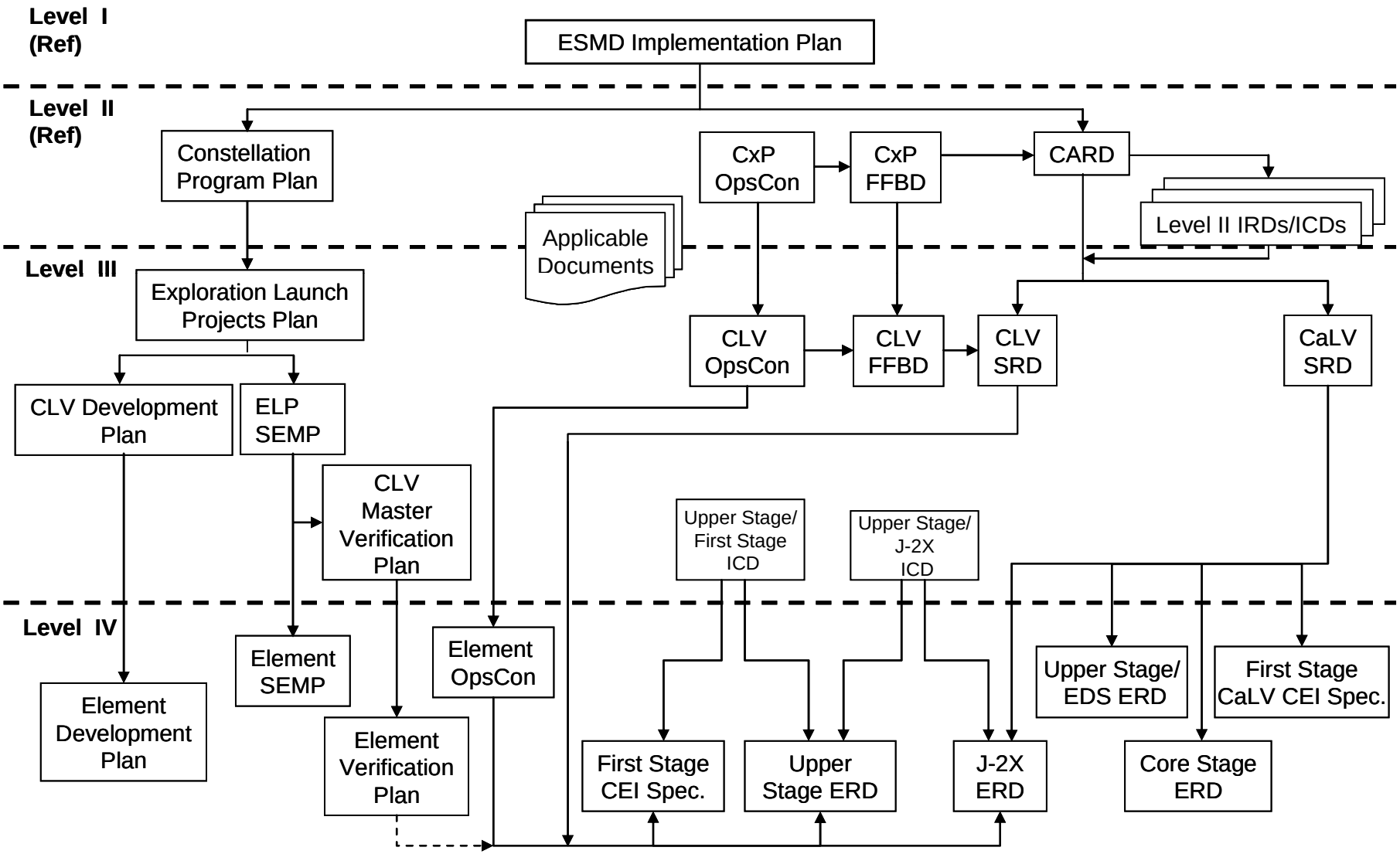


Ares I - Upper Stage – Expanded View



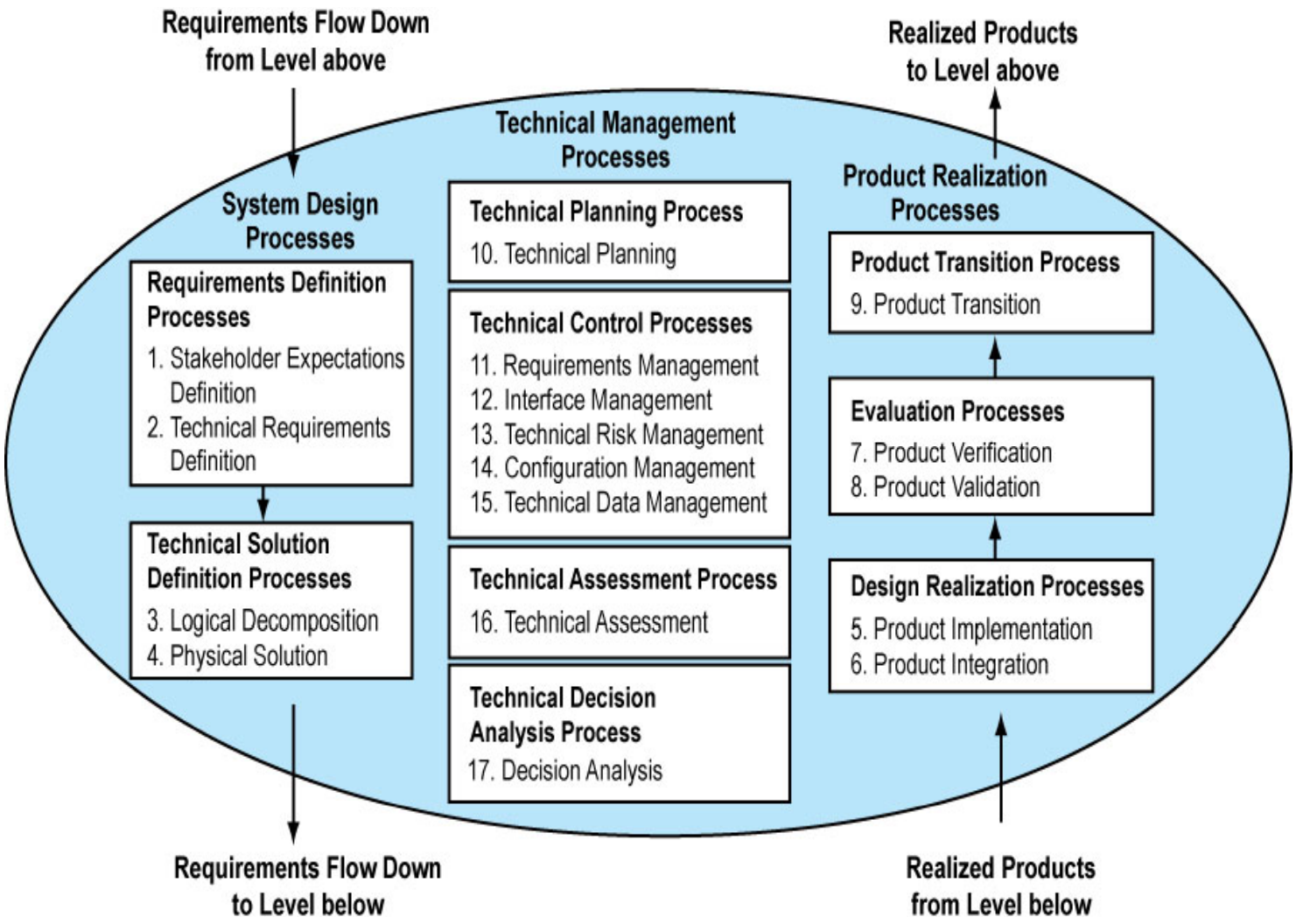
Upper Stage Design: Requirements Flow Down

Constellation Document Tree Showing Requirements Flow Down



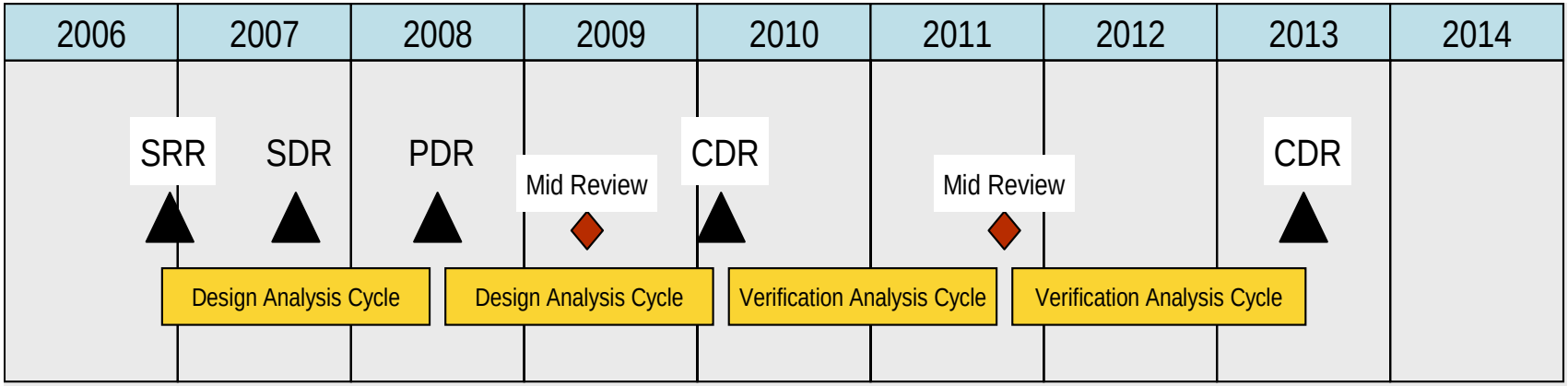
Upper Stage Design: Systems Engineering

NASA Systems Engineering Process Model



Integrated Design and Analysis

- System requirements flow down from higher level to lower level through direct allocation, apportionment or derivation
- Requirements are met through design solutions
- Design is matured through a number of design and analysis cycles when going from SRR to CDR
- Trade studies are performed
- Risk management is done as an integral part of design and analysis



Integrated Design and Analysis Events for Ares I

Integrated Product Teams (IPT)

- Upper Stage Design and Development is carried out through a number of Integrated Product Teams (IPT):
  - Systems Engineering and Integration (SEI)
  - Main Propulsion System (MPS)
  - Structures and Thermal (S&T)
  - Manufacturing & Assembly (M&A)
  - Test
  - Avionics
  - Thrust Vector Control (TVC)
  - Reaction Control System (RCS)
  - Logistics
  - Small Solids
- SEI IPT has the overall responsibility for integration of Upper Stage
- There is significant interaction among the IPT's
- IPT works/products are integrated both horizontally and vertically

MPM Integration with US Design and Development

- **Design IPT Support**
  - Materials Data– physical and mechanical properties, data base
  - Consultation– availability, producibility, facility, tools and equipment, cost, vendor support
- **Trade Studies – Support alternate design concepts**
  - Common Bulkhead vs Separate Tanks
  - Metallic vs Composite Interstage
- **Development**
  - Manufacturing Development Articles
  - Construction Standards
  - Specifications
- **Design Verification**
  - Structural Development Test Articles
  - Materials Properties Data Book
- **Integrated Manufacturing and Assembly**
  - Manufacturing Process Development
  - Tools and Equipment
  - Facility Development

Upper Stage Construction

- MPM Engineers are responsible for making sure that the US hardware is in compliance with all NASA Standards for Construction as stated in the US Element Requirements Document
- A number of Level IV and Level V plans are generated to show how the Construction Standards will be met
- A number of specifications are generated to support materials, processes, manufacturing and assembly
- Examples are given in the next three slides

Upper Stage Construction Standards

- NASA-STD-(I)-5006: Welding Requirements for Aerospace Materials used in Flight Hardware
- NASA-STD-5007: General Fracture Control Requirements for Manned Space Flight Systems
- NASA-STD-5009: Standard NDE Guidelines and Requirements for Fracture Control Programs
- NASA-STD-5012: Strength and Life Assessments of Liquid Fueled Space Propulsion Systems
- NASA-STD-6016: Standard Manned Spacecraft Requirements for Materials and Processes
- CxP 70145: Constellation Program Contamination Control Plan
- CLV-USO-MP-25500: Upper Stage Manufacturing and Assembly Plan
- CLV-USO-MP-25505: Upper Stage Contamination Control Plan
- MSFC-SPEC-164: Specification for Cleanliness of components for Use in Oxygen, Fuel and Pneumatic Systems
- MSFC-STD-2594: Fastener Management and Control Practice Requirements
- MSFC-STD-3029: Selection of Metallic Materials for Stress Corrosion Cracking Resistance in Sodium Chloride Environments
- MSFC-STD-486B: Torquing of Threaded Fasteners
- ANSI/AIAA G-095-2004: Guide to Safety of Hydrogen and Hydrogen Systems
- ASTM MANL 36: Safe use of Oxygen and Oxygen Systems

Materials, Processes and Manufacturing Plans

- Upper Stage Element Manufacturing and Assembly (M&A) Plan
- Materials, Processes Selection, Control and Implementation Plan
- Materials Usage Agreements
- Materials Identification and Usage List
- Contamination Control Plans, including Foreign Object Debris/Damage
- Non-destructive Evaluation Plan
- Fracture Control Plan
- Electric, Electronic, and Electromechanical (EEE) Parts Control Plan
- Limited Life Items List

Materials, Processes and Manufacturing Specifications

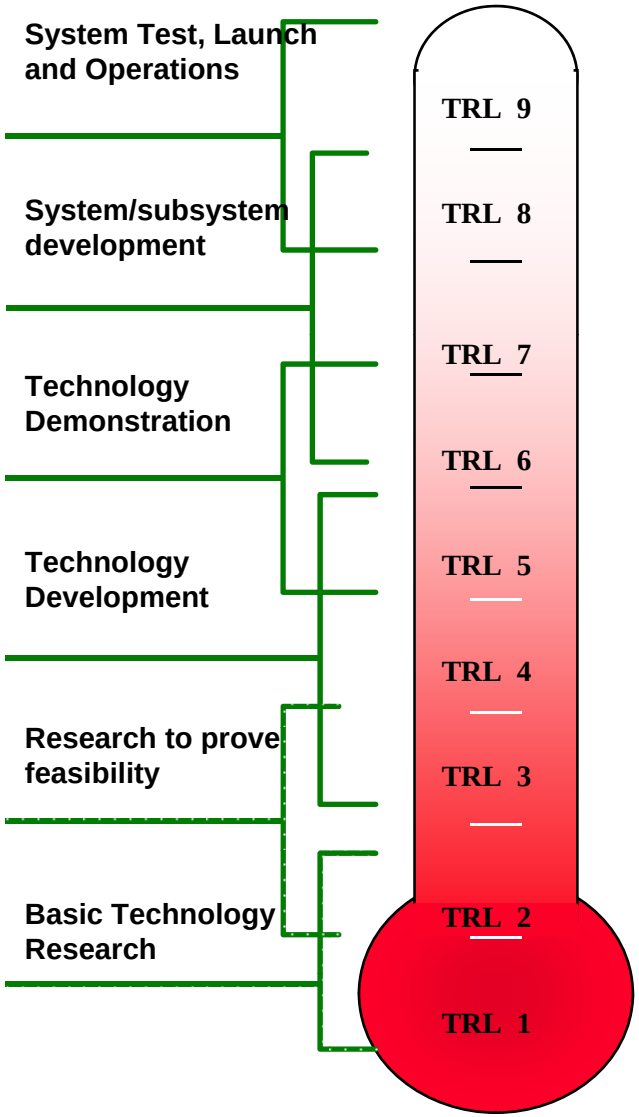
- Aluminum-Lithium 2195 Ingot, Alloy Plate and Extruded Rod
- Aluminum Thrust Cone Casting specification
- Honeycomb Core, Phenolic Reinforced
- Honeycomb Core, Splice Adhesive
- Cryogenic Insulation Materials and Processes
- Stretch Forming and Aging of 2195 Aluminum Gore Panels for Liquid Hydrogen and Liquid Oxygen Cryogenic Tanks
- Forming and Aging of Aluminum 2195 Barrel Panels
- Spin Forming of 2219, 2014, 2195 and 7075 Alloys
- Roll Ring Forging of 2195, 2219 Ingots
- Fiction Stir Welding
- Bump Forming and Aging of Common Bulkhead Bolting Ring
- Machining of Honeycomb Core
- Structural Bonding of Common Bulkhead
- Surface Preparation for Adhesive Bonding and Sealing
- Adhesive Bonding and Sealing
- Lifting and Handling Requirements Specification for Common Bulkhead
- Standard Repair Procedures (for various situations)
- Prof Test Requirements for Common Bulkhead and Cryogenic Tanks
- US TPS Materials and Processes Control Plan
- Cleaning Processes for US Components

Technology Readiness and Maturation

- MPM engineers must make sure that the technologies used in the program are sufficiently mature and do not pose a significant technical risk to the project.
- Technologies should be at Technology Readiness Level (TRL) of 6 or higher.
- TRLs do apply to Materials and Processes.
  - Materials Readiness Levels
  - Process Readiness Levels
- If the TRL is low then the technologies must be maturated to TRL 6 in a timely manner.

Technology Maturation Process

Technology Readiness levels



TRL 9 — Actual system "flight proven" through successful mission operations

TRL 8 — Actual system completed and "flight qualified" through test and demonstration (Ground or Flight)

TRL 7 — System prototype demonstration in a space environment

TRL 6 — System/subsystem model or prototype demonstration in a relevant environment (Ground or Space)

TRL 5 — Component and/or breadboard validation in relevant environment

TRL 4 — Component and/or breadboard validation in laboratory environment

TRL 3 — Analytical and experimental critical function and/or characteristic proof-of-concept

TRL 2 — Technology concept and/or application formulated

TRL 1 — Basic principles observed and reported

Material and Process Readiness Levels Are Analogs to TRLs*

Materials Readiness Level (MRL)		Process Readiness Level (PRL)
Material is a commodity material in high volume production.	9	**Process is in high volume production. Integration and operations processes are fully developed and mature**
Material is off-the-shelf, but not in high volume production	8	**Process is in low volume production. Integration and operations processes are developed**
Material is custom off-the-shelf.	7	**Process is performed on contract. Integration and operations processes are mostly developed**
Material available and used in components acceptable for flight	6	**Process applied to object has produced defect free flight-acceptable components; process parameter ranges identified, int and ops procedures partially developed**
Material applied to shapes of the size and type of objective component with verified properties	5	**Process has been applied to shapes of the size and type of the objective component. Int & ops concepts identified**
Material applied to objective shape with verified properties	4	**Process has been modified to apply to objective shape, notional options for integration and operations**
Material data properties verified	3	**Process produces desired physical and mechanical properties; notional options for integration and operations**
Material within family identified	2	**Process has been applied to simple test coupons**
Material family/families identified	1	**General classes of possible processes identified**

*Courtesy: Aerospace Corporation

Risk Mitigation

- Risk Types: Technical, Programmatic (cost & schedule), Safety
- Risk identification and mitigation are an integral part of the design, development and verification process
- Upper Stage Risk is managed through US Risk Management Team
- Risks internal to M&A IPT are managed internally
- Risks outside M&A but within Upper Stage are managed through Upper Stage Risk Management Team
- MPM Engineers have the primary responsibility for identifying and mitigating technical risks in their discipline areas.
- Some current risks are shown in the next chart

MPM Risk Mitigation

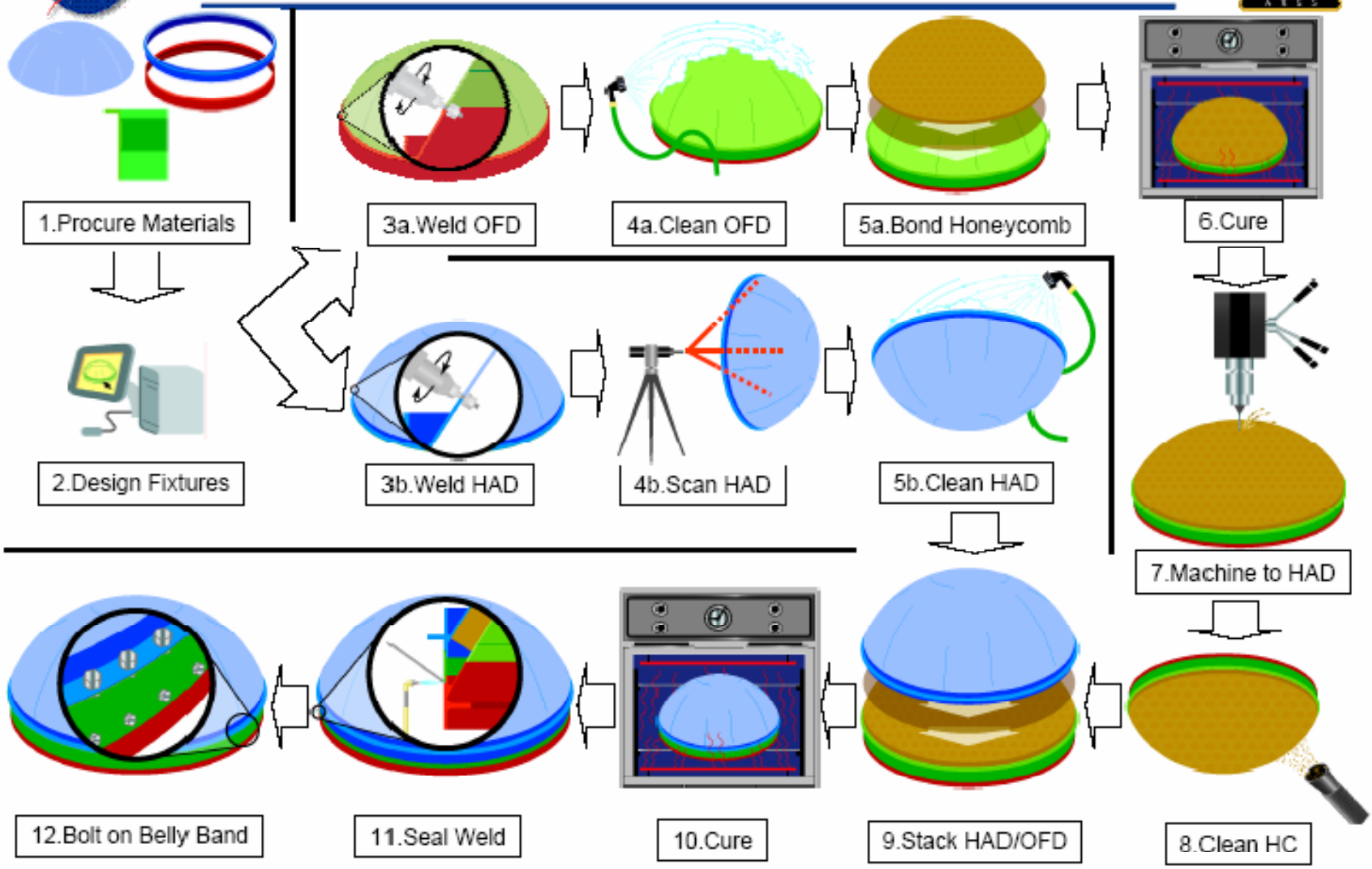
Category	Risk	Mitigation Approach
Materials	Lack of materials characterization—lack of fracture data for Al-Li alloys	Generate necessary data for fracture control
	Hexavalent Chrome Material Obsolescence – currently used for conversion coating	Develop alternate surface treatment approaches
	HCFC-141b blowing agent material obsolescence – currently used on Shuttle, but not available for Ares	Develop alternate materials as blowing agents
	Lack of qualified vendors for Al-Li 2195 alloy; loss of supply base for Al-Li 2195	Qualify new vendors – e.g., Alcan
Processes	Friction stir welding technology for gores, barrels and CB not fully developed	Manufacturing Demonstration Articles (MDA)
	Friction plug welding not fully developed	MDA
Manufacturing	Manufacturing CB – proposed technology is not proven	MDA and SDTA (Structural Development Test Articles)
	Long lead items – procurement takes too much time—schedule risk	Speed up procurement (has limitations)

Manufacturing Demonstration Articles (MDA)

- MDA – Technology demonstrators for building confidence in the materials, processes, manufacturing and assembly technologies
- Confidence level should be high enough (TRL 6 or better) for the design to proceed to CDR
- Planned MDA's: All major components and assembly steps
- Basic Components: Barrel Panels, Dome Gores, Dome fittings, Y-rings, Dome caps
- Basic Assemblies: Barrel assembly, Dome assembly
- Demonstrators:
  - Dome and barrel assembly representative of US Hydrogen Forward Dome to develop Al-Li 2195 component forming and friction stir welding
  - Common Bulkhead Assembly to develop AL 2014 to Al-Li 2195 welding practices, complex honeycomb bonding and curing, and overall manufacturing and assembly processes

MDA: Barrel and Dome Assembly

Common Bulkhead Assembly Sequence



Structural Development Test Articles (SDTA)

- SDTA: Second major step to verify hardware design for Ares I – US prior to CDR
  - Structural test data will ensure that a redesign is not required
  - A current list of SDTA's is given in the next chart
- SDTA data will feed into the Main Propulsion Test Article (MPTA)
- MPM engineers work closely with S&T IPT to develop and manufacture SDTA's
- SDTA's prove that the materials, processes and manufacturing technologies used in the project have indeed done their job and test articles can be manufactured as designed.
- Materials engineers generate material properties data needed to define structural margins and safety factors

Structural Development Test Articles

SDTA	Title	Purpose
SD02	Wide Panel Compression Test Article	Characterize compression behavior
SD03	CB Development Test Article	Characterize CB acreage and Y-ring design, LH2 forward and LOX aft Y-ring designs
SD05	LOX Tank Aft Dome/Thrust Structure Development Test	LOX Tank Aft Dome/Thrust Structure Development Test
SD06	Wide Composite Panel Compression Testing Article	Characterize compression behavior of the composite Interstage panels
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SD19	Development Test of the CB (follow-on to SD03)	Characterize the growth of known damage in CB

Summary

- Materials, Processes and Manufacturing (MPM) are integral to the design and development of Ares I Upper Stage
- During the design phase MPM engineers work closely with design teams to ensure a robust design that can be manufactured affordably and hardware can be delivered on time
- MPM engineers continuously monitor the risks in materials and processes and manufacturing technologies and mitigate them in a timely manner
- NASA design and construction standards are met through development of a number of materials, processes and manufacturing specifications
- Technology risks are mitigated through a series of Manufacturing Development Articles (MDA)
- Maturity and flightworthiness of hardware design and associated MPM technologies are proven through a series of Structural Development Test Articles (SDTA)