NASA Project Life Cycle

MAE 4160, 4161, 5160

V. Hunter Adams, PhD

Syllabus questions? (Please hold those about the projects)

Today’s topics:

- NASA project life cycle
- Mission concept/architecture and CONOPS
- Technical reviews
- Projects

Why does this life cycle exist?

- Space missions are complicated technically and logistically. Small mistakes can snowball into big problems.

Why should you care about it?

- This is the language of the industry.
- Your course project simulates this life cycle.
- This is *interesting*. This is how we collectively build machines that are not fully understood by any one person.

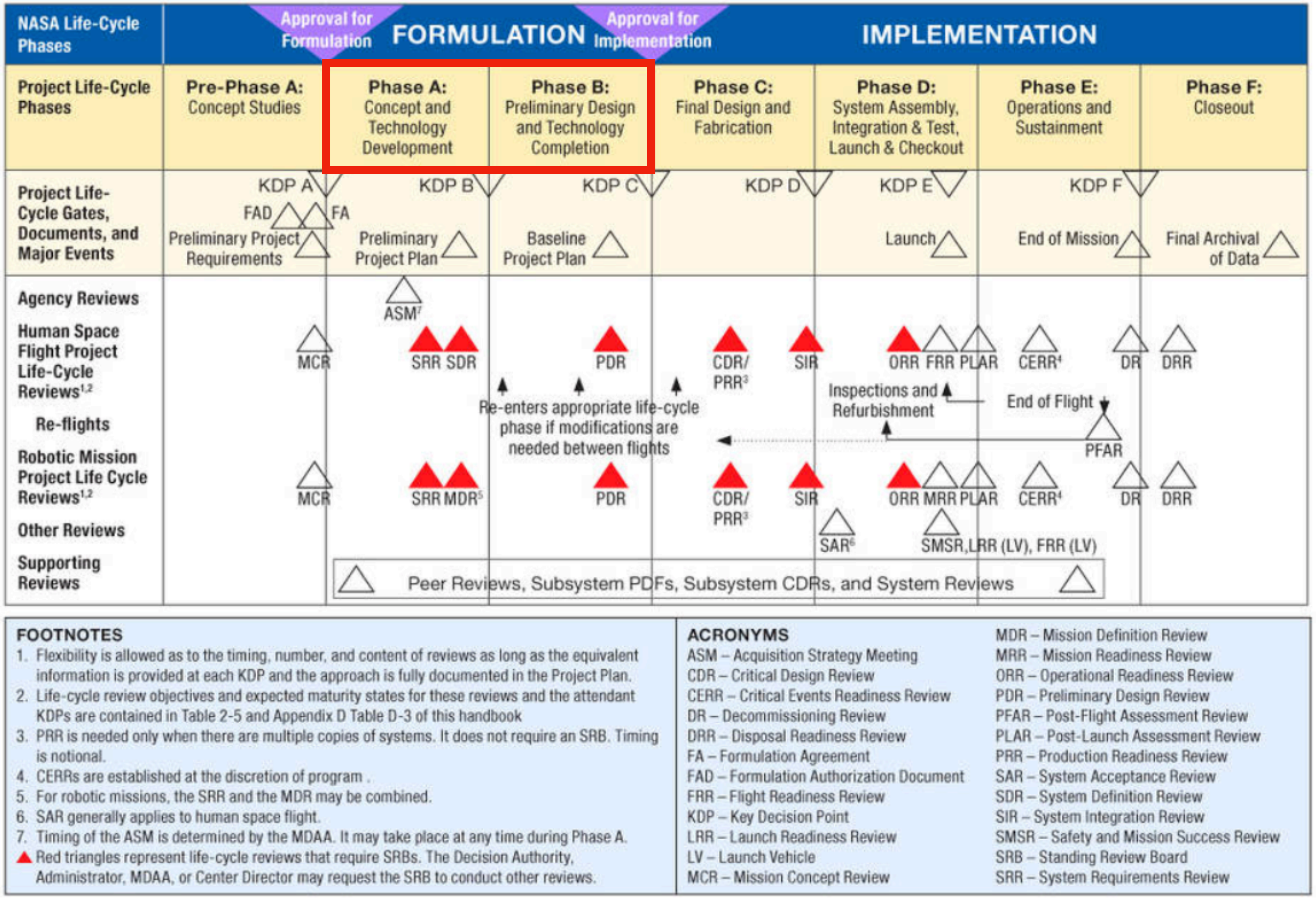

FIGURE 3.0-1 NASA Space Flight Project Life Cycle from NPR 7120.5E

Nasa Systems Engineering Handbook

Overview

- Project is separated into *phases*
- Each phase is separated by a Key Decision Point (KDP), which are natural points for go/no-go decisions
- Key Decisions are informed by *reviews*
- **Systems engineering done in the early phases has the greatest impact on mission success**

Each review creates a new system baseline

Baseline (n): An agreed-to set of requirements, designs, or documents

Baseline (v): The process of establishing a baseline (n)

- A baseline is a complete system description, which includes requirements, designs, and documents which will have future changes controlled through a formal configuration management process
- Baselines make certain that the entire team is working with the same requirements, designs, constraints, assumptions, interfaces, etc.
- Git analogy

Pre-Formulation

- Pre-Phase A

Formulation

- Phase A
- Phase B

Implementation

- Phase C
- Phase D
- Phase E
- Phase F

Pre-Formulation → Formulation → Implementation

Pre-Formulation

- *Pre-Phase A*

Formulation

- Phase A
- Phase B

Implementation

- Phase C
- Phase D
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- Phase F

Pre-Phase A: Concept Studies

Goals:

- To produce a variety of ideas and alternatives from which new programs/projects can be selected.
- To study the feasibility of the desired system.
- To develop mission concepts.
- To identify potential technology needs

Outcomes:

- Mission concepts and draft system-level requirements

Reviews:

- Mission Concept Review (MCR)

Pre-Phase A: Concept Stu

Often motivated by a NASA Announcement of Opportunity (AO) (e.g. 2019 Discovery AO)

The National Aeronautics and Space Administration (NASA) Science Mission Directorate (SMD) is releasing this Announcement of Opportunity (AO) to solicit Principal Investigator (PI)-led space science investigations for the Discovery Program.

The AO Cost Cap for a Discovery mission is $500M in NASA Fiscal Year (FY) 2019 dollars for Phases A-D, not including the cost of standard launch vehicle and launch services or any contributions. Application of AO-specified incentives and/or charges may result in a proposal-specific Adjusted AO Cost Cap. Foreign contributions to science instruments should not exceed approximately one-third of the science payload. Proposals shall include a discussion of the scale of the internationally-contributed instruments, how the proposed contribution is consistent with NASA's policy that the contribution does not exceed approximately one-third of the science payload, and how the programmatic risks associated with the contribution will be handled. Proposed investigations will be evaluated, selected, and down-selected through a two-step competitive process. NASA intends to select up to five Step-1 proposals for the conduct of Phase A concept studies and submission of Concept Study Reports to NASA. The down-selected mission(s) must be ready for launch during at least one of two available launch periods: 1) July 1, 2025, through December 31, 2026, and/or 2) July 1, 2028, through December 31, 2029. NASA expects to down-select up to two mission(s), one for each launch period, to proceed into Phase B and subsequent mission phases.

om which new

- Mission concepts and draft s

- advance scientific knowledge and exploration of the elements of our Solar System;
- add scientific data, maps, and other products to the Planetary Data System archive for all scientists to access;
- announce scientific progress and results in the peer-reviewed literature, popular media, scholastic curricula, and materials that can be used to inspire and motivate students to pursue careers in science, technology, engineering, and mathematics;
- expand the pool of well-qualified Principal Investigators and Project Managers for implementation of future missions in Discovery and other programs, through current involvement as Co-Investigators and other team members; and
- implement technology advancements proven in related programs.

Reviews:

- Mission Concept Review (MC

Pre-Phase A: Concept Studies

<u>The Mission Concept Review (MCR)</u>: Affirms the mission/project need and evaluates the proposed mission's objectives and the ability of the concept to fulfill those objectives.

<u>Pass Criteria</u>:

1. Mission objectives are clearly defined and stated and are unambiguous and internally consistent.
2. The selected concept(s) satisfactorily meets the stakeholder expectations.
3. The mission is feasible. A concept has been identified that is technically feasible. A rough cost estimate is within an acceptable cost range.
4. The concept evaluation criteria to be used in candidate systems evaluation have been identified and prioritized.
5. The need for the mission has been clearly identified.
6. The cost and schedule estimates are credible and sufficient resources are available for project formulation.
7. The program/project has demonstrated compliance with applicable NASA and implementing Center requirements, standards, processes, and procedures.
8. TBD and TBR items are clearly identified with acceptable plans and schedule for their disposition
9. Alternative concepts have adequately considered the use of existing assets or proucts that could satisfy the mission or parts of the mission.
10. Technical planning is sufficient to proceed to the next phase.
11. Risk and mitigation strategies have been identified and are acceptable based on technical risk assesments.
12. Software components meet the exit criteria defined in the NASA-HDBK-2203, NASA Software engineering handbook.
13. Concurrence by the responsible center spectrum manager that RF needs have been properly identified and addressed.

<u>In short</u>: Do we need this mission, what are the objectives, do those objectives meet the needs of stakeholders?

Pre-Phase A: Concept Studies

What is a mission concept?

- A **high-level vision or idea** that **rationalizes** and **guides** the rest of the architecture process
- Often based on an analogy (e.g. crane, airbag)
- Starts defining the design variables and technologies that will be necessary
- Reduces ambiguity

Pre-Formulation —**downselect**→ *<u>Formulation</u>* ——→ Implementation

Pre-Formulation
- Pre-Phase A

<u>Formulation</u>
- *<u>Phase A</u>*
- *<u>Phase B</u>*

Implementation
- Phase C
- Phase D
- Phase E
- Phase F

Project Formulation: Phases A-B

Please read the following, from NASA's Systems Engineering Handbook:

The program Formulation Phase establishes a cost-effective program that is demonstrably capable of meeting Agency and mission directorate goals and objectives. The program Formulation Authorization Document (FAD) authorizes a Program Manager (PM) to initiate the planning of a new program and to perform the analyses required to formulate a sound program plan. The lead systems engineer provides the technical planning and concept development or this phase of the program life cycle. Planning includes identifying the major technical reviews that are needed and associated entrance and exit criteria. Major reviews leading to approval at KDP I are the SRR, SDR, PDR, and governing Program Management Council (PMC) review. A summary of the required gate products for the program Formulation Phase can be found in the governing NASA directive (e.g., NPR 7120.5 for space flight programs, NPR 7120.7 for IT projects, NPR 7120.8 for research and technology projects). Formulation for all program types is the same, involving one or more program reviews followed by KDP I where a decision is made approving a program to begin implementation.

Project Formulation: Phases A-B

Please read the following, from NASA's Systems Engineering Handbook:

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Goal: To establish a cost-effective program that is demonstrably capable of meeting the Agency and mission directorate [customer] goals and objectives

Phase A: Concept and Technology Development

Goals:

- To determine the feasibility and desirability of a suggested new major system and establish an initial baseline compatible with NASA's strategic plans.
- Develop final mission concept, system-level requirements, and needed system structure technology developments.
- Initiate technology developments.

Outcomes:

- Mission architecture and CONOPS
- Top-level requirements
- Work breakdown structure
- Systems Engineering Management Plan
- Technologies

Reviews:

- System Requirements Review (SRR) - halfway through
- System Definition Review

Phase A: Concept and Technology Development

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Mission Architecture

System Architecture: The description of the high-level *functions* and *components* of the system as well as the **relationships** between them.

Primary functions may include acquiring, storing, and sending mission data. Secondary functions include all subsystem responsibilities.

SMAD separates a mission into 8 *components.*

Table 4-1. The Space Mission Architecture Consists of Eight Elements or Components Plus the Mission Concept and End User. All of these must work together to meet the mission objectives and needs of the end user at a reasonable cost, risk, and schedule.

Segment	Description	Where Discussed
1. Subject	What the spacecraft observes (***passive subject***) or interacts with (***active*** or ***controllable subject***).	Sec. 15.2
Space Segment or Spacecraft Consisting of:		
2. Payload	Spacecraft hardware and software that observe or interact with the subject.	Chaps. 15, 16, 17
3. Spacecraft Bus	The other spacecraft subsystems needed to support the payload.	Chap. 14
4. Ground Segment	The communications equipment and facilities that communicate with and control the spacecraft.	Chap. 28
5. Mission Operations	The people and software that run the space mission on a day-to-day basis.	Chaps. 29, 30
6. Command, Control, and Communications Architecture	How all of the parts of the space mission communicate with each other.	Secs. 16.2, 21.1
7. Orbit	The path of the spacecraft during its operational mission. If there is more than one spacecraft in coordinated orbits, it's a ***constellation***.	Chaps. 9, 10
8. Launch Segment	How the spacecraft gets into orbit; may include ***upper stages*** or ***integral propulsion***.	Chaps. 26, 27
Mission Concept	The ***end users*** are the people or equipment that actually make use of the data generated or transmitted by the spacecraft. The ***mission concept*** is the definition of how the mission elements work together to meet the needs of the end user.	Secs. 1.1, 3.4, 4.3

Mission Architecture

System Architecture: The description of the high-level *functions* and *components* of the system

The cost of correcting defects is lowest in the architecture phase.

Decisions at this phase are of high consequence. They commit most of the project's lifecycle cost, determine the ability of the system to satisfy stakeholder needs, and determine the system's scalability, flexibility, robustness, etc.

This is the first step in translating a defined problem into a solution.

Analogous to architects for buildings.

Prima
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respo

SMAD separates a mission into 8 *components.*

ept and End
and schedule.

		Where Discussed
		15.2
		s. 15, 16, 17
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CONOPS: Concept of Operations

CONOPS: Describes the overall high-level concept of how the system will be **used** to meet stakeholder expectations, usually in a time sequenced manner. It **describes the system from an operational perspective** and helps facilitate an understanding of the system **goals**. It stimulates the development of the requirements and architecture related to the user elements of the system. It serves as the basis for subsequent definition documents and provides the foundation for the long-range operational planning activities.

This is the mission narrative, and includes the various spacecraft modes and mission phases.

Elements for a CONOPS, from SMAD:

- **Data delivery:** Where do we do data processing (onboard vs. on ground)?
- **Tasking, scheduling, and control:** How do we schedule/control the payload? How do we do spacecraft attitude/orbital control? How much of this is commanded vs. autonomous?
- **Communications architecture:** How will various components of the system communicate? Direct downlink? Deep space network? Near Earth Network? How will information be distributed to users on the ground? Internet?
- **Timeline:** If the mission were a movie, this is the storyboard.

CON… …ions

CONOPS: Describes the overall hig… …meet stakeholder expectations, usually in a time sequenced manner. … …**perspective** and helps facilitate an understanding of the system **goals**. … …and architecture related to the user elements of the system. It serves as … …d provides the foundation for the long-range operational planning acti…

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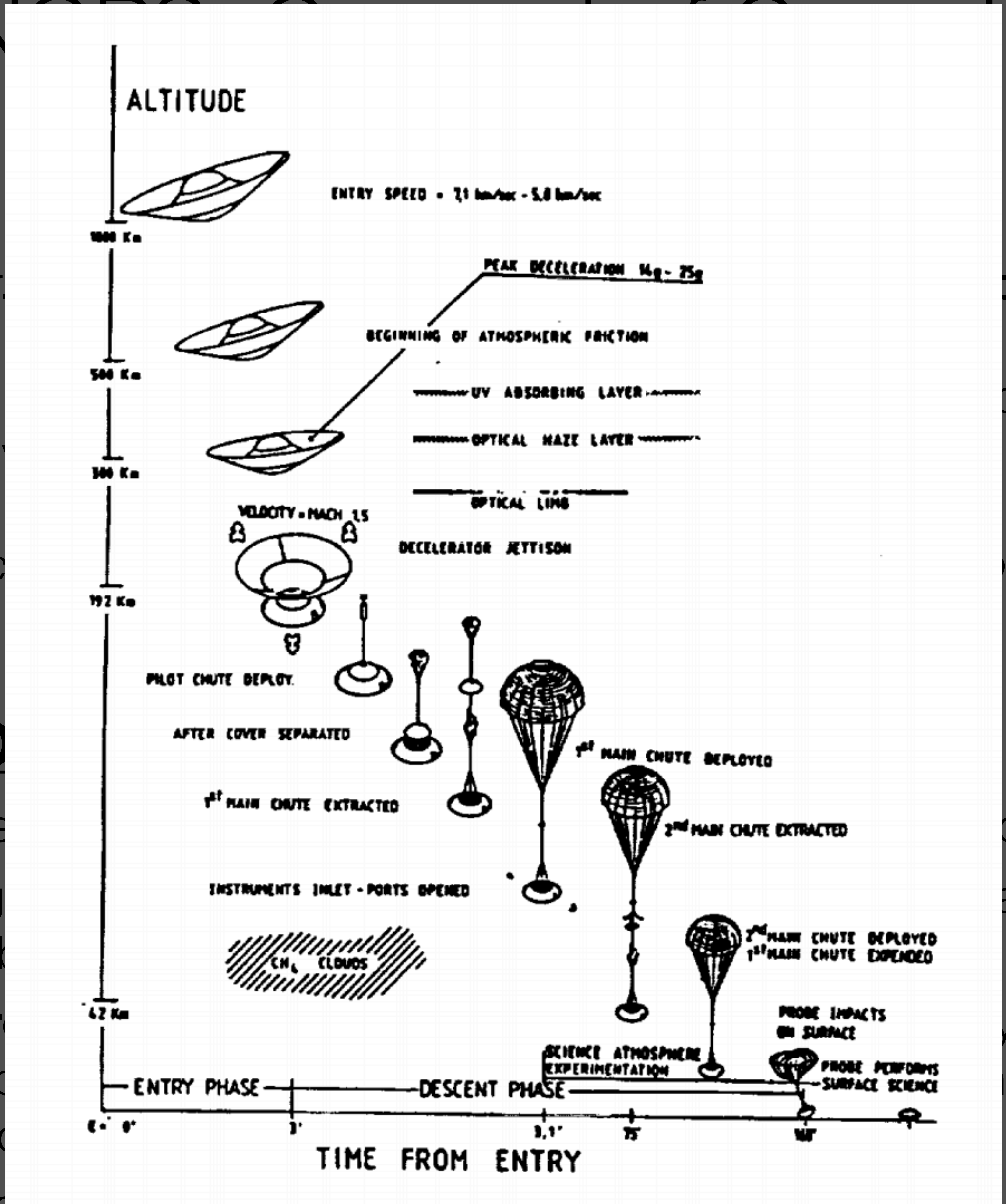

Elements for a CO…

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NASA-TM-103374, CASSINI. Report on the Phase A study: Saturn Orbiter and Titan probe. 1988.

Phase A: Concept and Technology Development

Goals:

- To determine the feasibility and desirability of a suggested new major system and establish an initial baseline compatible with NASA's strategic plans.
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Outcomes:

- Mission architecture and CONOPS
- Top-level requirements
- Work breakdown structure
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- Technologies

Reviews:

- **System Requirements Review (SRR) - halfway through**
- System Definition Review

Phase A: Concept and Technology Development

System Requirements Review: The SRR evaluates whether the functional and performance requirements defined for the system are responsive to the program's requirements and ensures the preliminary project plan and requirements will satisfy the mission.

Pass Criteria:

1. The functional and performance requirements defined for the system are responsive to the parent requirements and represent achievable capabilities.
2. The maturity of the requirements definition and associated plans is sufficient to begin Phase B.
3. The project utilizes a sound process for the allocation and control of requirements throughout all levels, and a plan has been defined to complete the requirements definition at lower levels within schedule constraints.
4. Interfaces with external entities and between major internal elements have been identified.
5. Preliminary approaches have been determined for how requirements will be verified and validated.
6. Major risks have been identified and technically assessed, and viable mitigation strategies have been defined.
7. The program/project has demonstrated compliance with applicable NASA and implementing Center requirements, standards, processes, and procedures.
8. TBD and TBR items are clearly identified with acceptable plans and schedule for their disposition.
9. Software components meet the exit criteria defined in NASA-HDBK-2203, NASA Software Engineering Handbook.
10. Concurrence by the responsible Center spectrum manager that the program/project has provided requisite RF system data.

In short: Will the requirements for the system meet the system objectives?

Phase A: Concept and Technology Development

How to think about a spacecraft/mission at an SRR-level of abstraction:

At this stage in the development cycle, the spacecraft *is the requirements*. The spacecraft itself does not exist yet, not even in your mind.

The spacecraft is a blackbox system understood only in *what it does* and *how it is used*.

5.3 Probe System

- The Probe shall provide accommodation and resources for the science instruments and a means to enter the Titan atmosphere and implement the Titan Probe mission profile.
- The Probe Support subsystem shall provide the Probe's Spin Eject Device, the relay antenna and antenna pointing equipment, as well as the Probe Interface to the Orbiter for power, command and telemetry.
- The Probe mass allocation is 192.3 kg and the Probe Support Subsystem mass allocation is 61.3 kg.
- The outer envelope of the Probe system shall be compatible with the allowable envelope constraints of the Orbiter under the launch vehicle fairing.
- Telemetry and telecommand communication with the Probe shall be available through the Orbiter until separation of the Probe from the Orbiter. After Probe release, the only Probe communication will be the telemetry data relay via the relay link to the Orbiter and DSN.
- The Probe system shall be designed to withstand 52 R_J Jupiter flyby, Saturnian and ring plane crossing environments, in the clear zones and sparsely populated regions.
- The Probe system shall be capable of activation for calibration once or twice per year.
- The Probe system shall be capable of activation to full operational status after an interplanetary cruise time of 6.5 years.
- The Probe will be targeted for Titan and be separated from the Orbiter during the first Saturn centered orbit. The second orbit is the back-up opportunity.

Huygen's Probe requirements

SRR answers these questions:

1. What is required for full mission success?
2. What is required for partial mission success?
3. What is required for minimal mission success?
4. What are the system-level requirements (functional, performance, external)?
5. What is required of the propulsion subsystem?
6. What is required of the CDH subsystem?
7. What is required of the thermal subsystem?
8. What is required of the attitude determination and control subsystem?
9. What is required of the telemetry and command subsystem?
10. What is required of the structure subsystem?
11. What is required of the power subsystem?
12. What is required of any other relevant subsystems?
13. The key trade studies to be investigated before PDR
14. The major risks and preliminary mitigation strategies

NASA-TM-103374, CASSINI. Report on the Phase A study: Saturn Orbiter and Titan probe. 1988.

Phase A: Concept and Technology Development

How to think about a spacecraft at an SRR-level of abstraction:

At this stage in the development cycle, the spacecraft *is the requirements*. The spacecraft itself does not exist yet, not even in your mind.

The spacecraft is a blackbox system understood only in *what it does* and *how it is used*.

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Huygen's Probe requirements

SRR answers these questions:

The next lecture is devoted to learning to write these requirements.

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6. What is required of the CDH subsystem?
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Phase A: Concept and Technology Development

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Outcomes:

- Mission architecture and CONOPS
- Top-level requirements
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- Systems Engineering Management Plan
- Technologies

Reviews:

- System Requirements Review (SRR) - halfway through
- **System Definition Review**

Phase A: Concept and Technology Development

<u>System Definition Review</u>: The SDR evaluates whether the proposed mission/system architecture is responsive to the program mission/system functional and performance requirements and requirements have been allocated to all functional elements of the mission/system.

<u>Pass Criteria</u>:

1. The proposed mission/system architecture is credible and responsive to program requirements and constraints, including resources.
2. The mission can likely be achieved within available resources with acceptable risk.
3. The project's mission/system definition and associated plans are sufficiently mature to begin Phase B.
4. All technical requirements are allocated to the architectural elements.
5. The architecture tradeoffs are completed, and those planned for Phase B adequately address the option space.
6. Significant development, mission, and health and safety risks are identified and technically assessed, and a process and resources exist to manage the risks.
7. Adequate planning exists for the development of any enabling new technology.
8. The operations concept is consistent with proposed design concept(s) and is in alignment with the mission requirements.
9. The program/project has demonstrated compliance with applicable NASA and implementing Center requirements, standards, processes, and procedures.
10. TBD and TBR items are clearly identified with acceptable plans and schedule for their disposition.
11. Software components meet the exit criteria defined in NASA-HDBK-2203, NASA Software Engineering Handbook.
12. Concurrence by the responsible Center spectrum manager that RF spectrum considerations have been addressed.

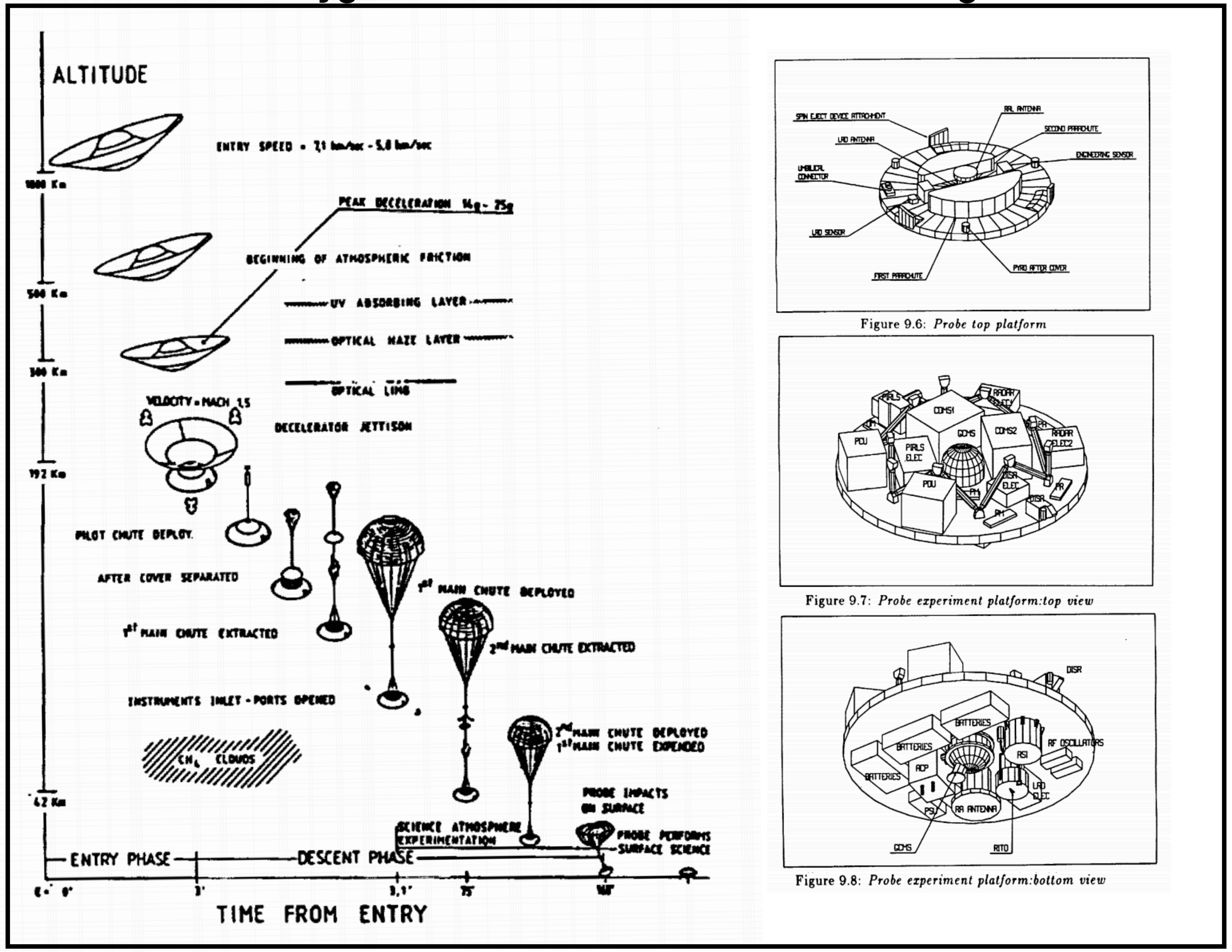
<u>In short</u>: Have trades among various architectures taken place? Does the chosen system architecture meet program requirements and constraints?

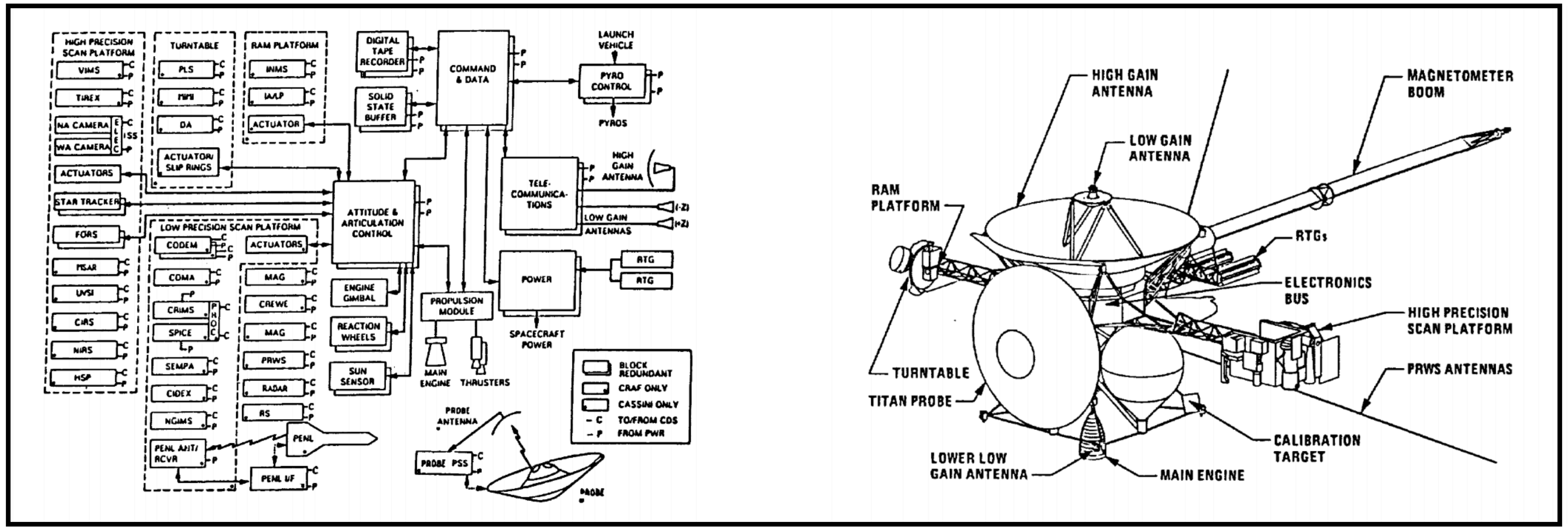
Phase A: Concept and Technology Development

How to think about a spacecraft/mission at an SDR-level of abstraction:

By SDR, there should be a coherent mission architecture, and the spacecraft system architecture should be established. This means that the specific actuators/sensors/processors/etc that compose each particular subsystem have been chosen, after conducting trade studies, in order to satisfy the requirements from the SRR.

Huygen's descent timeline and block diagram





Cassini block diagram and early design

NASA-TM-103374, CASSINI. Report on the Phase A study: Saturn Orbiter and Titan probe. 1988.

Phase B: Preliminary Design and Technology Completion

Goals:

- To define the project in enough detail to establish an initial baseline capable of meeting mission needs.
- Generate a preliminary design for each system structure end product.
- Finalize technology development.

Outcomes:

- Baseline design
- Interface control documents
- Updated requirements
- Science/operations plan
- Technologies

Reviews:

- Preliminary Design Review (PDR)

Phase B: Preliminary Design and Technology Completion

<u>Preliminary Design Review</u>: The PDR demonstrates that the preliminary design meets all system requirements with acceptable risk and within the cost and schedule constraints and establishes the basis for proceeding with detailed design.

<u>Pass Criteria</u>:

1. The top-level requirements, including mission success criteria, TPMs, and any sponsor-imposed constraints are agreed upon, finalized, stated clearly, and consistent with the preliminary design.
2. The flow down of verifiable requirements is complete and proper or, if not, an adequate plan exists for timely resolution of open items. Requirements are traceable to mission goals and objectives.
3. The program cost, schedule, and JCL analysis (when required) are credible and within program constraints and ready for NASA commitment.
4. The preliminary design is expected to meet the requirements at an acceptable level of risk.
5. Definition of the technical interfaces (both external entities and between internal elements) is consistent with the overall technical maturity and provides an acceptable level of risk.
6. Any required new technology has been developed to an adequate state of readiness, or backup options exist and are supported to make them viable alternatives.
7. The project risks are understood and have been credibly assessed, and plans, a process, and resources exist to effectively manage them.
8. Safety and mission assurance (e.g., safety, reliability, maintainability, quality, and Electrical, Electronic, and Electromechanical (EEE) parts) have been adequately addressed in preliminary designs and any applicable SandMA 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.
9. Adequate technical and programmatic margins (e.g., mass, power, memory) and resources exist to complete the development within budget, schedule, and known risks.
10. The operational concept is technically sound, includes (where appropriate) human systems, and includes the flow down of requirements for its execution.
11. Technical trade studies are mostly complete to sufficient detail and remaining trade studies are identified, plans exist for their closure, and potential impacts are understood.
12. The program/project has demonstrated compliance with applicable NASA and implementing Center requirements, standards, processes, and procedures.
13. TBD and TBR items are clearly identified with acceptable plans and schedule for their disposition.
14. Preliminary analysis of the primary subsystems has been completed and summarized, highlighting performance and design margin challenges.
15. Appropriate modeling and analytical results are available and have been considered in the design.
16. Heritage designs have been suitably assessed for applicability and appropriateness.
17. Manufacturability has been adequately included in design.
18. Software components meet the exit criteria defined in NASA-HDBK-2203, NASA Software Engineering Handbook.
19. Concurrence by the responsible Center spectrum manager that the program/project has provided requisite RF system data.

<u>In short</u>: Have all system requirements flowed down to subsystem requirements, and have all subsystems been designed in accordance with those requirements?

Project Introduction

There are five project options, each of which is assumed to have passed the Mission Concept Review (MCR)

You will choose a project option and, in teams of up to four individuals, you will create:

- An SRR (System Requirements Review) document
- An SDR (System Definition Review) document
- A short “PDR” (Preliminary Design Review) Presentation
- A CDR (Critical Design Review) plan
- A final report that includes the analysis associated with your PDR presentation

To the extent which is possible, we are simulating the formulation stage of the NASA project life cycle

Each option is meant to be *feasible*, but challenging, and with an open design space.

1. Life on Titan

Objectives:

- Place a 1x1 meter, 150 kg artificial reef on the bottom of Kraken Mare (unknown depth, 2-15 meters) on Titan
- Communicate data from sensors (cameras and chemistry sensors) on the reef to operators on Earth for a duration of not less than 4 weeks.

2. A Mysterious Startup

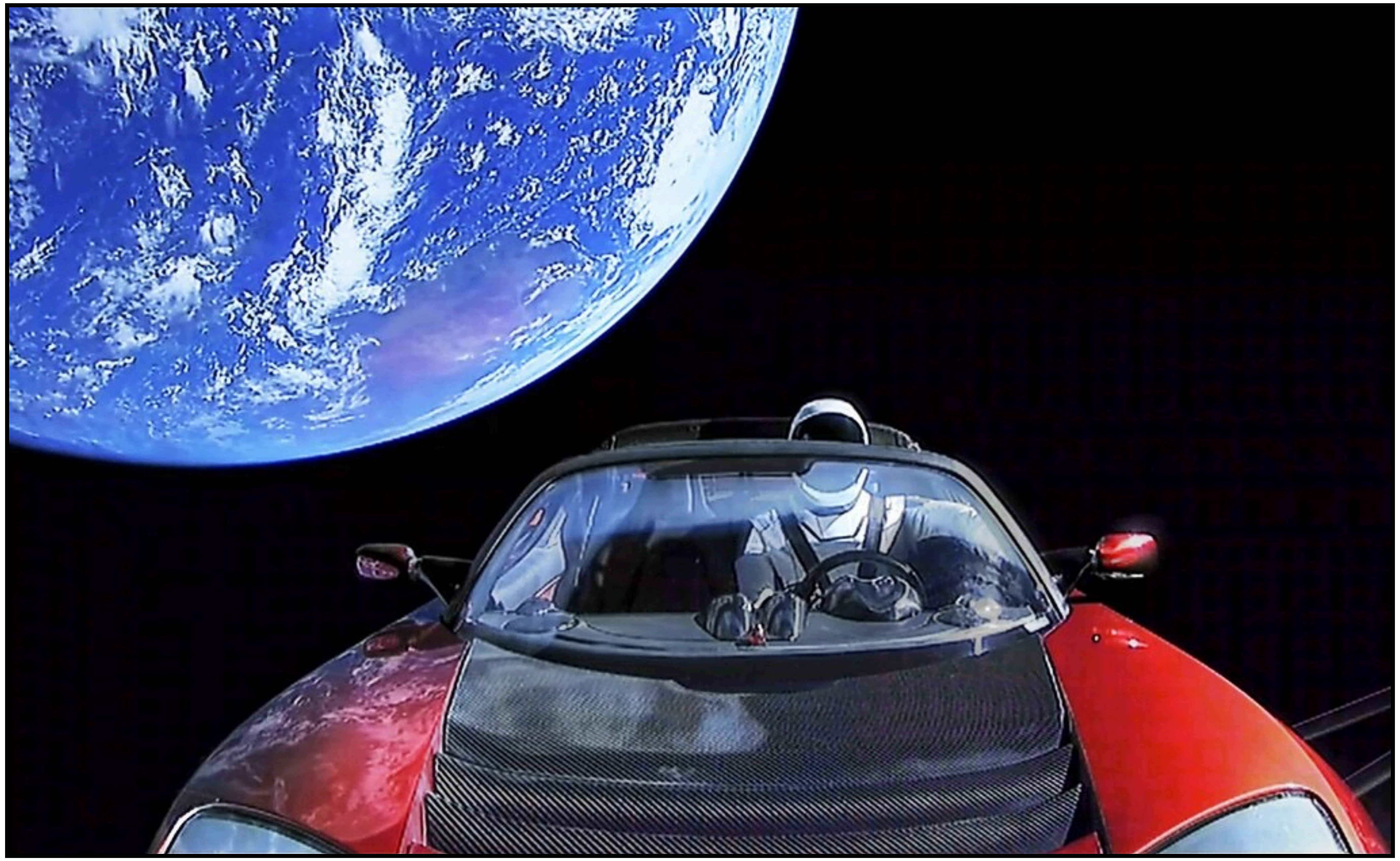
Objectives:

- Design a spacecraft which can track an SR-71 Blackbird (i.e. keep the boresight of an instrument pointed at it) at top speed (~2200 mph)
- Design a constellation of such spacecraft to provide persistent global coverage for altitudes up to 26 km.

3. The Car Collector

Objectives:

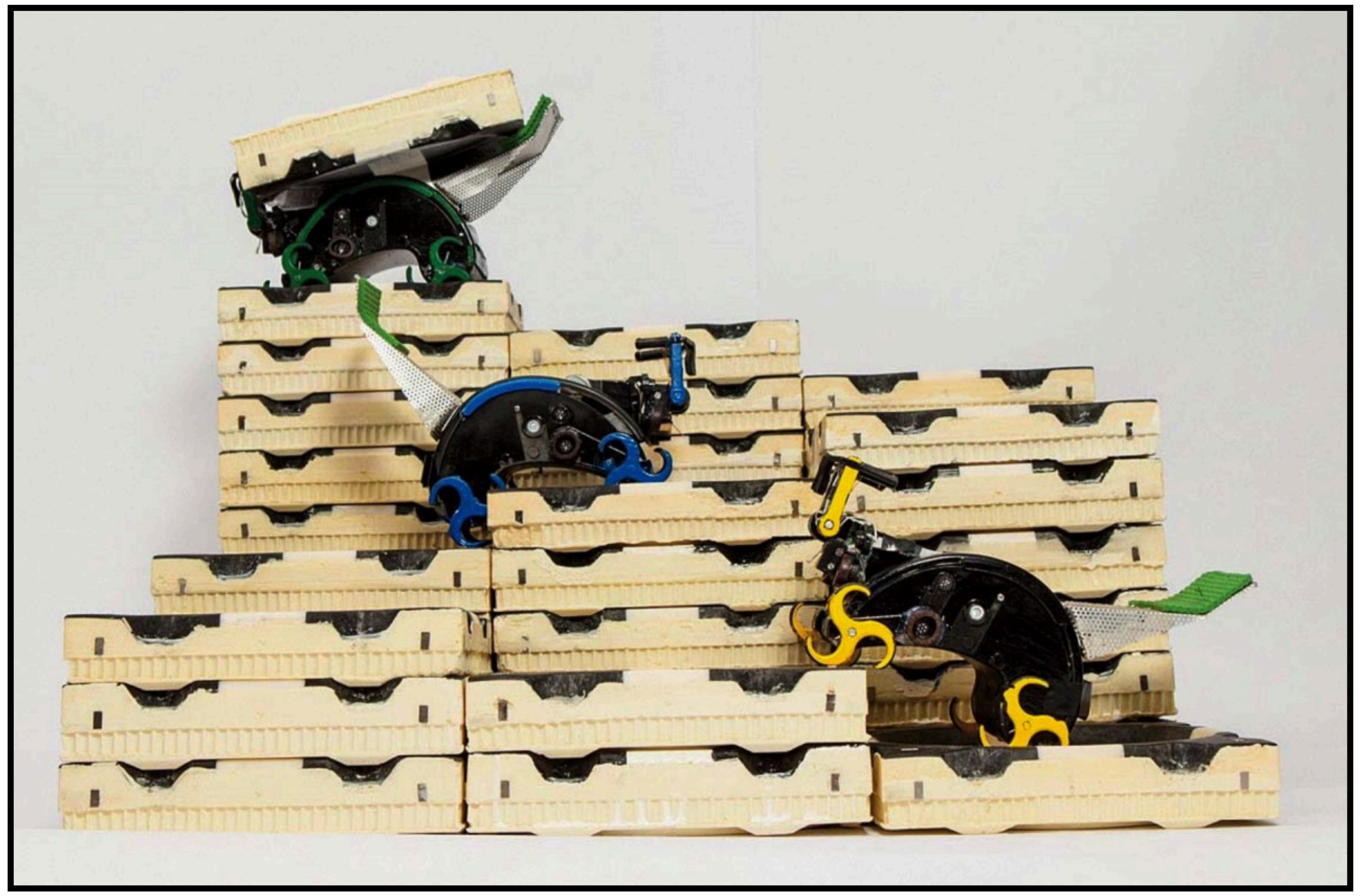
- Return the Tesla Roadster to the surface of the Earth without damaging it in 30 years or less.



4. Lunar Termites

Objectives:

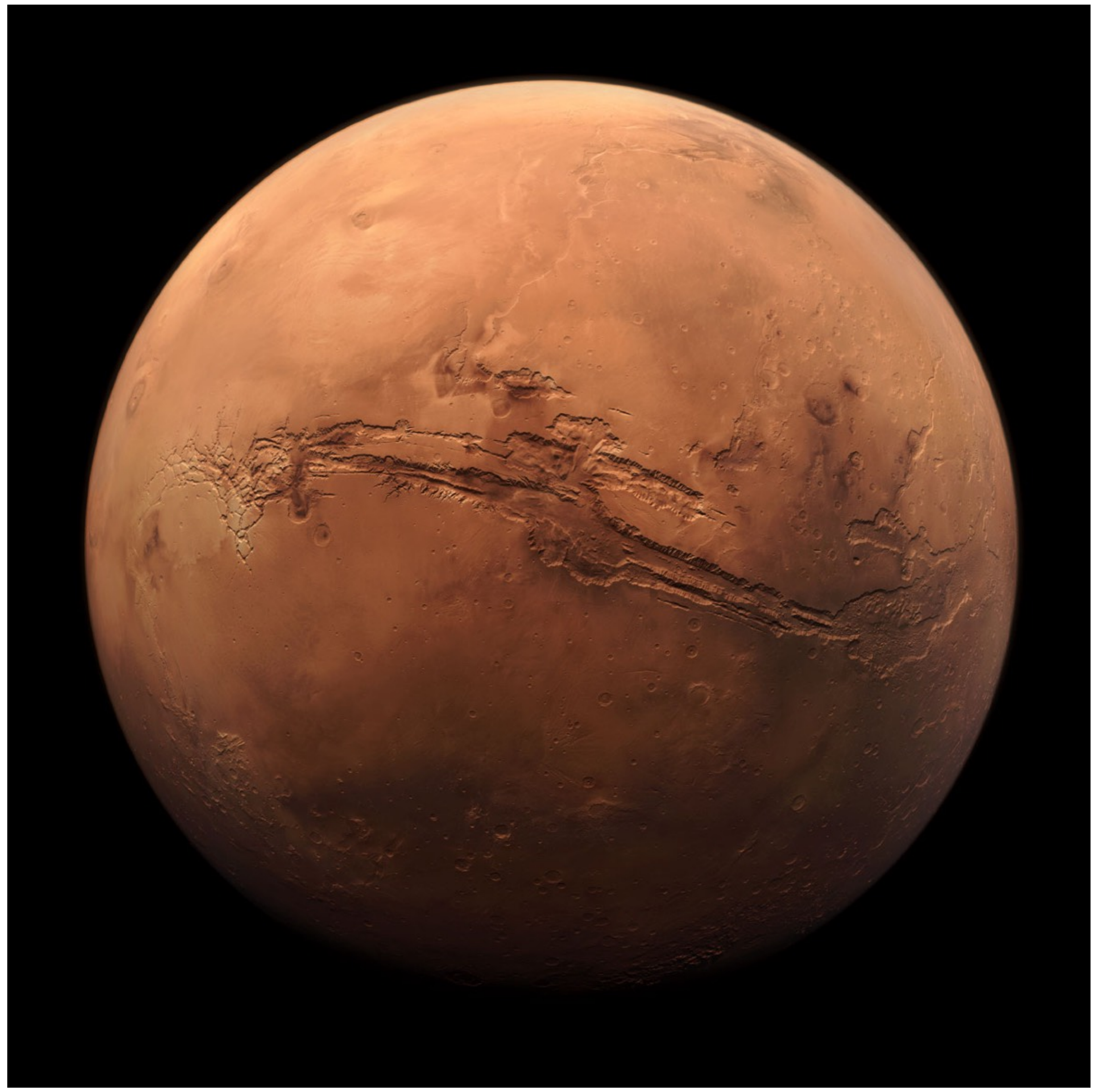
- Place 100 of Prof. Petersen's robots on the surface of the Moon without damaging them (assume fragility equivalent to Mars Exploration Rovers).
- Communicate sufficient information to ground operators to maintain knowledge of each robot's health and status, and their collective construction progress for not less than 1 year. This includes health and status information from each robot, and at least 10 4k photos of construction progress each day.



5. Martian Positioning System

Objectives:

- Create a martian positioning system that enables receivers anywhere on the surface of the Moon to determine position/velocity at any time with accuracy/precision equal to that of GPS.
- Design the system such that the receivers are of equivalent size/power draw used for Earth's global positioning system.
- You may assume access to SLS/Starship/Superheavy



First deliverable:

- Your group preference
- Your project preference (top 3, ranked)

How to be successful:

- Set aside 1-2 hours each week to meet with your group
- Use the material that we've covered in class that week to draft the relevant sections of your SRR/SDR
- Commit to that schedule now, and do not schedule other obligations over your weekly meeting with your group.

Pre-Formulation **downselect** → Formulation **downselect** → *Implementation*

Pre-Formulation

- Pre-Phase A

Formulation

- Phase A
- Phase B

Implementation

- *Phase C*
- *Phase D*
- *Phase E*
- *Phase F*

Phase C: Final Design and Fabrication

Goals:

- Complete and document the detailed design of the system that meets detailed requirements to fabricate, code, or otherwise realize the products.
- Generate final designs for each system structure end product.
- Fabricate hardware, code software, plan integration and testing

The last phase before assembly, and the last phase that we'll consider in as much detail.

Outcomes:

- Finalized design and components
- Integration plan and procedures
- Verification and validation procedures
- Operations plan

Reviews:

- **Critical Design Review (CDR)**
- System Integration Review (SIR)

Phase C: Final Design and Fabrication

Critical Design Review: The CDR demonstrates that the maturity of the design is appropriate to support proceeding with full-scale fabrication, assembly, integration, and test. CDR determines that the technical effort is on track to complete the system development, meeting performance requirements within the identified cost and schedule constraints.

Pass Criteria:

1. The detailed design is expected to meet the requirements with adequate margins.
2. Interface control documents are sufficiently mature to proceed with fabrication, assembly, integration, and test, and plans are in place to manage any open items.
3. The program cost and schedule estimates are credible and within program constraints.
4. High confidence exists in the product baseline, and adequate documentation exists or will exist in a timely manner to allow proceeding with fabrication, assembly, integration, and test.
5. The product verification and product validation requirements and plans are complete.
6. The testing approach is comprehensive, and the planning for system assembly, integration, test, and launch site and mission operations is sufficient to progress into the next phase.
7. Adequate technical and programmatic margins (e.g., mass, power, memory) and resources exist to complete the development within budget, schedule, and known risks.
8. Risks to mission success are understood and credibly assessed, and plans and resources exist to effectively manage them.
9. Safety and mission assurance (e.g., safety, reliability, maintainability, quality, and EEE parts) have been adequately addressed in system and operational designs, and any applicable SandMA 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.
10. The program/project has demonstrated compliance with applicable NASA and implementing Center requirements, standards, processes, and procedures.
11. TBD and TBR items are clearly identified with acceptable plans and schedule for their disposition.
12. Engineering test units, life test units, and/or modeling and simulations have been developed and tested per plan.
13. Material properties tests are completed along with analyses of loads, stress, fracture control, contamination generation, etc.
14. EEE parts have been selected, and planned testing and delivery will support build schedules.
15. The operational concept has matured, is at a CDR level of detail, and has been considered in test planning.
16. Manufacturability has been adequately included in design.
17. Software components meet the exit criteria defined in NASA-HDBK-2203, NASA Software Engineering Handbook.
18. Concurrence by the responsible Center spectrum manager that the program/project has provided requisite RF system data.

In short: Does the finalized design meet all requirements and constraints, and is it complete enough to begin full-scale fabrication?

Phase C: Final Design and Fabrication

How to think about a spacecraft/mission at a CDR-level of abstraction:

At CDR, the design is complete enough that you could handoff the documents to somebody else and they could build the entire system. Furthermore, that system would function and would meet all of the requirements from previous phases. The spacecraft is finished, but not yet built/tested. At this point, the spacecraft "looks" exactly like the spacecraft will look when it is built. There is no more abstraction.

Phase C: Final Design and Fabrication

Goals:

- Complete and document the detailed design of the system that meets detailed requirements to fabricate, code, or otherwise realize the products.
- Generate final designs for each system structure end product.
- Fabricate hardware, code software, plan integration and testing

The last phase before assembly, and the last phase that we'll consider in as much detail.

Outcomes:

- Finalized design and components
- Integration plan and procedures
- Verification and validation procedures
- Operations plan

Reviews:

- Critical Design Review (CDR)
- **System Integration Review (SIR):** ensures segments, components, and subsystems are on schedule to be integrated into the system, and integration facilities, support personnel, and integration plans and procedures are on schedule to support integration.

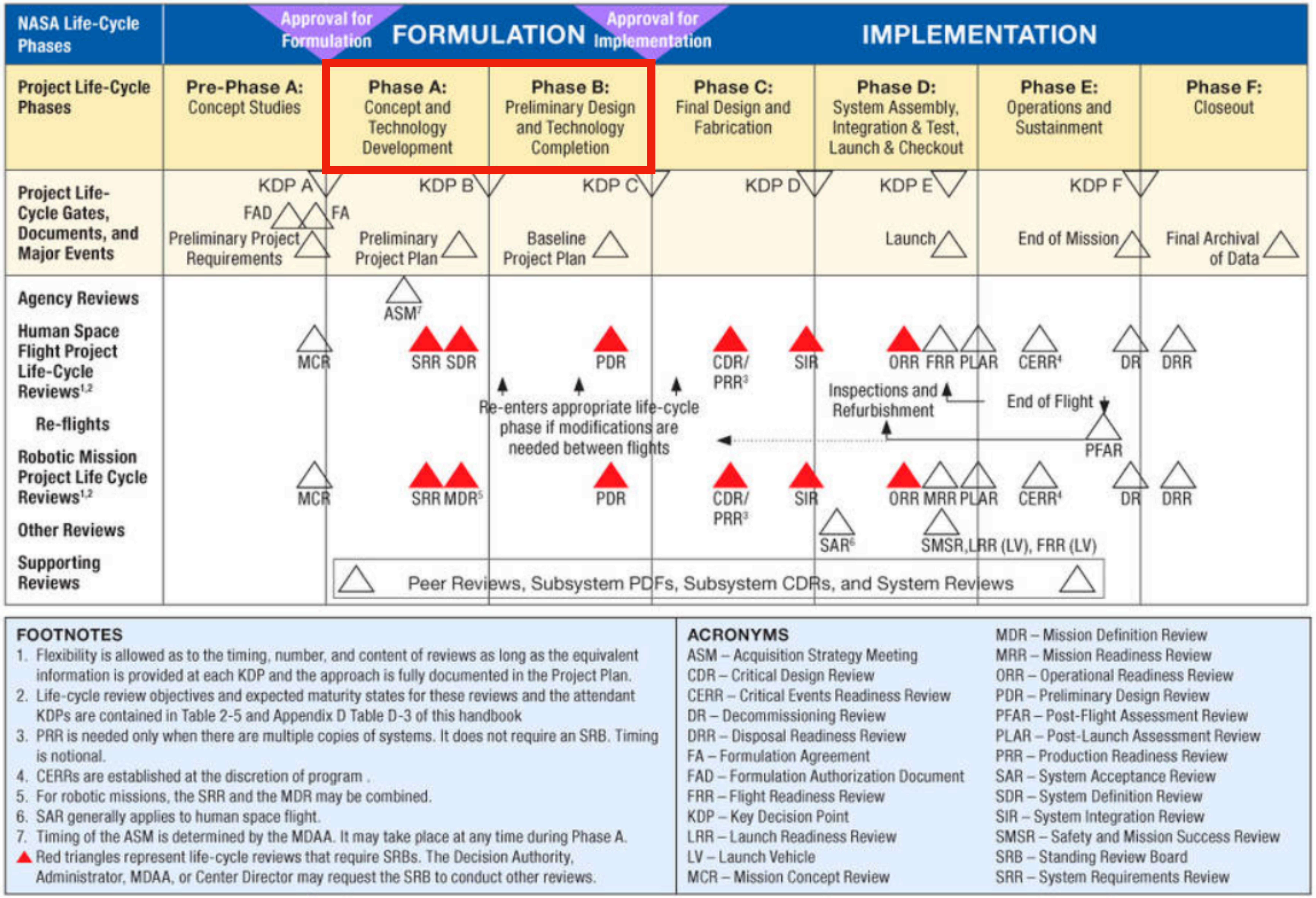


FIGURE 3.0-1 NASA Space Flight Project Life Cycle from NPR 7120.5E

A reminder of where we are

Nasa Systems Engineering Handbook

Phase D: System Assembly, Integration, Test, Launch

- **Test Readiness Review (TRR)**: A TRR for each planned test or series of tests ensures that the test article (hardware/software), test facility, support personnel, and test procedures are ready for testing and data acquisition, reduction, and control. - in the lab

- **System Acceptance Review (SAR)**: The SAR verifies the completeness of the specific end products in relation to their expected maturity level, assesses compliance to stakeholder expectations, and ensures that the system has sufficient technical maturity to authorize its shipment to the designated operational facility or launch site. - ready to ship

- **Operations Readiness Review (ORR)**: The ORR ensures that all system and support (flight and ground) hardware, software, personnel, procedures, and user documentation accurately reflect the deployed state of the system and are operationally ready. - at the launch site

- **Flight Readiness Review (FRR)**: The FRR examines tests, demonstrations, analyses, and audits that determine the system's readiness for a safe and successful flight or launch and for subsequent flight operations. The FRR also ensures that all flight and ground hardware, software, personnel, and procedures are operationally ready. - at the launch site

Launch

Phase E: Operations and Sustainment

- **<u>Post-Launch Assessment Review</u>**: A PLAR evaluates the readiness of the spacecraft systems to proceed with full, routine operations after post-launch deployment. The review also evaluates the status of the project plans and the capability to conduct the mission with emphasis on near-term operations and mission-critical events.

- **<u>Critical Event Readiness Review</u>**: A CERR evaluates the readiness of the project and the flight system to execute the critical event during flight operation (e.g. thruster burn, changing operational phase in CONOPS)

- **<u>Post-Flight Assessment Review (humans only)</u>**: The PFAR evaluates how well mission objectives were met during a mission and identifies all flight and ground system anomalies that occurred during the flight and determines the actions necessary to mitigate or resolve the anomalies for future flights of the same spacecraft design.

Phase F: Closeout

- **Decommissioning Review (DR)**: A DR confirms the decision to terminate or decommission the system and assesses the readiness of the system for the safe decommissioning and disposal of system assets.

Pre-Formulation

- Pre-Phase A

downselect →

Formulation

- Phase A
- Phase B

downselect →

Implementation

- Phase C
- Phase D
- Phase E
- Phase F

TABLE 3.0-1 SE Product Maturity from NPR 7123.1

Products	Formulation				Implementation					
Uncoupled/ Loosely Coupled	KDP 0		KDP I	Periodic KDPs						
Tightly Coupled Programs	KDP 0			KDP I	KDP II		KDP III		Periodic KDPs	
Projects and Single Project Programs	Pre-Phase A	Phase A		Phase B	Phase C		Phase D		Phase E	Phase F
	KDP A	KDP B		KDP C	KDP D		KDP E		KDP F	
	MCR	SRR	MDR/SDR	PDR	CDR	SIR	ORR	FRR	DR	DRR
Stakeholder identification and	**Baseline	Update	Update	Update						
Concept definition	**Baseline	Update	Update	Update	Update					
Measure of effectiveness definition	**Approve									
Cost and schedule for technical	Initial	Update	Update		Update	Update	Update	Update	Update	Update
SEMP[1]	Preliminary	**Baseline	**Baseline	Update	Update	Update				
Requirements	Preliminary	**Baseline	Update	Update	Update					
Technical Performance Measures definition			**Approve							
Architecture definition			**Baseline							
Allocation of requirements to next lower level			**Baseline							
Required leading indicator trends			**Initial	Update	Update	Update				
Design solution definition			Preliminary	**Preliminary	**Baseline	Update	Update			
Interface definition(s)			Preliminary	Baseline	Update	Update				
Implementation plans (Make/ code, buy, reuse)			Preliminary	Baseline	Update					
Integration plans			Preliminary	Baseline	Update	**Update				
Verification and validation plans	Approach		Preliminary	Baseline	Update	Update				
Verification and validation results						**Initial	**Preliminary	**Baseline		
Transportation criteria and instructions					Initial	Final	Update			
Operations plans				Baseline	Update	Update	**Update			
Operational procedures					Preliminary	Baseline	**Update	Update		
Certification (flight/use)							Preliminary	**Final		
Decommissioning plans				Preliminary	Preliminary	Preliminary	**Baseline	Update	**Update	
Disposal plans				Preliminary	Preliminary	Preliminary	**Baseline	Update	Update	**Update

** Item is a required product for that review

1 SEMP is baselined at SRR for projects, tightly coupled programs and single-project programs, and at MDR/SDR for uncoupled, and loosely coupled programs.

What happens when this process fails?

- At best, cost overruns
- At worst, catastrophe

Hubble Telescope

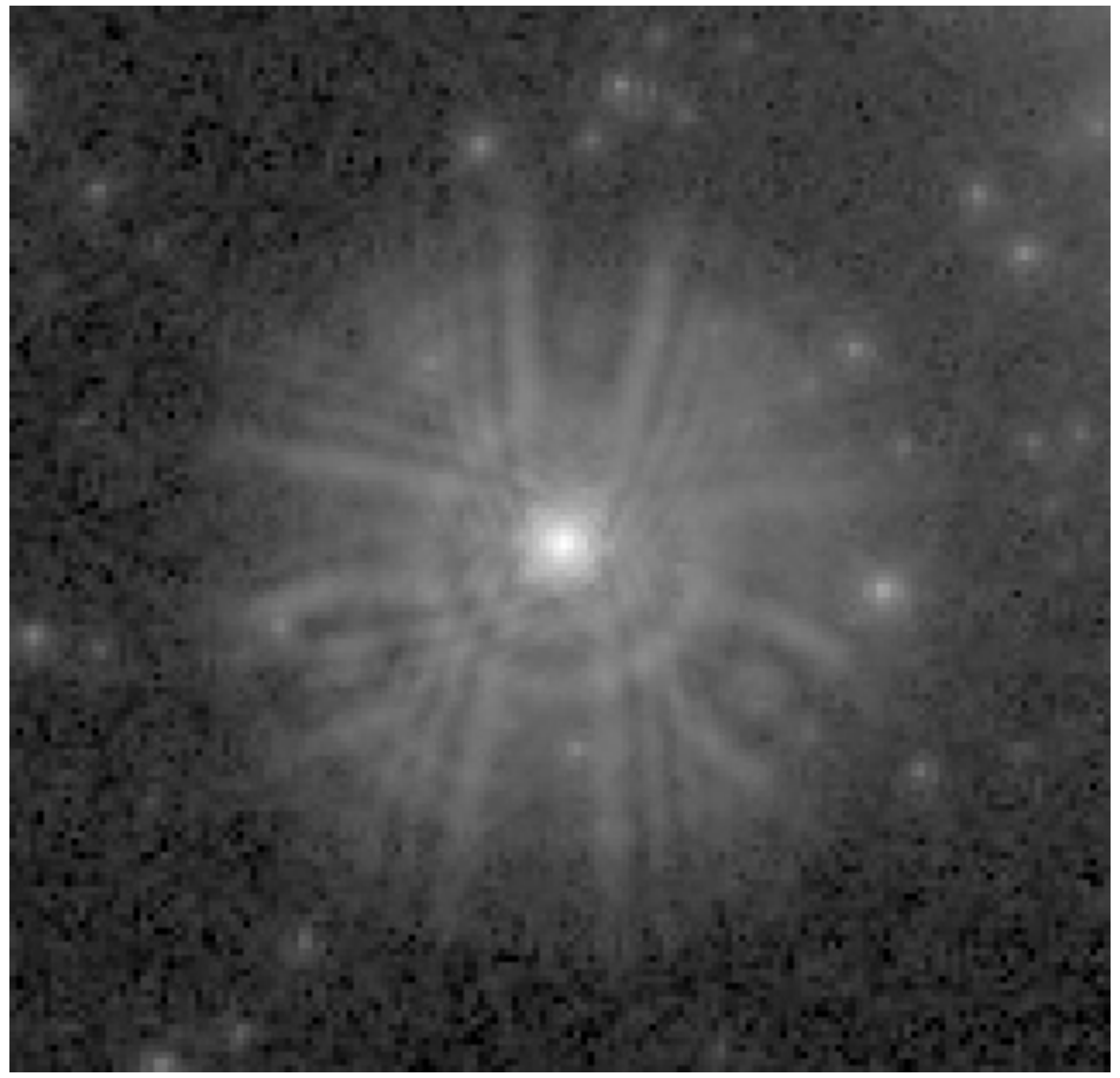
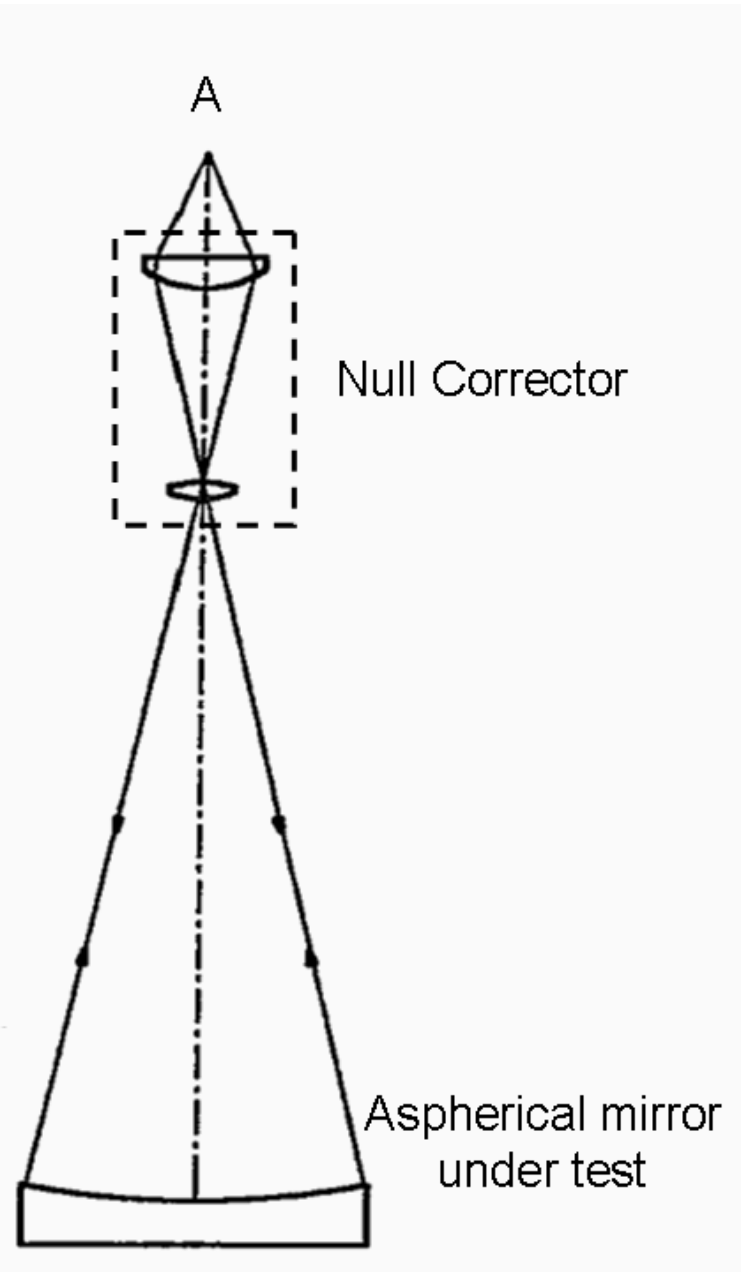


image of a star through faulty optics

The situation after launch:

- $4.7B
- Design requirement: point spread function concentrated within 0.1 arcsec
- Performance: point spread function >1 arcsec
- *catastrophe*

At which review should this have been prevented?



The problem:

- Manufacturers tested the shape of the mirror using an incorrectly assembled null corrector, and thus the lens was ground to the wrong shape
- Other null correctors correctly identified the error, but were ignored because the faulty one was considered more accurate

Mars Climate Orbiter

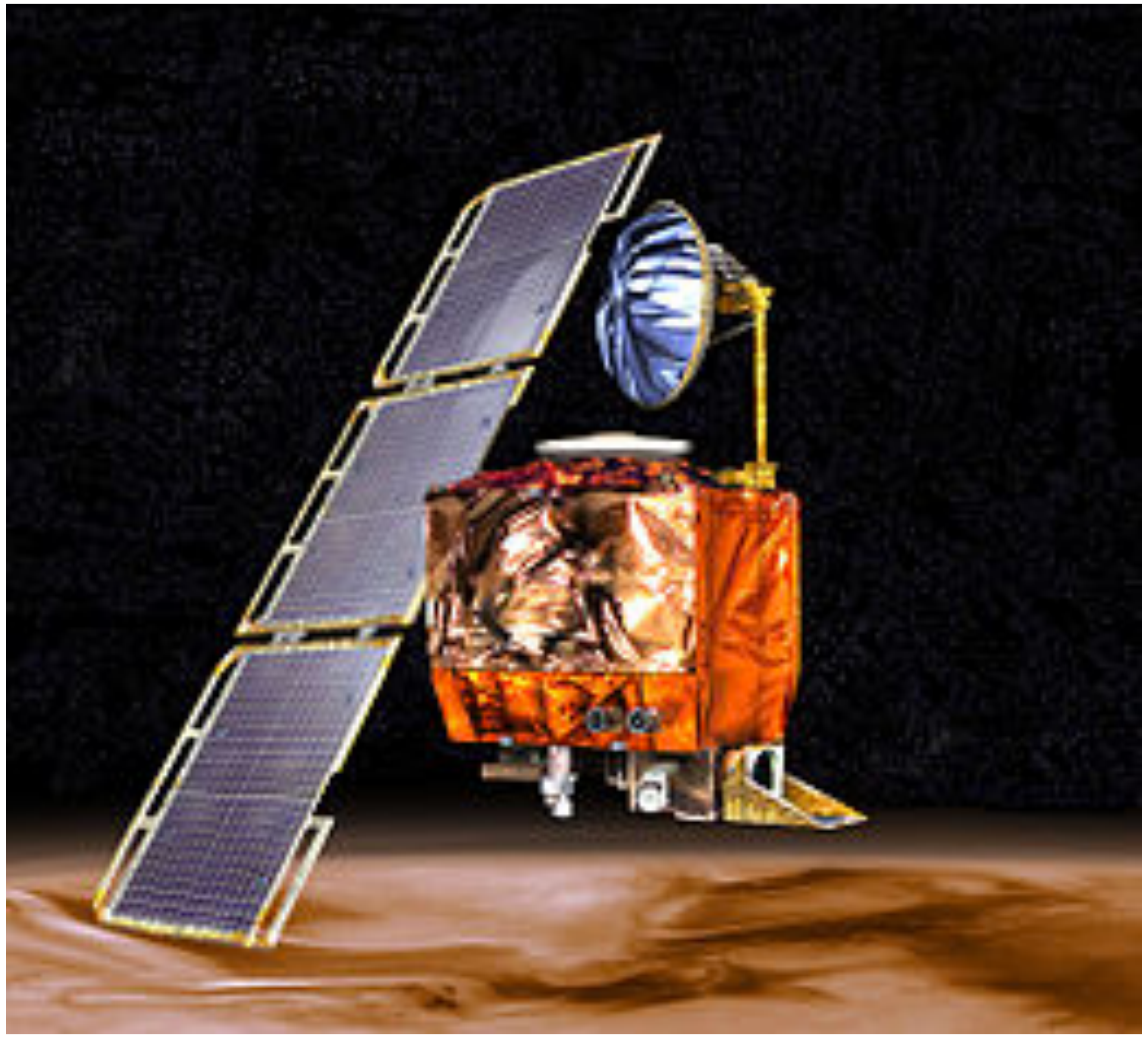
The problem:

- Lockheed Martin created thruster software in imperial units, NASA assumed metric units
- Incorrect thrust was used, and the MCO burned up in the martian atmosphere

“The problem here was not the error; it was the failure of NASA's systems engineering, and the checks and balances in our processes, to detect the error. That's why we lost the spacecraft.”

-Edward Weiler, NASA associate administrator for space science

At which stage of the process should this have been prevented?



We covered:

- NASA project life cycle
- Mission concept/architecture and CONOPS
- Technical reviews
- Projects

Next time:

- Writing requirements
- Verification and validation
- Risk analysis
- Trade studies