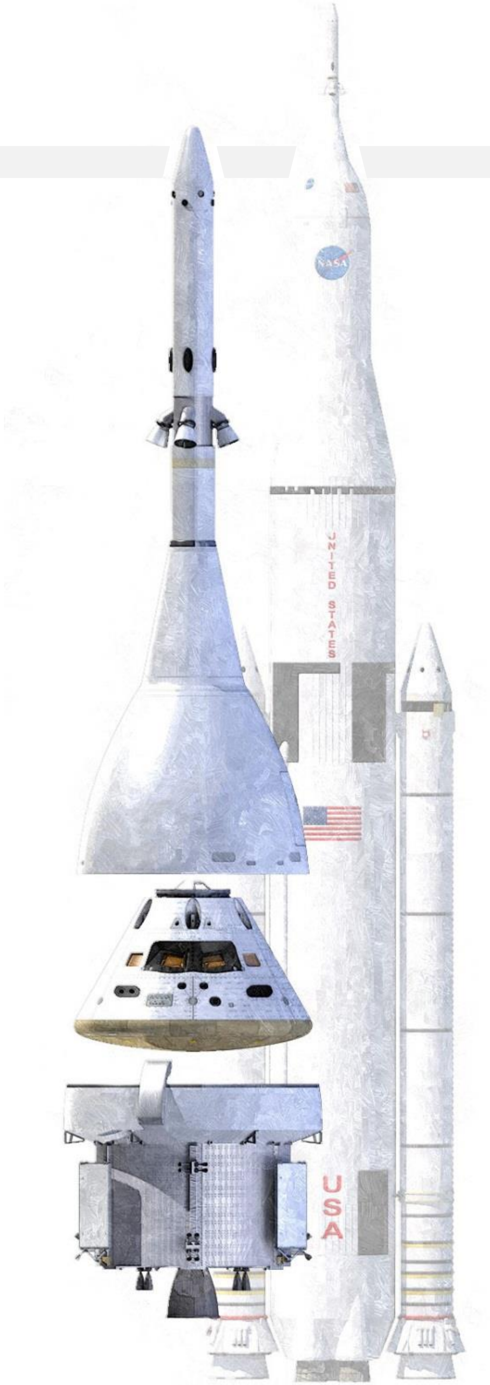

Reality Systems Engineering

INCOSE Conference “A Renewal in Exploration”

May 3, 2018

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NASA, Orion Program, Crew and Service Module Office

Introduction

Reality Systems Engineering

- **Merging the rules and principles of systems engineering into the program realities of cost, schedule, and international partnerships**

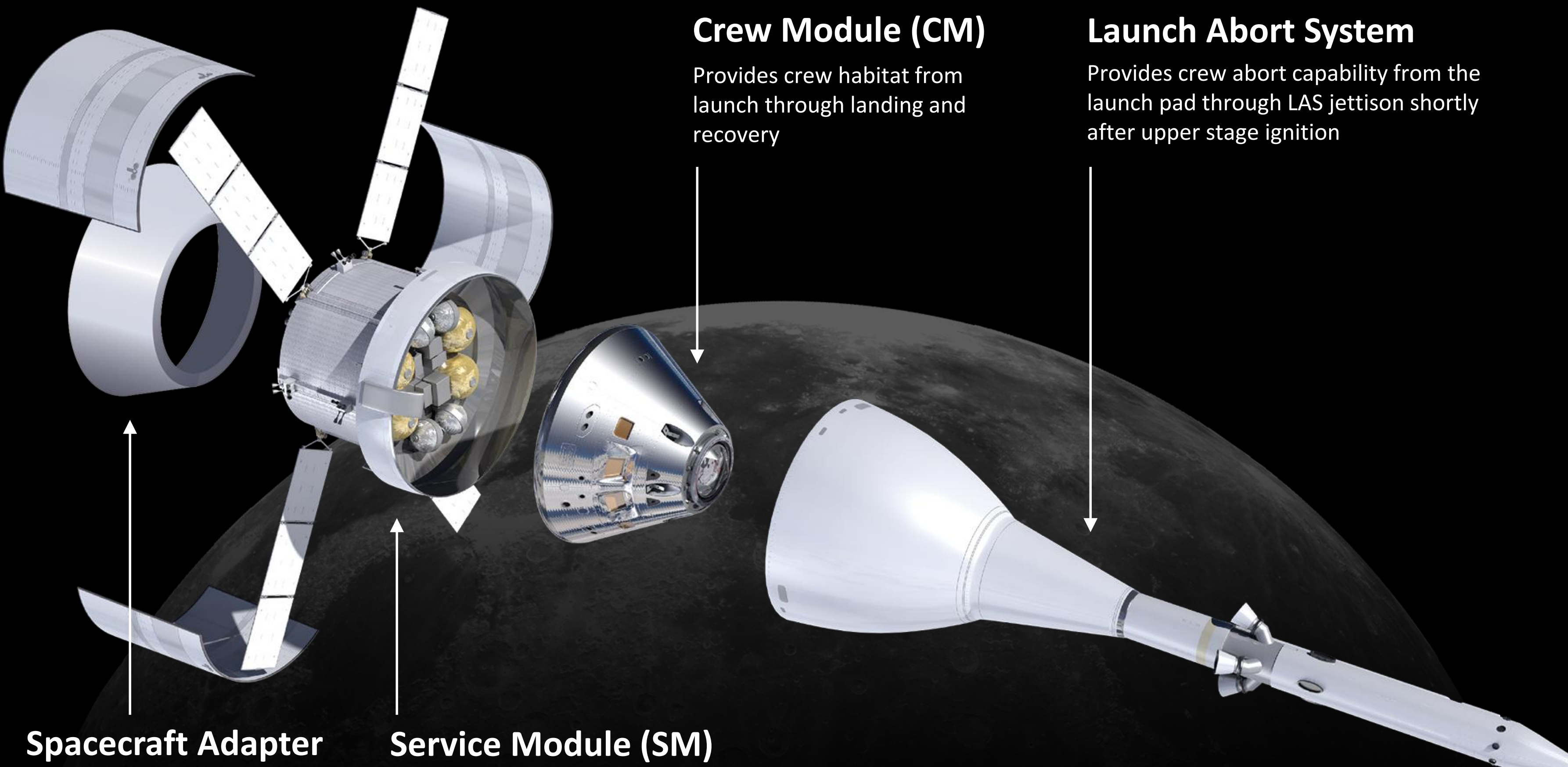
- **A summary of the challenges planning and executing the Orion Critical Design Review (CDR) in 2015 and the approaches employed to adapt systems engineering processes to program realities**

Plans are nothing; planning is everything.
Dwight D. Eisenhower

Outline

- **Orion Vehicle and Mission Overview**
- **Program Realities**
  - Prolonged Design and Manufacturing Schedule Driven by Flat Budget
  - Asynchronous Development with International Partner
- **Final Thoughts**

ORION MPCV SPACECRAFT OVERVIEW



Crew Module (CM)

Provides crew habitat from launch through landing and recovery

Launch Abort System

Provides crew abort capability from the launch pad through LAS jettison shortly after upper stage ignition

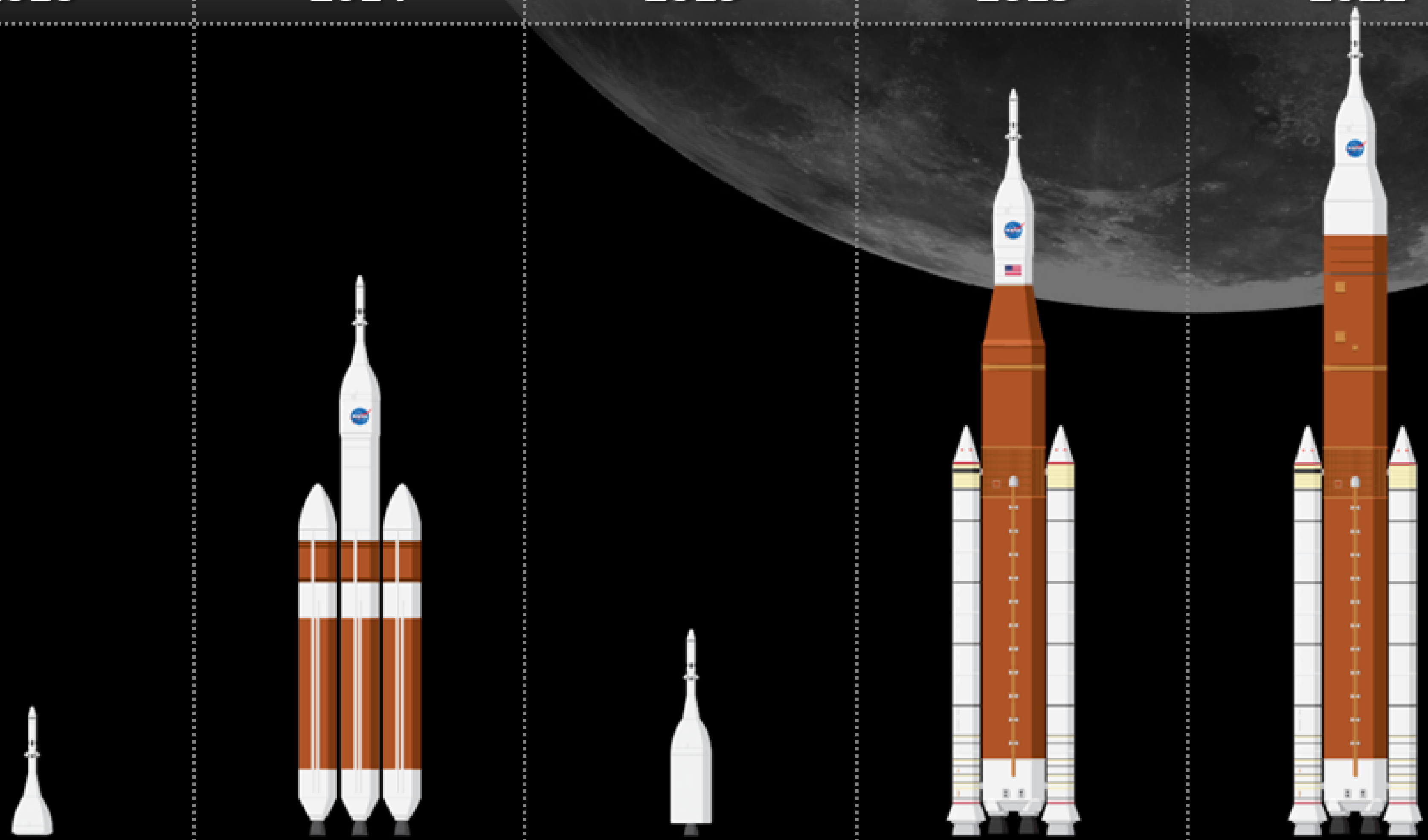
Spacecraft Adapter

Provides mass efficient structural capability from launch through fairing jettison

Service Module (SM)

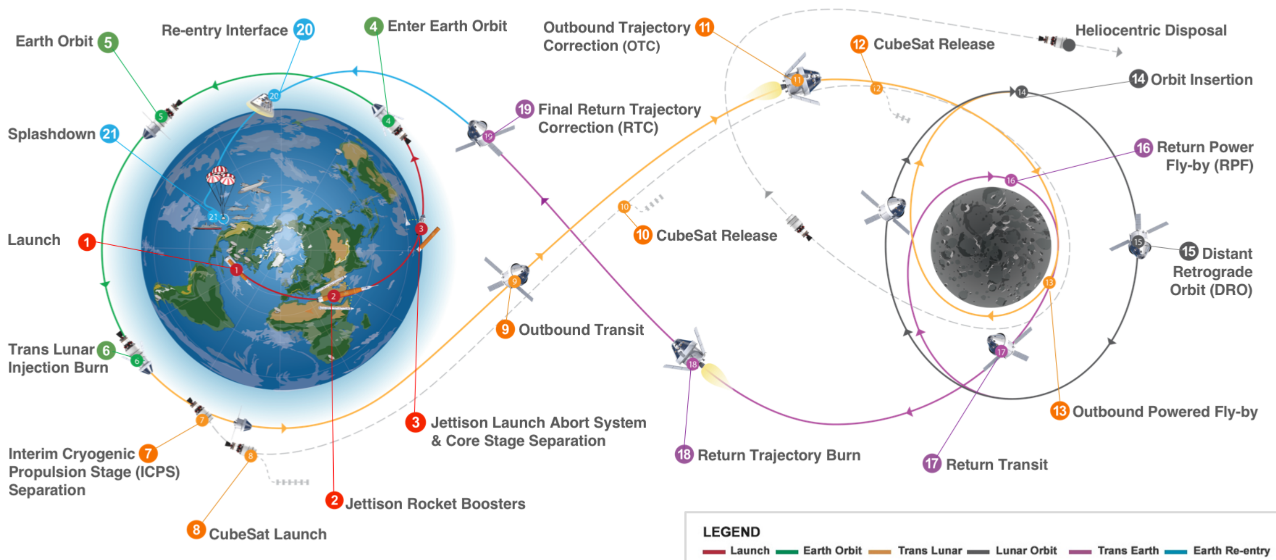
Provides electrical power generation, propulsion, thermal control and consumables storage until just prior to re-entry

ORION'S PATH TO EXPLORATION



2010	2014	2019	2019	2022
PA-1	EFT-1	AA-2	EM-1	EM-2
COMPLETED	COMPLETED			

Design Reference Missions: EM-1 & EM-2

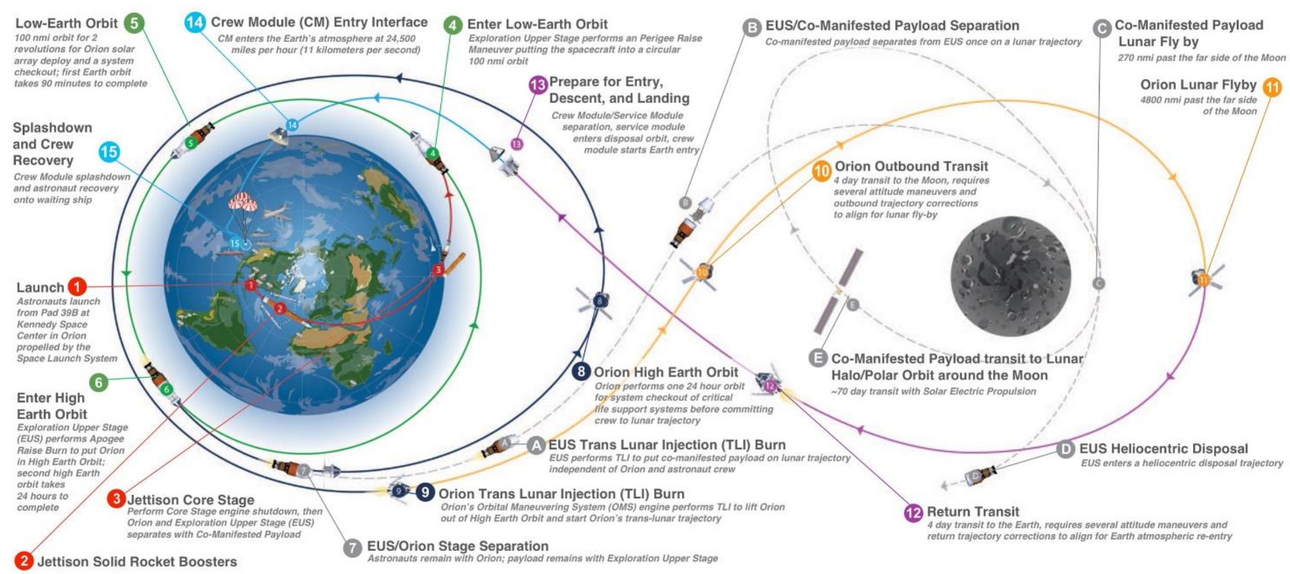


EM-1: Uncrewed Distant Retrograde Orbit (DRO)

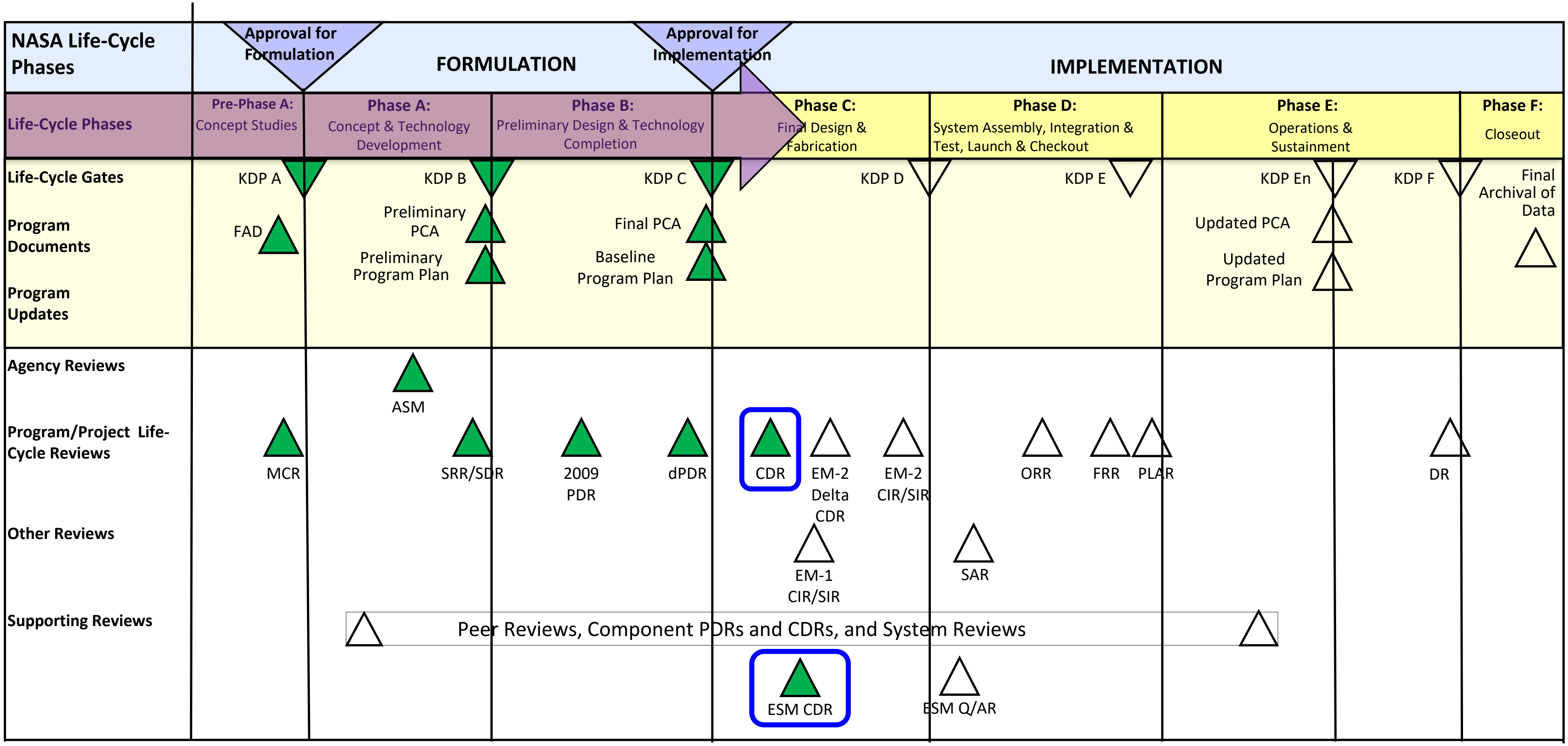
- Mission Duration: 25.5 days
- Orion: Fully functional core systems and capabilities for uncrewed missions, and Development Flight Instrumentation system
- SLS: 5 segment SRBs, 4 RS-24D, Interim Cryogenic Propulsion Stage

EM-2: Crewed High Earth Orbit, Lunar Flyby

- Mission Duration: 9 days
- Orion: Added capabilities for crewed missions include full ascent abort, flight crew equipment, and life support system
- SLS: 5 segment SRBs, 4 RS-24D, Exploration Upper Stage



Orion MPCV Life Cycle Progression



Maintained Compliance with NPR 7120.5E and NPR 7123.1B

Critical Design Review (CDR) Scope

- **CDR addressed the integrated spacecraft at a system and subsystem level**
  - Component level CDRs were conducted and scheduled based on component procurement needs
- **CDR included common aspects of the EM-1 and EM-2 designs, and unique EM-1 subsystems such as Development Flight Instrumentation**
  - Covers applicable extensible performance requirements
  - Demonstrates a design evolution path to deferred requirements such as Extravehicular Activities and Rendezvous and Docking
- **EM-2 unique systems to be addressed EM-2 CDR in Fall 2018**
- **CDR addressed ESA Service Module (ESM) aspects affecting the interfaces and the integrated spacecraft and subsystems**
  - ESM design details addressed at the ESM CDR
- **CDR addressed Flight Software (FSW) detailed requirement flow-down, overall design and interface definition, development plans, and test plans**
  - FSW Detailed Design Reviews performed with each incremental software build will cover the detailed FSW modeling, code production, and test results

Summary of EM-2 Unique Content
ECLSS • Air Revitalization • Fire Detection and Suppression • Full CM Pressure Control • Waste Management • Liquid Cooling Garment
Crew Systems/Flight Crew Equipment • Suits • Food System • Stowage System
Cabin Lights, Power Utility Panels
Displays and Controls
Full EM-2 Flight Software • Crew / Piloting Support • Backup Flight Software
Communications and Tracking • Emergency Comm • Recovery Comm • Audio System
Active Launch Abort System

CDR Objectives and Success Criteria

Objectives

Demonstrate that the maturity of the design is appropriate to support proceeding with full-scale fabrication, assembly, integration and test

Determine that the technical effort is on track to complete the system development while meeting performance requirements within the identified cost and schedule constraints.

Success Criteria

CDR Success Criteria complies with NPR 7123.1B and Lockheed Martin Command Media with exception of tailored Software Criteria

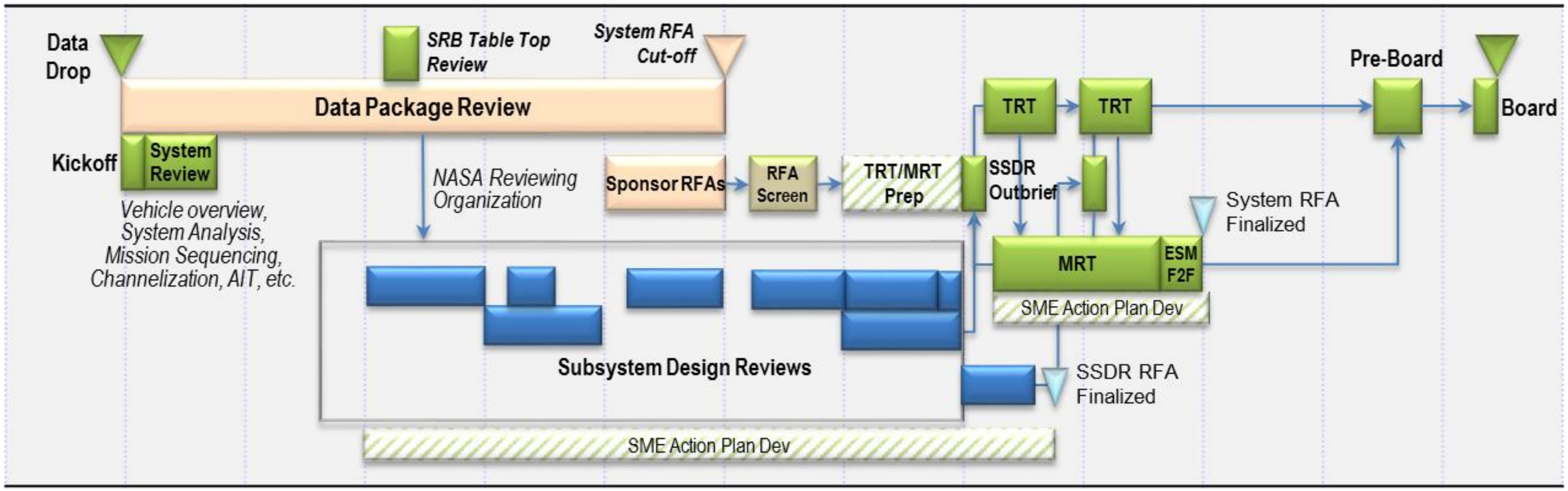
Software success criteria was tailored to align with the model-based, incremental development approach of the Orion flight software

Subsystem Success Criteria defined and applied to all Subsystem Design Reviews (SSDRs)

No	Success Criteria*	7123.1B Mapping
1	Requirements and Plans	10, 11
2	Verification, Validation, and Test	5, 6
3	Design, Analysis, and Manufacturability	1, 4, 12, 13, 14, 16
4	Technical Interfaces	2
5	Software	17 *(tailored)*
6	Technical Margins	7
7	Safety and Mission Assurance	9
8	Assembly and Integration	6
9	Ground, Mission & Recovery Operations	6, 15
10	Cost and Schedule	3, 7
11	Risk	8

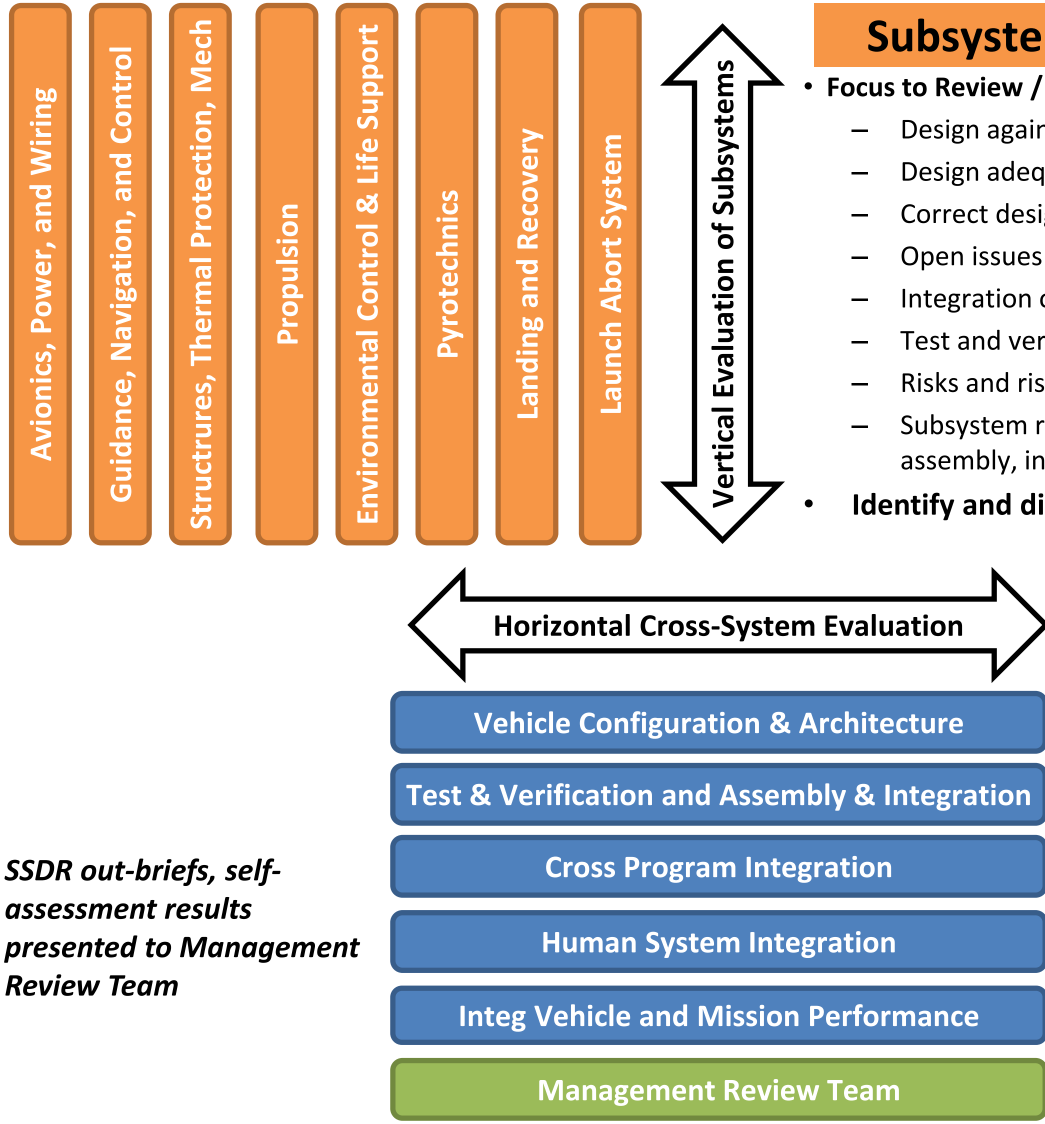
**Full description in Backup*

CDR Schedule and Process Flow



- **Process provides for system, subsystem, and cross-system evaluation of the design**
  - **Data Drop:** System and subsystem products released for review
  - **Kick-off:** Review objectives, criteria, process, and product orientation
  - **System Review:** Provides system level overviews of performance analysis, vehicle design overview, test and verification, and assembly and integration
  - **Subsystem Design Reviews (SSDRs):** Vertical evaluation & discussion of issues at the subsystem level
  - **Targeted Review Teams (TRTs):** Horizontal evaluation of key cross system threads

Performing Vertical and Horizontal Evaluation



SSDR out-briefs, self-assessment results presented to Management Review Team

Subsystem Design Reviews (SSDRs)

- **Focus to Review / Evaluate:**
  - Design against functional and performance specs
  - Design adequacy and maturity
  - Correct design options have been selected
  - Open issues and adequacy of forward plans
  - Integration of subsystems with the rest of the vehicle
  - Test and verification approach
  - Risks and risk management strategies
  - Subsystem readiness to proceed to fabrication, assembly, integration, and test
- **Identify and disposition subsystem level RFAs**

Targeted Review Teams (TRTs)

- Perform a cross-system evaluation of the design organized by system-level integration challenges
- Identify and disposition associated RFAs
- Provide recommendation to proceed to Pre-Board

Management Review Team (MRT)

- Disposition RFAs for overarching programmatic items against success criteria not covered by the Targeted Review Teams (Ex: S&MA, Rqmts)
- Conducts ESM Face-to-Face with ESA/Airbus
- Serves as ad hoc Pre-Board during the course of Targeted Reviews to adjudicate issues elevated from the Targeted Review Teams or SSDRs
- Provide recommendation to proceed to Pre-Board

Reality:

Prolonged Design and Manufacturing Schedule Driven by Flat Budget

Reality: Prolonged Design and Manufacturing Schedule Driven by Flat Budget

- **Budget challenges are not new and will be a reality for the foreseeable future**
- **The challenge of a flat budget is that it stretches out the design and manufacturing timeframe adding integration complexities**
  - Results in “leading” and “lagging” subsystem designs driven by the procurement, fabrication, and assembly and integration schedules
- **From NASA Office of Inspector General (OIG), NASA’s Management of the Orion Multi-Purpose Crew Vehicle Program (Report No. IG-16-029):**

“…the Orion Program’s budget profile through at least 2018 has been nearly flat with an annual rate between 5 and 10 percent of total design, development, test, and evaluation costs”

“GAO guidance shows a bell-shaped curve as the optimal funding profile for research, development, testing, and evaluation because more resources are needed as development progresses and programmatic risks are identified and remediated”

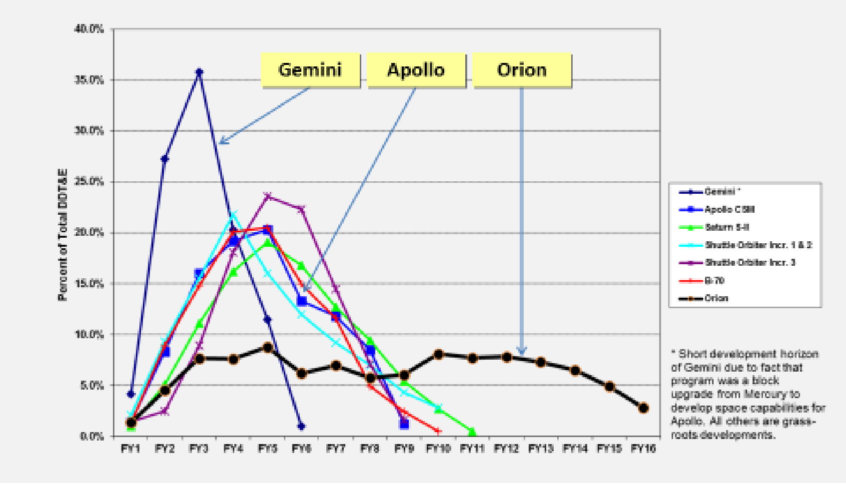


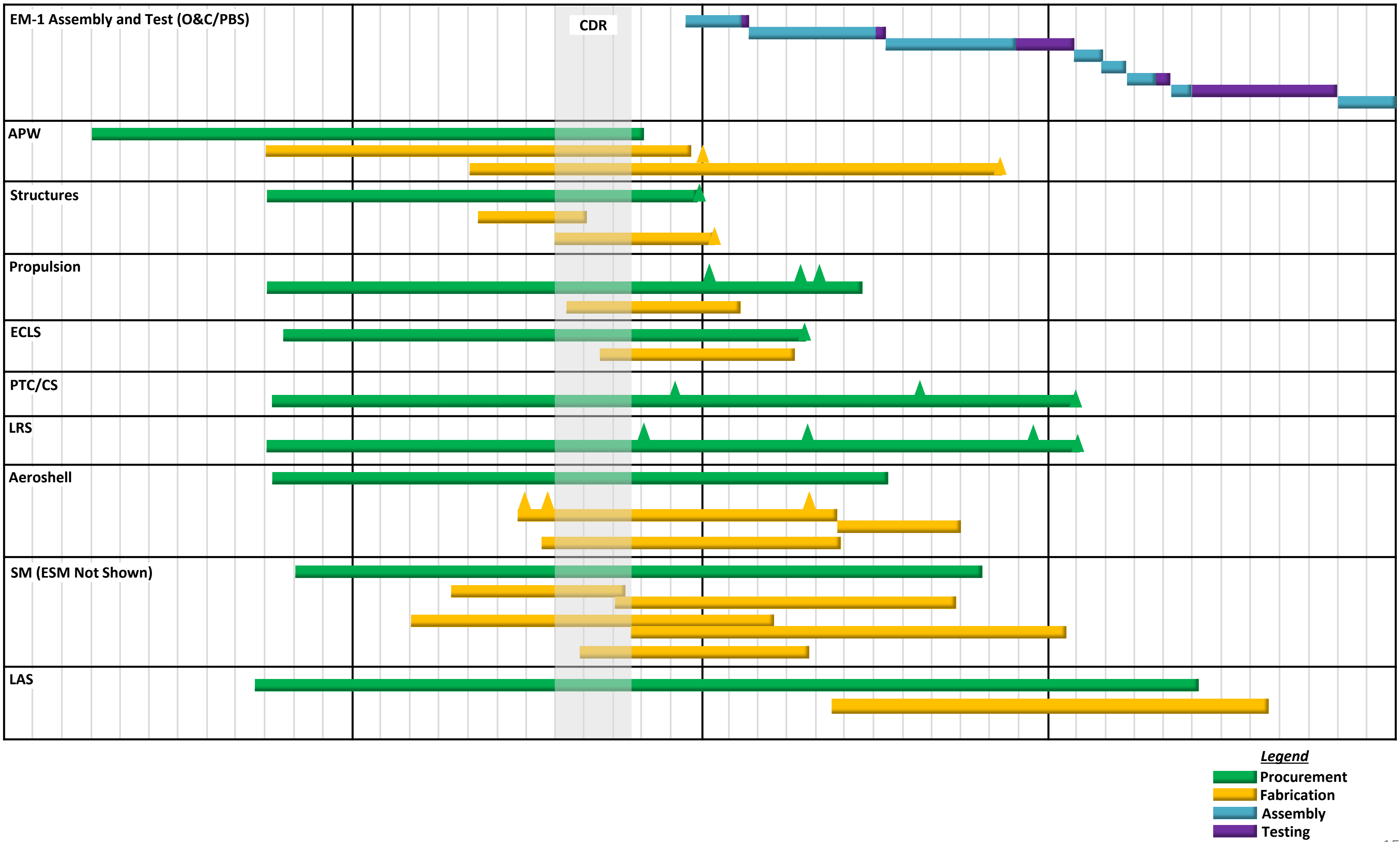
Figure compares Orion Program funding to funding for Gemini, Apollo, and other development programs.

Addressing A Prolonged Design Timeframe

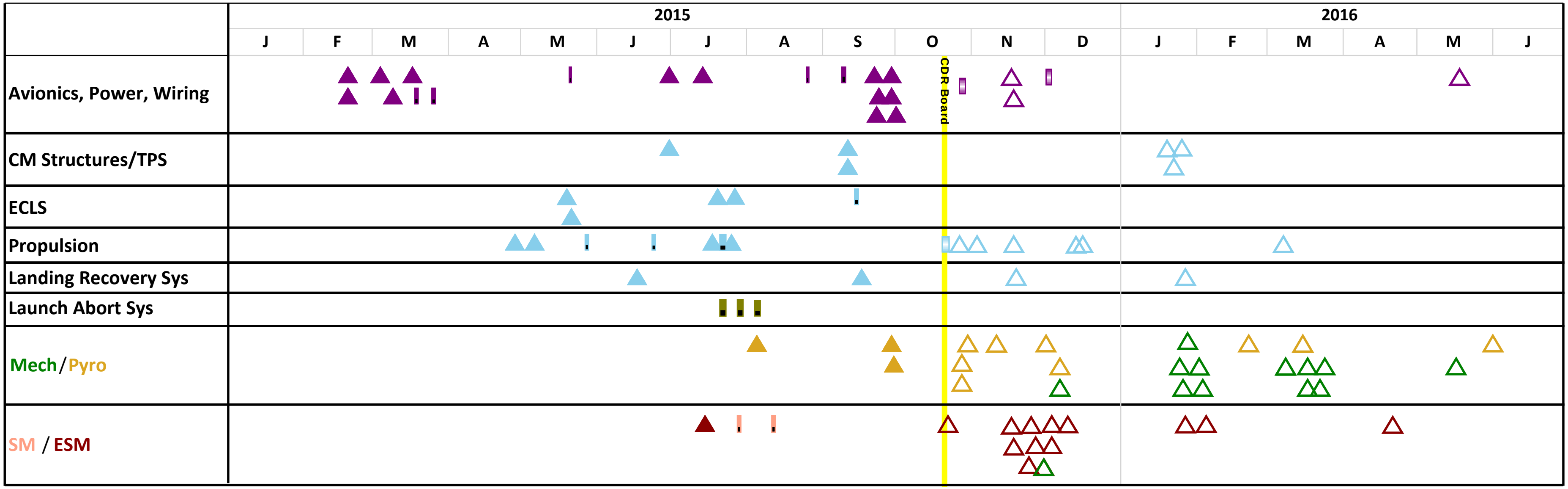
- **Assess the design integration risk to “leading” and “lagging” subsystem or component designs**
  - Maturity of the interface design
  - Maturity of the environments for “leading” designs
  - Integrated subsystem and system performance margins
  - Maturity of “lagging” subsystem or component development
    - Development testing
    - Engineering release schedule
    - Design heritage, technology readiness
    - Degree by which design is coupled to other aspects of the vehicle

- **Establish the needed integration activities and milestones**
  - Incremental design integration
  - Conduct reviews preceding and following the life cycle reviews
    - Lock-down designs and interfaces for “leading” designs
    - Assess subsystem or system level impacts for “lagging” designs, and ensure system-level stakeholders engagement

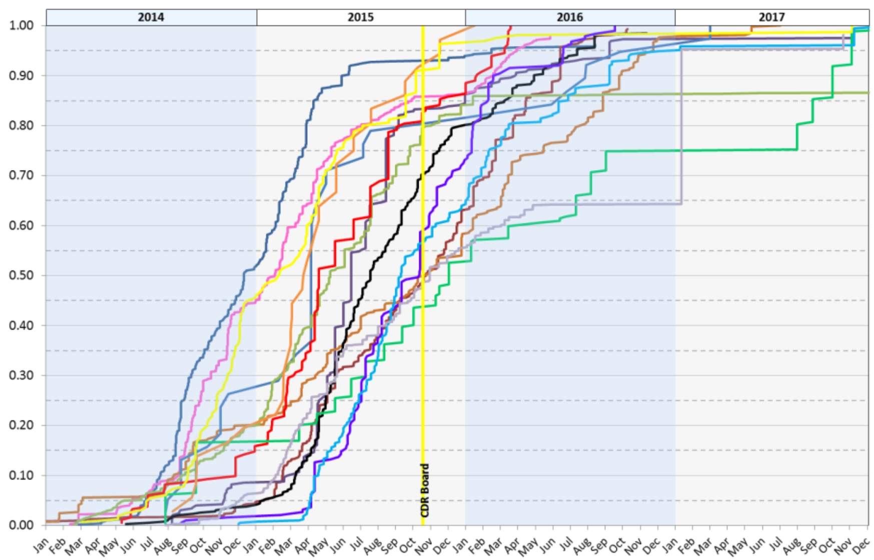
Hardware Procurement and Fabrication Schedule



Component and Engineering Release Schedules



EM-1 Component CDR Schedule



EM-1 Drawing Release Schedule

"Leading" Subsystem: Structures

- **Crew Module structure design and fabrication was a leading design for the EM-1 build**
- **Interim design reviews implemented to enable release of long lead procurements to support build milestones**

Hardware Review

- Interfaces
- Loads and Environments
- Manufacturability
- Materials and Processes
- Test Overview

Stress/Sizing Review

- Load Conditions
- Analysis Approach/Tools
- Preliminary Analysis Results

Mass Checkpoint Review

- Final assessment of mass prior to engineering release

EM-1 Crew Module Pressure Vessel

“Lagging” Subsystem: Mechanisms and Aeroshell

- **Lagging designs driven primarily by manufacturing needs and budget constraints**

- **Placed controls to ensure that design integration was addressed and to limit risk**
  - Interfaces
  - Mass
  - Completion of development tests
  - Sufficient design maturity – Ex: preliminary sizing
  - Vet incremental analyses, margin assessment

- **Established integration milestones. Ex: Close-Out Engineering Review Boards**
  - Occur following the lagging component design reviews
  - Purpose to update technical baseline and address system integration issues

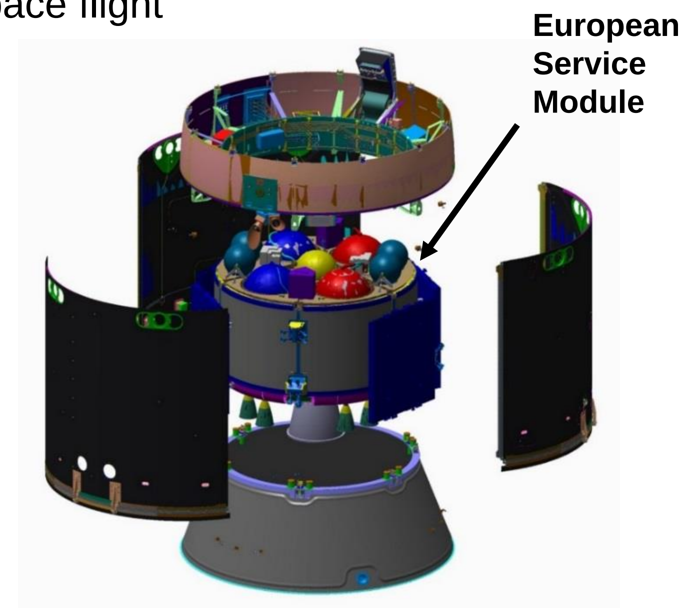
EM-1 Heatshield

Reality:

Asynchronous Development with International Partner

European Service Module (ESM)

- **ESM is an integral part of several subsystems**
- **ESM development schedule trails the rest of the Program**
- **ESM supports the following capabilities**
  - In-space translational delta-V capability to transfer the vehicle Provide orbital maintenance and attitude control
  - High altitude ascent abort propulsion after LAS jettison
  - Consumables to support in-space habitable environment while attached to the CM (Water, O2, and N2 storage)
  - Power generation and storage required for in-space flight
  - Primary thermal control while mated with CM
- **ESM interfaces**
  - Structural
  - Consumable storage
  - Thermal control
  - Electrical
  - Software (CMA) – Controllers (ESM)
  - GNC (CM) – Propulsion (ESM)



Addressing Asynchronous Development with an International Partner

- **Define design content necessary to meet subsystem and system development schedule**
  - Data product maturity expectations and delivery schedule
  - Importance of mapping to bilateral agreements
  - Greater importance of effective bilateral design team coordination
- **Be adaptable to schedule changes**
  - To the extent possible de-couple development interdependencies and schedules
- **Establish clear re-integration activities and milestones to manage risk when design content is immature**

ESM Content Expectations for CDR

- **All System Level products incorporate ESM Content**
  - Examples: CAD, MEL, PEL, etc.
- **The SSDRs will address interface and integration aspects of the ESM subsystem design**
  - Overview of the ESM subsystem design including a summary of open design trades, issues, and requirement non-compliances that impact or represent a risk to the integrated system, subsystem or interfaces
  - Details of the subsystem hardware and software interface designs
  - Results of integrated subsystem performance and mission analysis including subsystem level technical margins and technical performance measures
  - Integrated subsystem test and verification, and assembly and integration plans
  - Integrated subsystem operations concepts
  - Integrated subsystem safety and reliability analysis, and risks
- **Review of the ESM provided subsystem hardware design occurred at the ESM component and subsystem CDRs**

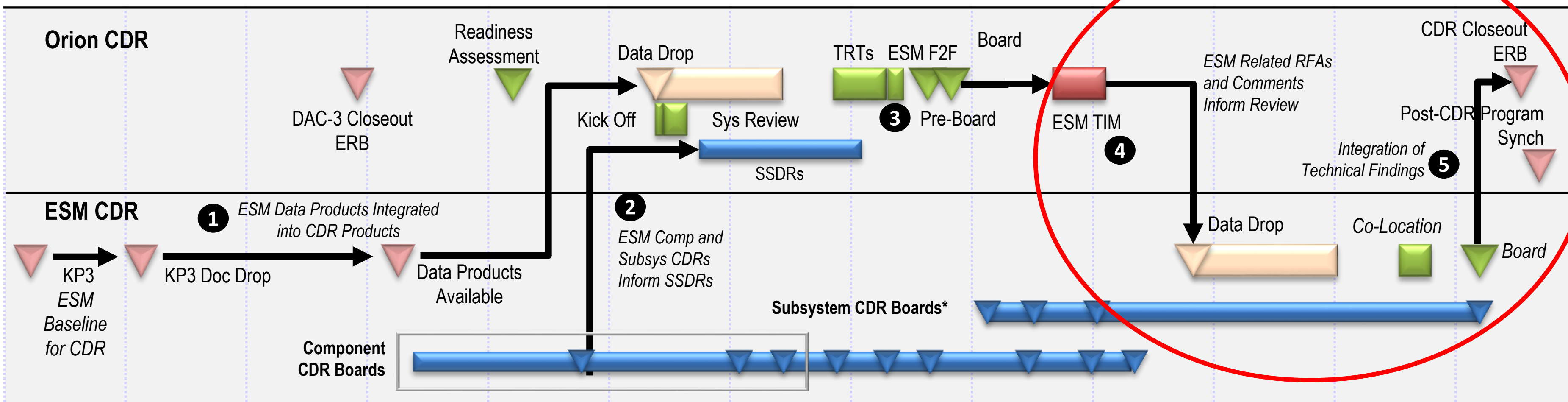
Re-Integration Activities and Milestones

- **Post CDR re-integration milestones and objectives were added to the Program to address areas that did not meet CDR maturity**
  - Results from Component CDRs occurring after CDR Board, such as Aeroshell, Mech and Pyro
  - Results from ESM CDR planned to occur after CDR Board
  - Pre-declared RFAs and significant CDR findings

- **Established CDR Closeout Engineering Review Boards**
  - Present, discuss, and address technical integration issues resulting from the ESM CDR and component CDRs completed post System CDR
  - Establish updated technical baseline based on the conclusion of the ESM CDR and component CDRs completed post System CDR
  - Attendance to include stakeholders and CDR Pre-Board members

- **Established a Post-CDR Program Synch meeting**
  - Address critical actions from the CDR Closeout ERBs
  - Status results of post-ESM CDR re-integration analyses, design and verification activities
  - Assess closure progress of high criticality RFA's and Board actions (including ESM CDR RIDs)
  - Attendance to include stakeholders and CDR Board Members

ESM CDR Integration Schedule



Integration activities and milestones established to mitigate impacts of the Orion CDR preceding the ESM CDR

1. ESM content incorporated into the system level products
2. ESM content affecting the subsystem interfaces and the integrated subsystem were addressed at the SSDRs
3. ESM F2F established to gain ESA/Airbus agreement on ESM related RFA closure plans, and inform ESA/Airbus on ESM CDR relevant comments
4. ESM TIM discussed ESA/Airbus ability to capture the relevant ESM CDR comments in the ESM CDR data products
5. ESM CDR technical findings and any necessary technical baseline changes were addressed at the CDR Closeout ERB. Results of the CDR Closeout ERB, status of any required re-integration activities, and a status of high criticality RFAs will be reported out at the Post-CDR Program Synch.

Final Thoughts – Key Principles

- **Stakeholder coordination**
- **Communicate risk and gain Program and Tech Authority acceptance**
- **Fully understand the intent of the systems engineering requirements, but ask what is meaningful to the Program**
  - Tailor as needed but demonstrate how that intent is being met
  - Maintain traceability
- **Strong industry-to-government collaboration**
- **Continuously communicate The Plan**
- **Never become complacent with the current plan – it will change**
- **Principles apply to all phases, not just design**

Backup

Success Criteria (1 of 2)

1. **Requirements and Plans:**
   a) All program specifications are current and consistent with detailed design
   b) Component specifications are complete or sufficiently mature to support program procurement, fabrication, and assembly plans
   c) The program/project has demonstrated compliance with applicable NASA Exploration System, Program and implementing Center requirements, standards, processes, and procedures
   d) Full upward and downward requirement traceability is maintained.
   e) TBD and TBR items are clearly identified with acceptable plans and schedule for their timely disposition and closure.

2. **Verification, Validation, and Test:**
   a) The product verification and product validation requirements and plans are complete.
   b) The testing approach is comprehensive, test requirements defined, and the test plans are complete and sufficient to progress into the next phase.
   c) TLYF exceptions are identified; and risk/mitigation associated with each TLYF exception has been assessed

3. **Design, Analysis, and Manufacturability:**
   a) The detailed design is expected to meet the functional and performance requirements with adequate margins.
   b) Analysis of the system and subsystems has been completed, summarized, and demonstrates that system meets the functional, performance, and mission requirements with acceptable margins.
   c) Appropriate modeling and analytical results are available and have been considered in the design
   d) The product technical baseline is complete and adequate to proceed with fabrication, assembly, integration, and test.
   e) Engineering test units, life test units, and/or modeling and simulations have been developed and tested per plan.
   f) Material properties tests are completed along with analyses of loads, stress, fracture control, contamination generation, etc.
   g) EEE parts have been selected, and planned testing and delivery will support build schedules.
   h) Manufacturability has been adequately included in design.
   i) Any required new technology has been developed or the viable alternative has been selected to proceed with fabrication, assembly, integration, and test.

4. **Technical Interfaces:**
   a) External and internal interface control documents are sufficiently mature to proceed with fabrication, assembly, integration, and test, and plans are in place to manage any open items.

Success Criteria (2 of 2)

5. **Software:**
   a) Software components meet the exit criteria defined in NASA-HDBK-2203, NASA Software Engineering Handbook as modified by Appendix G.

6. **Technical Margins:**
   a) Adequate spacecraft technical margins (e.g. mass, power, memory) exist with respect to TPMs.

7. **Safety and Mission Assurance (S&MA):**
   a) Safety and mission assurance (e.g., safety, reliability, maintainability, and quality) have been adequately addressed in system and operational designs, and any applicable S&MA products (e.g., PRA, system safety analysis, and failure modes and effects analysis) meet requirements, are at the appropriate maturity level for this phase of the program's life cycle, and indicate that the program safety/reliability residual risks will be at an acceptable level.

8. **Assembly and Integration:**
   a) The planning for system assembly, integration, and launch site operations is sufficient to progress into the next phase.

9. **Operations:**
   a) The operational concept has matured, is supported by the vehicle design, is at a CDR level of detail, and has been considered in test planning.
   b) The planning for mission operations (launch through recovery operations) is sufficient to progress into the next phase.

10. **Cost and Schedule:**
    a) The program cost and schedule estimates are credible and within program constraints.
    b) Adequate programmatic margins resources and control processes exist to complete the development within budget, schedule, and known risks.

11. **Risk:**
    a) Risks to mission success are understood and credibly assessed, and plans and resources exist to effectively manage them.