Massachusetts Institute of Technology

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

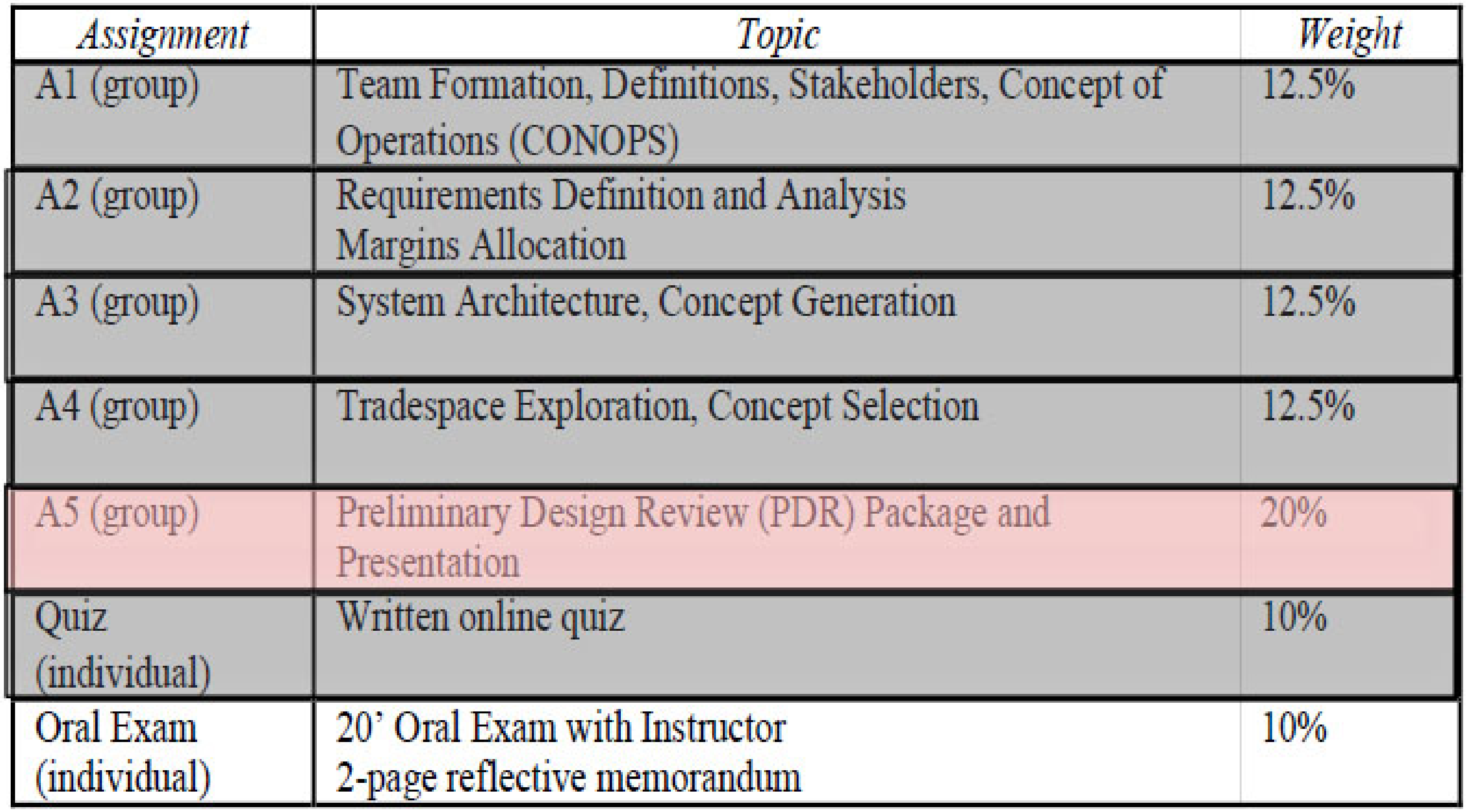
Fundamentals of Systems Engineering

Prof. Olivier L. de Weck
20 November 2015

Session 10

Commissioning and Operations

General Status Update

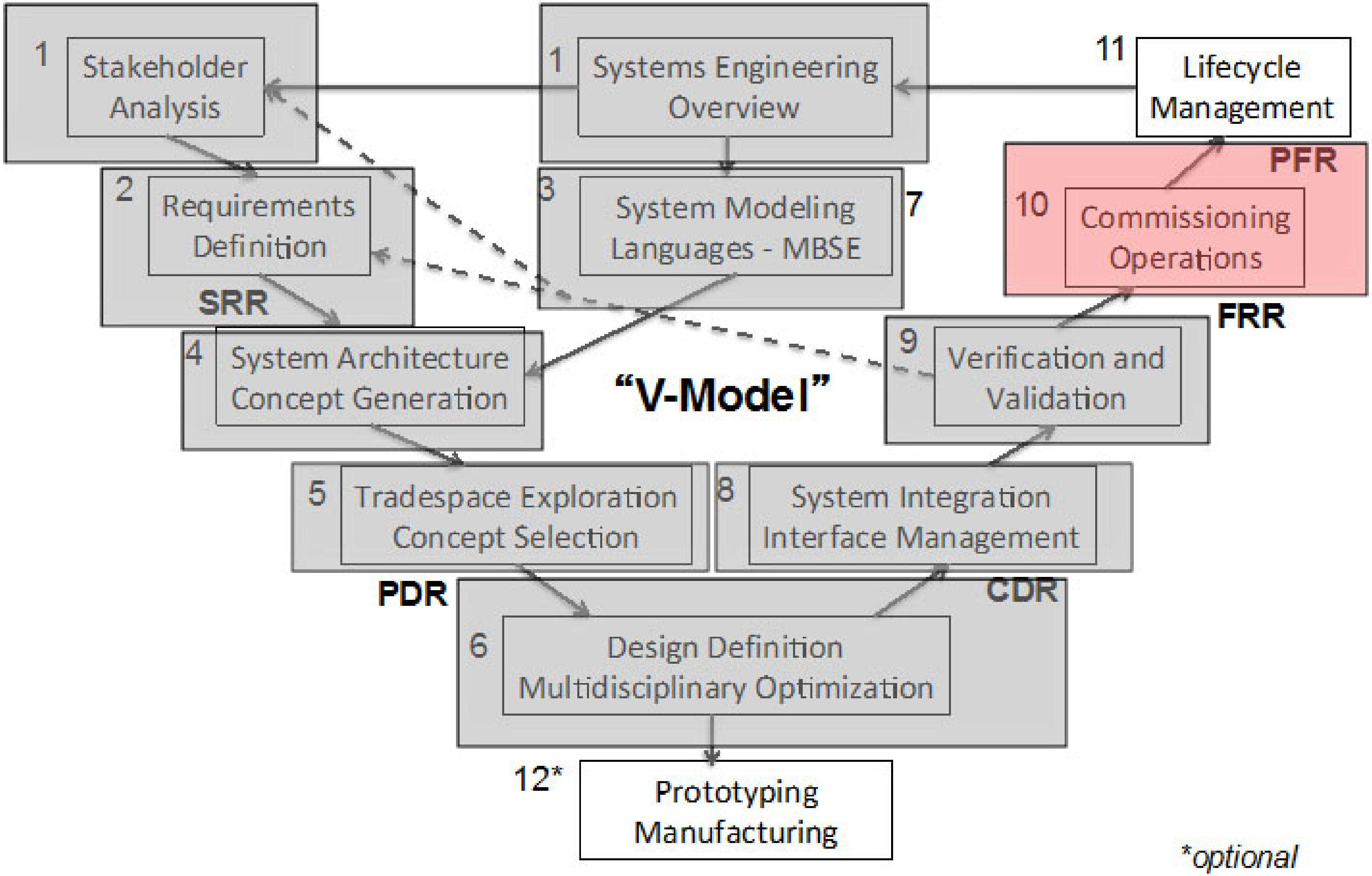


Assignment	*Topic*	*Weight*
A1 (group)	Team Formation, Definitions, Stakeholders, Concept of Operations (CONOPS)	12.5%
A2 (group)	Requirements Definition and Analysis Margins Allocation	12.5%
A3 (group)	System Architecture, Concept Generation	12.5%
A4 (group)	Tradespace Exploration, Concept Selection	12.5%
A5 (group)	Preliminary Design Review (PDR) Package and Presentation	20%
Quiz (individual)	Written online quiz	10%
Oral Exam (individual)	20' Oral Exam with Instructor 2-page reflective memorandum	10%

A5 is due today!

The “V-Model” of Systems Engineering

16.842/ENG-421 Fundamentals of Systems Engineering



**optional*

Numbers indicate the session # in this class

Outline for Today

- Operational Considerations
- Commissioning
- Research into Operations
  - Reconfigurability and Common Sparing for Mars Missions
  - Designing Systems for Operations in Partially Failed States
- Post-Flight Review (PFR)

The question …

- Why would a small mountainous country select a U.S. Navy military aircraft originally designed for a completely different operational mission?

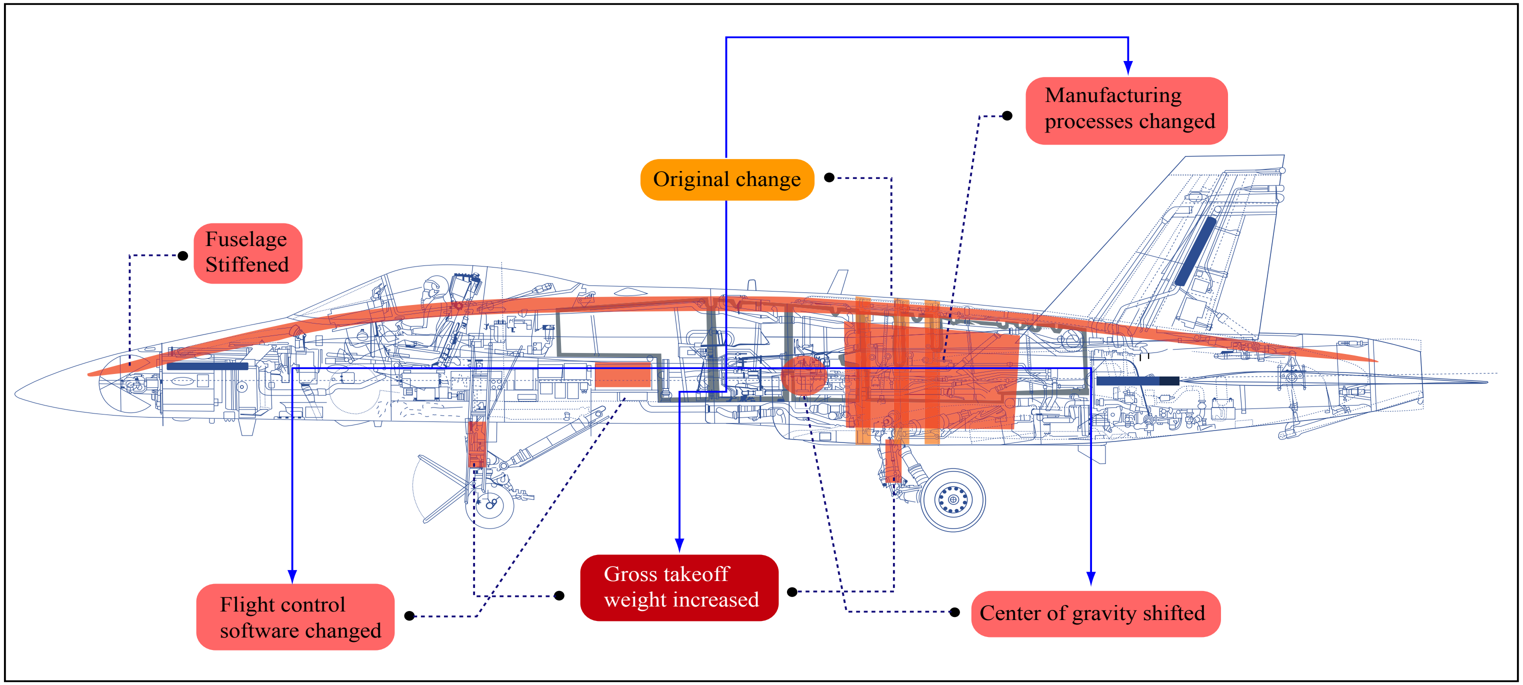


Image by MIT OpenCourseWare.

- Answer: Superior Lifecycle Properties
  - A) Flexibility (air patrol, intercept, ground attack)
  - B) Maintainability (21 vs 56 DMMH/FH)
  - C) Evolvability (spare capacity, e.g. in LEX)

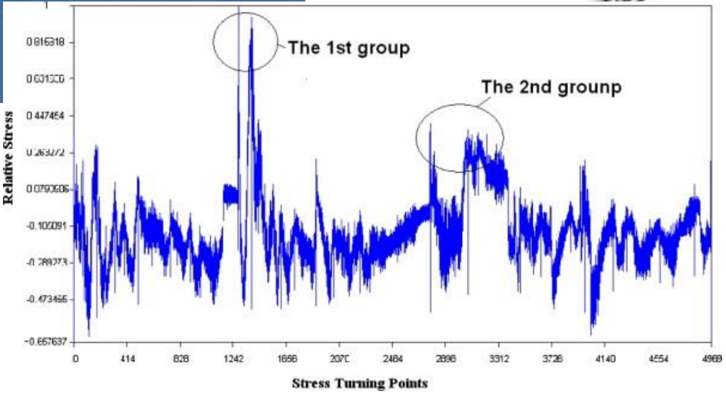
Flight Operations

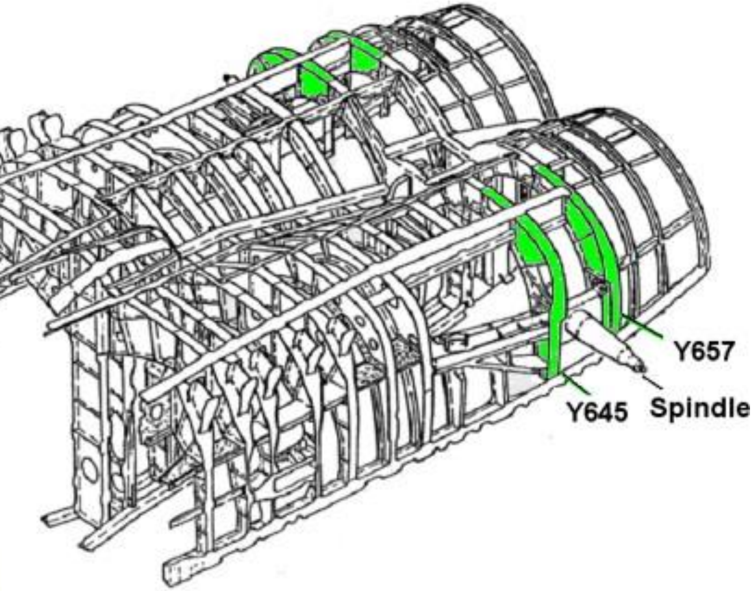
Turn-to-Partner Exercise

- What has been **your experience with operations** of a cyber-physical system? Did the system start-up well? What where the challenges? What would you do differently if you could do it again?
- Discuss.
- Share.

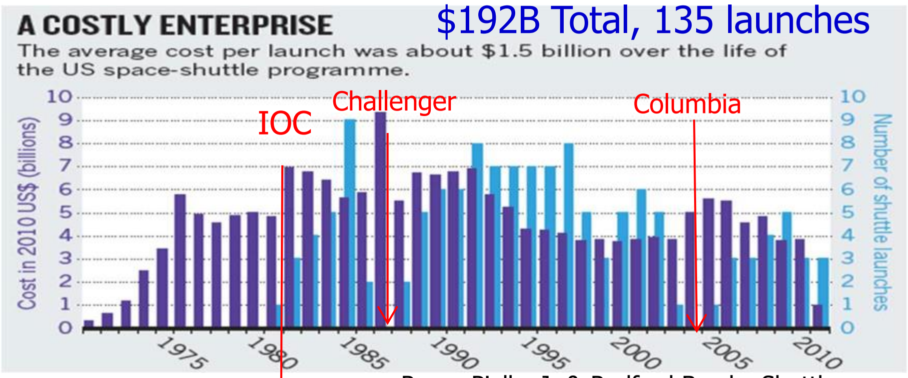
F/A-18 Fatigue Life Monitoring

International Journal of Fatigue
Volume 29, Issues 9–11, September–November 2007, Pages 1647–1657
Fatigue Damage of Structural Materials VI
The Sixth International Conference on Fatigue Damage of Structural Materials
Flight-by-flight fatigue crack growth life assessment
W. Zhuang, , S. Barter, L. Molent

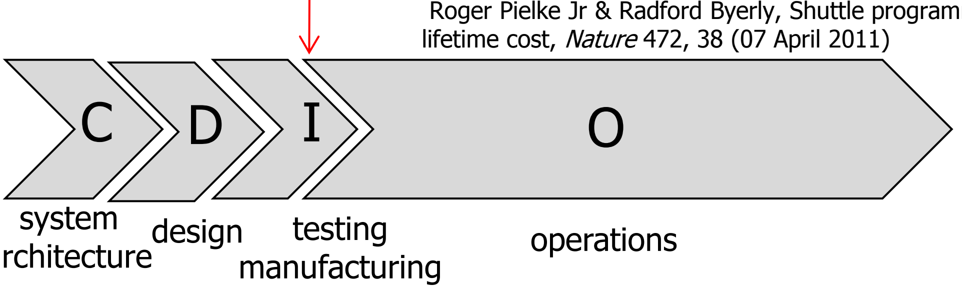




Space Shuttle Lifetime Cost (1971-2011)



Roger Pielke Jr & Radford Byerly, Shuttle programme lifetime cost, *Nature* 472, 38 (07 April 2011)



- Vision: partially reusable space vehicle with quick turnaround and high flight rate
- Actual: complex and fragile vehicle with average cost of about $1.5B/flight (20,000 workforce)
- Why?
  - Overoptimism
  - Congress capped RDT&E at $B5.15 (1971)
    - Focus on achieving launch performance (24 mt LEO)
    - Maintainability needed to be "designed-in"
    - No realistic lifecycle cost/value optimization done

What we wanted

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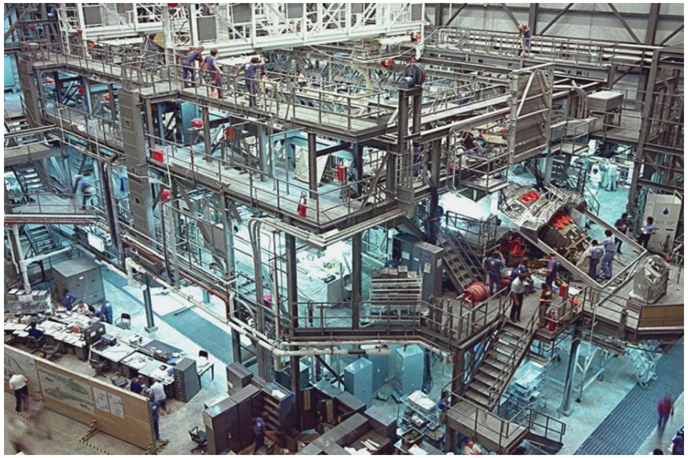
What we got



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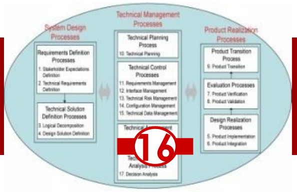
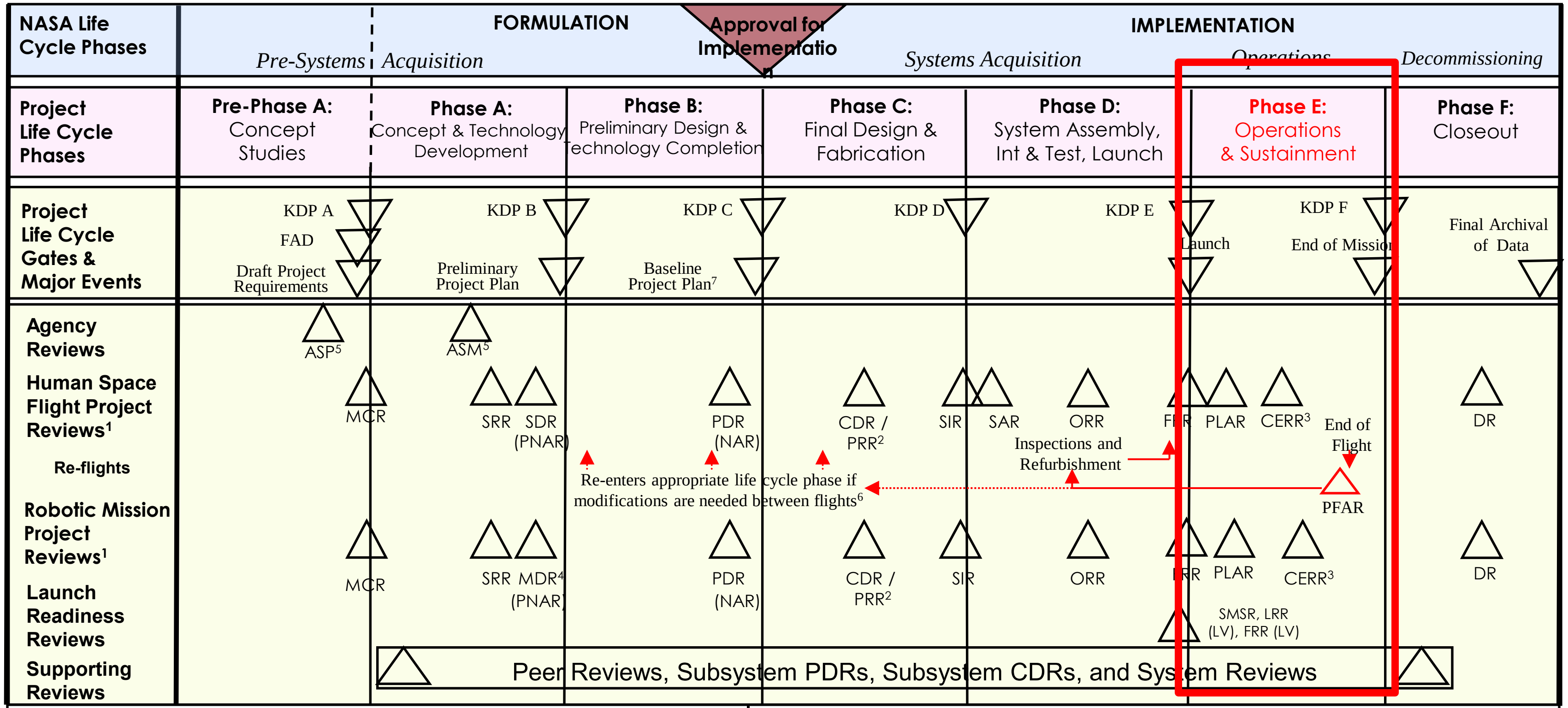
Operational Considerations

- How will the system be operated?
- What insights do the operators need into the system status?
- Before turning over to the operators what checks need to be performed?
- How might the system fail?
- What options are available to the operators in the event of system failures?!
  - What spares are needed to repair the system?
  - Will the system still perform even under partial failures?

NASA Life-Cycle Phases





FOOTNOTES

1. Flexibility is allowed in the timing, number, and content of reviews as long as the equivalent information is provided at each KDP and the approach is fully documented in the Project Plan. These reviews are conducted by the project for the independent SRB. See Section 2.5 and Table 2-6.
2. PRR needed for multiple (≥4) system copies. Timing is notional.
3. CERRs are established at the discretion of Program Offices.
4. For robotic missions, the SRR and the MDR may be combined.
5. The ASP and ASM are Agency reviews, not life-cycle reviews.
6. Includes recertification, as required.
7. Project Plans are baselined at KDP C and are reviewed and updated as required, to ensure project content, cost, and budget remain consistent.

ACRONYMS

ASP—Acquisition Strategy Planning Meeting
ASM—Acquisition Strategy Meeting
CDR—Critical Design Review
CERR—Critical Events Readiness Review
DR—Decommissioning Review
FAD—Formulation Authorization Document
FRR—Flight Readiness Review
KDP—Key Decision Point
LRR—Launch Readiness Review
MCR—Mission Concept Review
MDR—Mission Definition Review
NAR—Non-Advocate Review
ORR—Operational Readiness Review
PDR—Preliminary Design Review
PFAR—Post-Flight Assessment Review
PLAR—Post-Launch Assessment Review
PNAR—Preliminary Non-Advocate Review
PRR—Production Readiness Review
SAR—System Acceptance Review
SDR—System Definition Review
SIR—System Integration Review
SMSR—Safety and Mission Success Review
SRR—System Requirements Review

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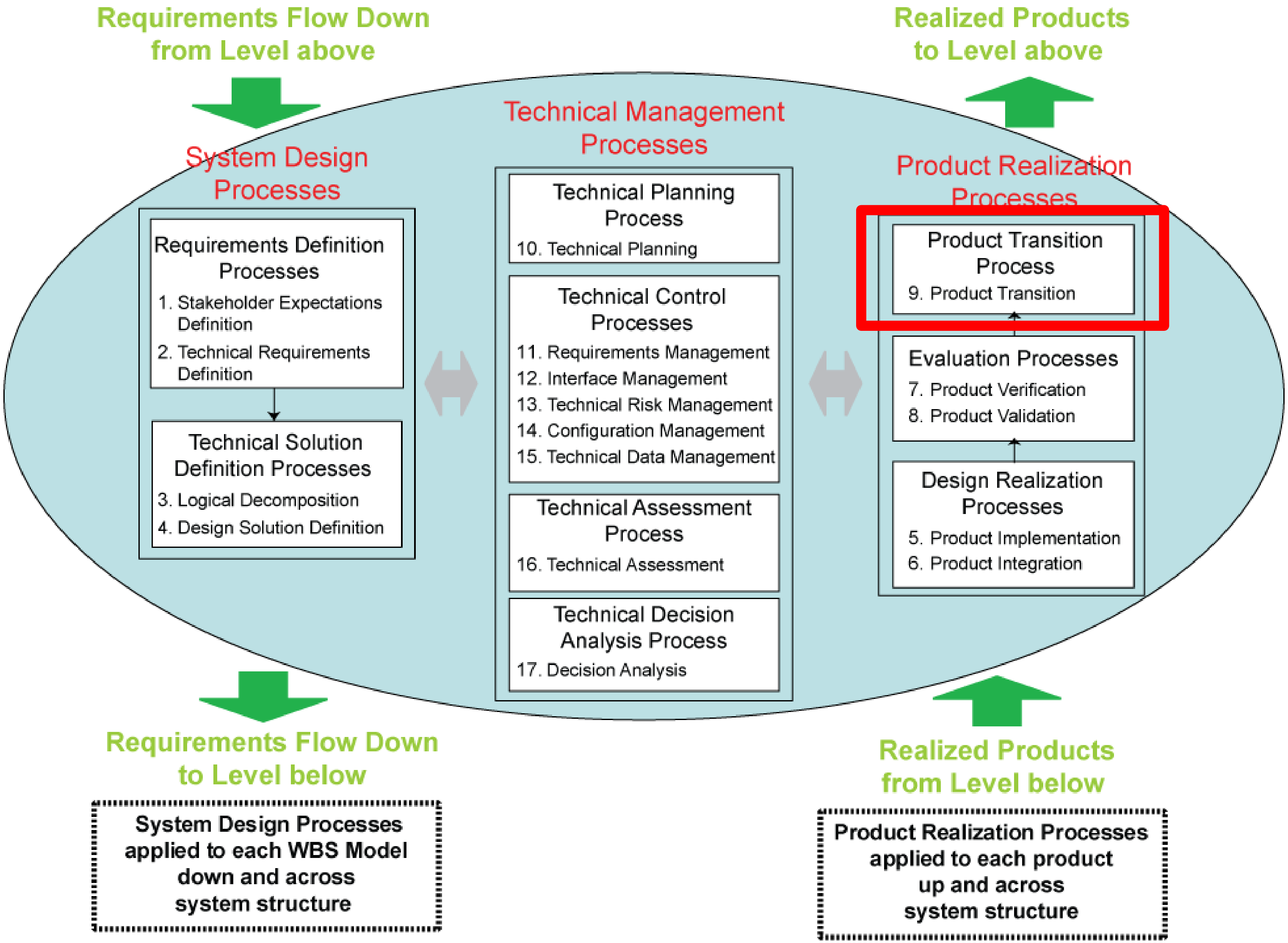
Transitioning and Operating

Phase D
System Assembly, Integration and Test, Launch
To assemble and integrate the products to create the system, meanwhile developing confidence that it will be able to meet the system requirements. Launch and prepare for operations. Perform system end product implementation, assembly, integration and test, and transition to use.

Phase E
Operations and Sustainment
To conduct the mission and meet the initially identified need and maintain support for that need. Implement the mission operations plan.

Common Technical Processes

“SE Engine”



Requirements Flow Down from Level above

Realized Products to Level above

System Design Processes

Requirements Definition Processes

1. Stakeholder Expectations Definition
2. Technical Requirements Definition

Technical Solution Definition Processes

3. Logical Decomposition
4. Design Solution Definition

Technical Management Processes

Technical Planning Process

10. Technical Planning

Technical Control Processes

11. Requirements Management
12. Interface Management
13. Technical Risk Management
14. Configuration Management
15. Technical Data Management

Technical Assessment Process

16. Technical Assessment

Technical Decision Analysis Process

17. Decision Analysis

Product Realization Processes

Product Transition Process

9. Product Transition

Evaluation Processes

7. Product Verification
8. Product Validation

Design Realization Processes

5. Product Implementation
6. Product Integration

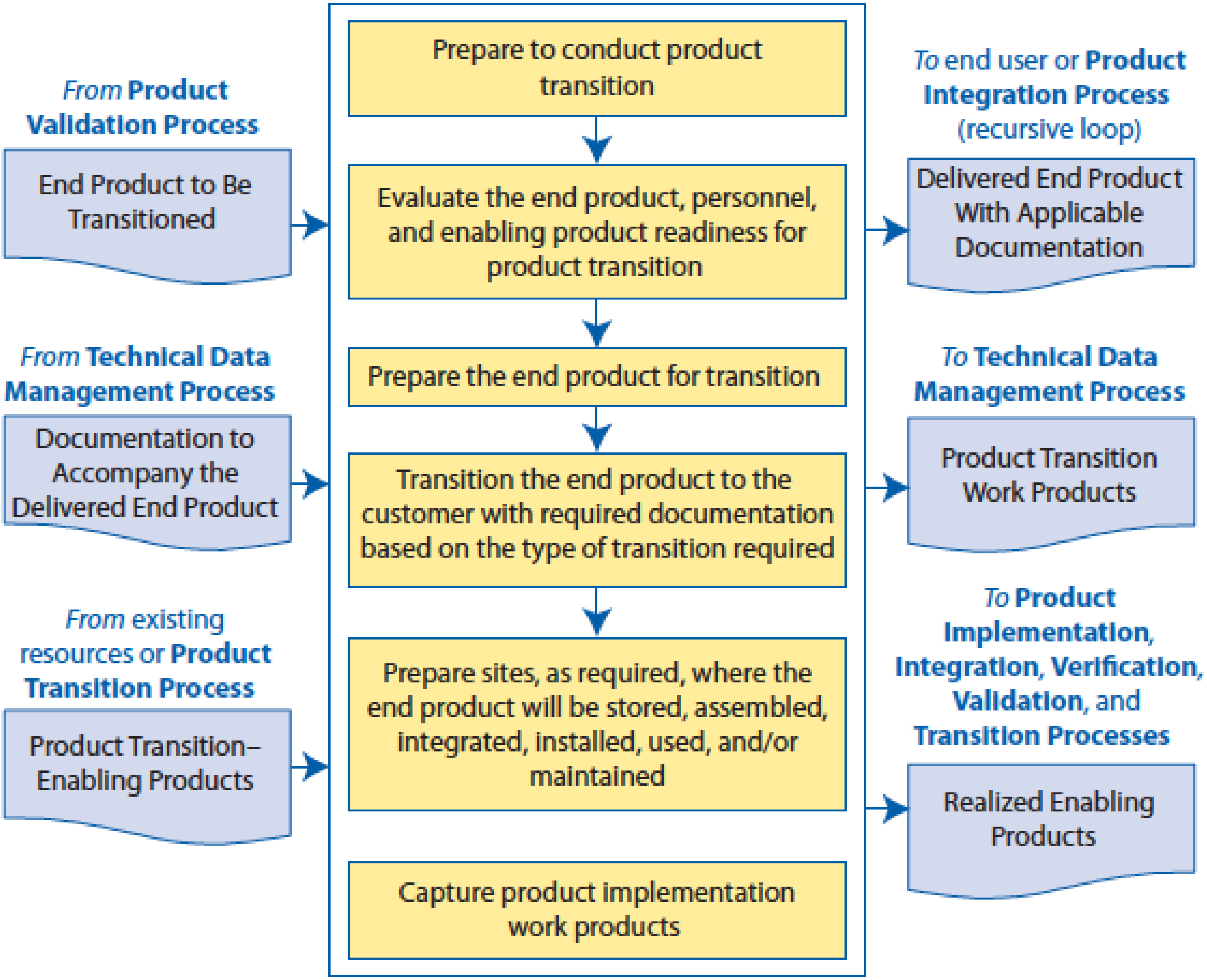
Requirements Flow Down to Level below

Realized Products from Level below

System Design Processes applied to each WBS Model down and across system structure

Product Realization Processes applied to each product up and across system structure

NASA Product Transition Process



From **Product Validation Process**

End Product to Be Transitioned

From **Technical Data Management Process**

Documentation to Accompany the Delivered End Product

From existing resources or **Product Transition Process**

Product Transition–Enabling Products

Prepare to conduct product transition

Evaluate the end product, personnel, and enabling product readiness for product transition

Prepare the end product for transition

Transition the end product to the customer with required documentation based on the type of transition required

Prepare sites, as required, where the end product will be stored, assembled, integrated, installed, used, and/or maintained

Capture product implementation work products

To end user or **Product Integration Process** (recursive loop)

Delivered End Product With Applicable Documentation

To **Technical Data Management Process**

Product Transition Work Products

To **Product Implementation**, **Integration**, **Verification**, **Validation**, and **Transition Processes**

Realized Enabling Products

Figure 5.5-1 Product Transition Process

Pg. 106, NASA SE Handbook

This image is in the public domain.

Product Transitioning → Commissioning

- Deploying System in the Field
  - Transition to operators (legally and physically)
  - Training of operators
- Checkout
  - Turning on all systems and subsystems
  - Comparing predicted parameters against actual behaviors
- Sustainment
  - Maintenance (preventative, corrective)
  - Spare Parts Management
  - Reconfiguring Systems during Use, Upgrades
  - Retrofits

NASA Operations Phases

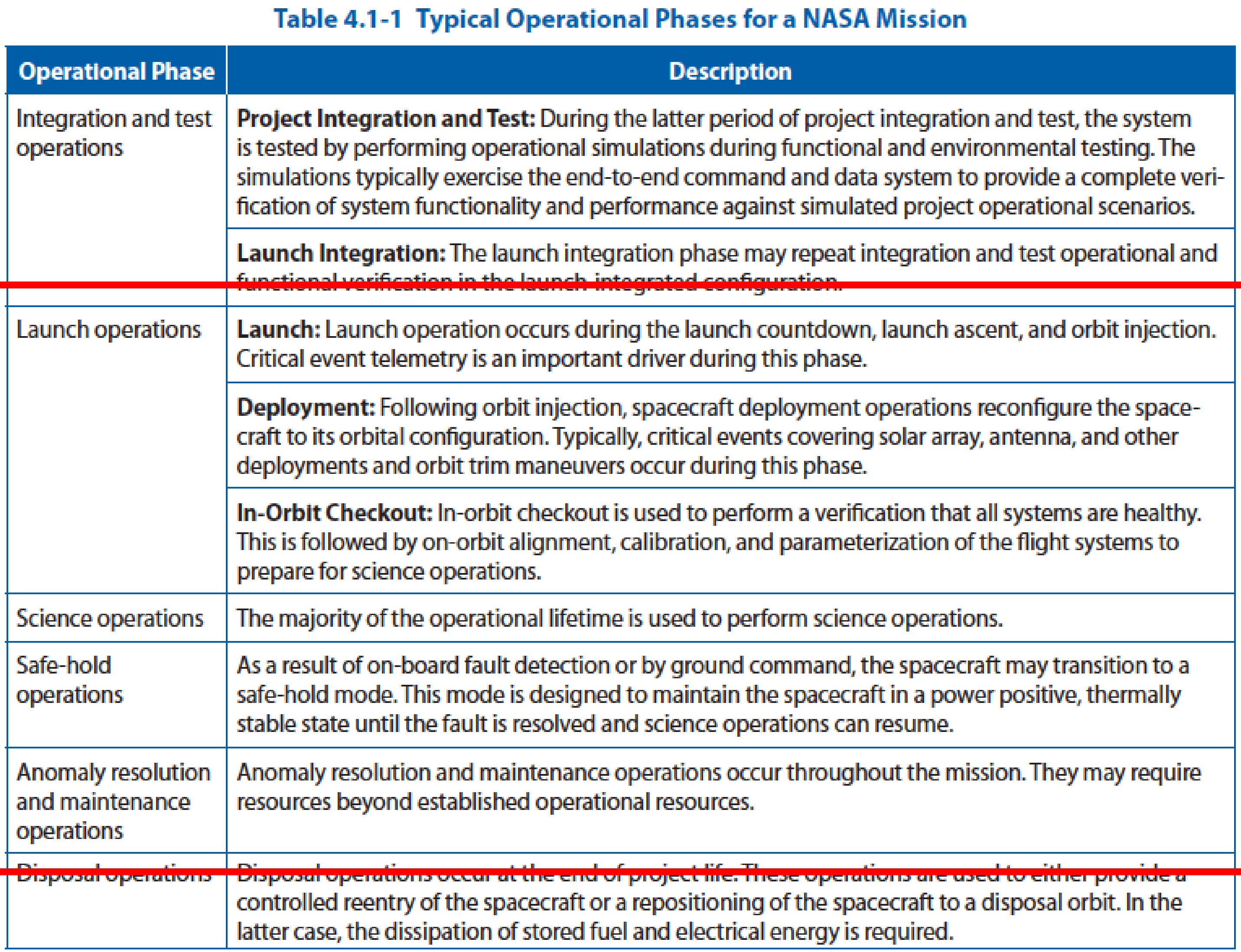


Table 4.1-1 Typical Operational Phases for a NASA Mission

Operational Phase	Description
Integration and test operations	**Project Integration and Test:** During the latter period of project integration and test, the system is tested by performing operational simulations during functional and environmental testing. The simulations typically exercise the end-to-end command and data system to provide a complete verification of system functionality and performance against simulated project operational scenarios.
	Launch Integration: The launch integration phase may repeat integration and test operational and functional verification in the launch-integrated configuration.
Launch operations	**Launch:** Launch operation occurs during the launch countdown, launch ascent, and orbit injection. Critical event telemetry is an important driver during this phase.
	Deployment: Following orbit injection, spacecraft deployment operations reconfigure the spacecraft to its orbital configuration. Typically, critical events covering solar array, antenna, and other deployments and orbit trim maneuvers occur during this phase.
	In-Orbit Checkout: In-orbit checkout is used to perform a verification that all systems are healthy. This is followed by on-orbit alignment, calibration, and parameterization of the flight systems to prepare for science operations.
Science operations	The majority of the operational lifetime is used to perform science operations.
Safe-hold operations	As a result of on-board fault detection or by ground command, the spacecraft may transition to a safe-hold mode. This mode is designed to maintain the spacecraft in a power positive, thermally stable state until the fault is resolved and science operations can resume.
Anomaly resolution and maintenance operations	Anomaly resolution and maintenance operations occur throughout the mission. They may require resources beyond established operational resources.
Disposal operations	Disposal operations occur at the end of project life. These operations are used to either provide a controlled reentry of the spacecraft or a repositioning of the spacecraft to a disposal orbit. In the latter case, the dissipation of stored fuel and electrical energy is required.

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JWST Deployment Video

JWST Deployment Video
https://www.youtube.com/watch?v=N8h_6WgSMjs

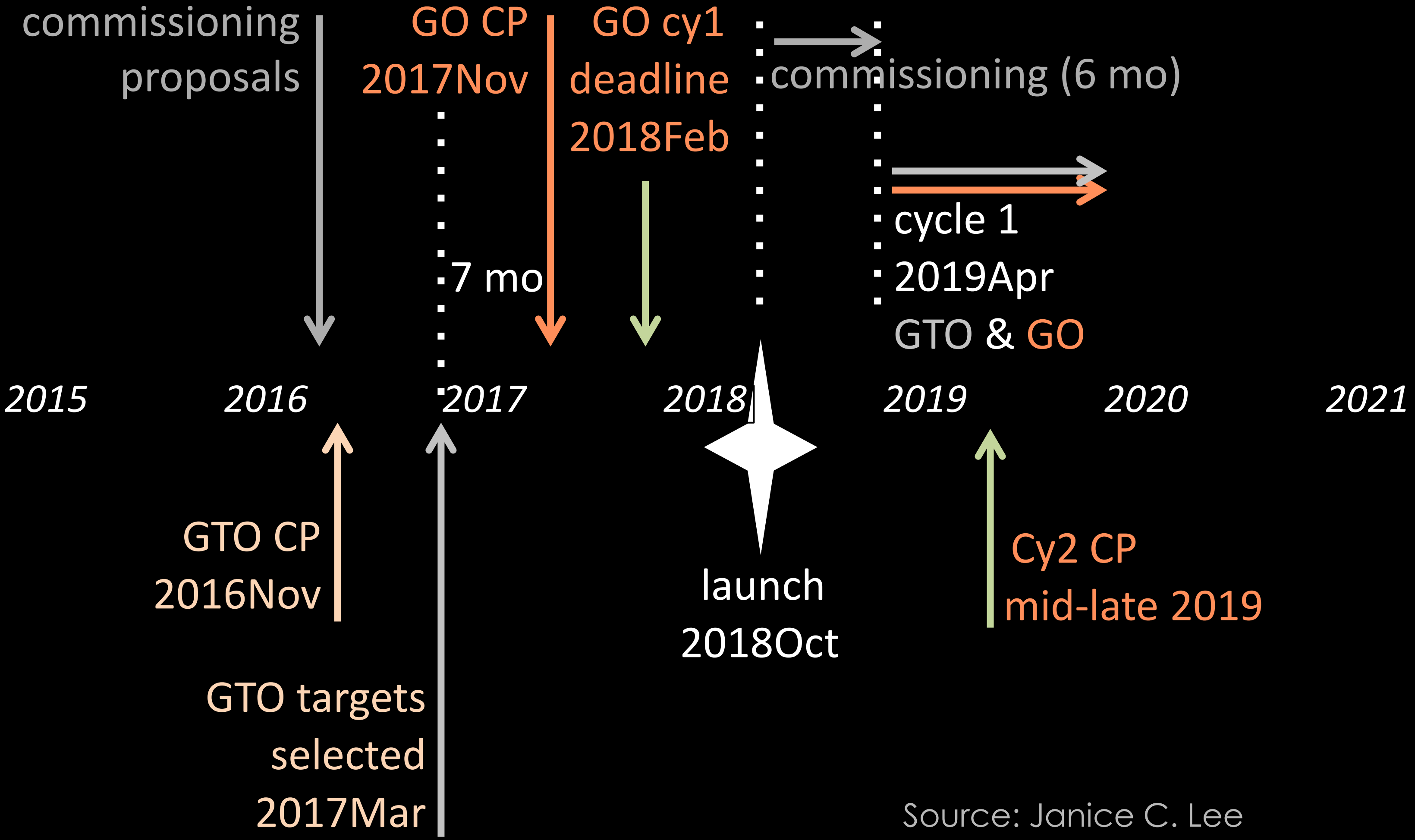
Concept Question 10

- How long is the **commissioning phase** of the James Webb Space Telescope (JWST) before science operations can begin?
- 3 days
- 1 week
- 3 weeks
- 1 month
- 3 months
- 6 months
- Not sure

Answer Concept Question 10
(see supplemental files)

JWST Science Planning Timeline

(as of 2014 Feb)



commissioning
proposals

GO CP
2017Nov

GO cy1
deadline
2018Feb

commissioning (6 mo)

7 mo

cycle 1
2019Apr
GTO & GO

2015 2016 2017 2018 2019 2020 2021

GTO CP
2016Nov

GTO targets
selected
2017Mar

launch
2018Oct

Cy2 CP
mid-late 2019

Source: Janice C. Lee
STScI Science Mission Office
March 13, 2014

JWST Timeline to Operations

Commissioning Program [6 mo: 2018 Oct-2019 Apr]

- *full schedule of deployment & check-out activities*
- *limited set of science calibration obs possible*
- *science obs highly unlikely*

Guest Observer Program [2019 Apr -]

- *use GO programs from HST, Spitzer, etc. as models*
- *will accommodate programs with range of sizes*
- *support archival research*
- *details TBD, consultations with JSTAC*

Guaranteed Time Observation Program [2019 Apr -]

- *3,960 hr total allocation in first 30 mo. after commissioning*
- *~10% of time available in nominal 5 yr lifetime*

Source: Janice C. Lee
STScI Science Mission Office
March 13, 2014

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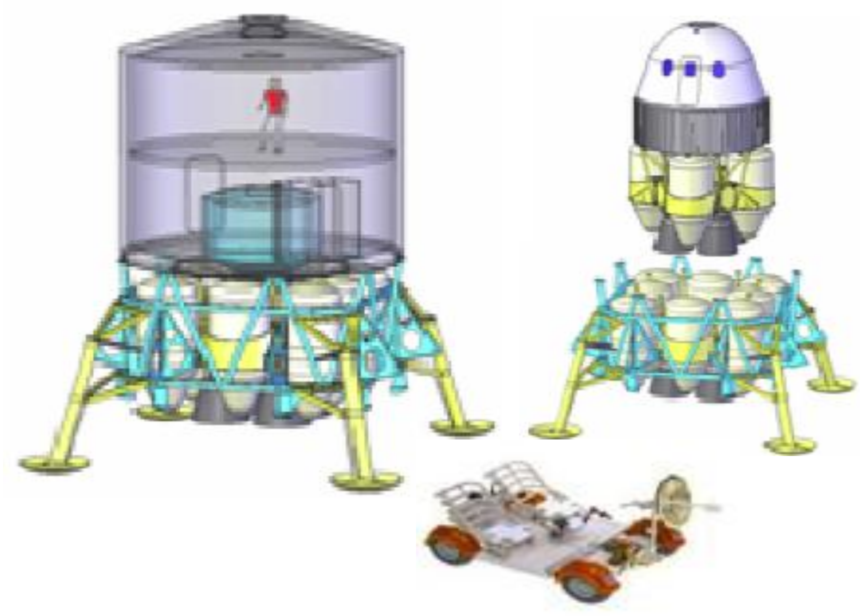
Some research into operations

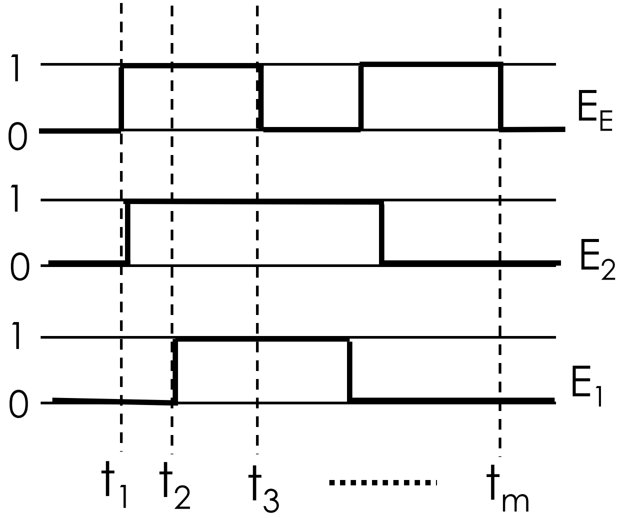
Siddiqi A., de Weck O., “Spare Parts Requirements for Space Missions with Reconfigurability and Commonality”, *Journal of Spacecraft and Rockets*, 44 (1), 147-155, January-February 2007

Impact of Reconfigurability on Logistics

- Reconfigurability across different elements in a mission was explored
- Effect of reconfigurable spares on system availability was quantified through allowance of temporary scavenging/cannibalization



Element Operational Profiles



- Operational cycles of elements are defined
- The number of available spares become a function of time
- System availability as function of spares level will be used for quantifying impact

Spare Parts Requirements Model - I

Failures modeled as Poisson process

$$p(n) = \frac{e^{-\lambda}\lambda^n}{n!}$$

$$\lambda = \int_{t_o}^{t_f} l\,dt = ql\Delta t$$

$$\lambda_e(t_i) = q_e l \sum_{k=1}^{i} [t_k - t_{k-1}]\Gamma_e(t_k)$$

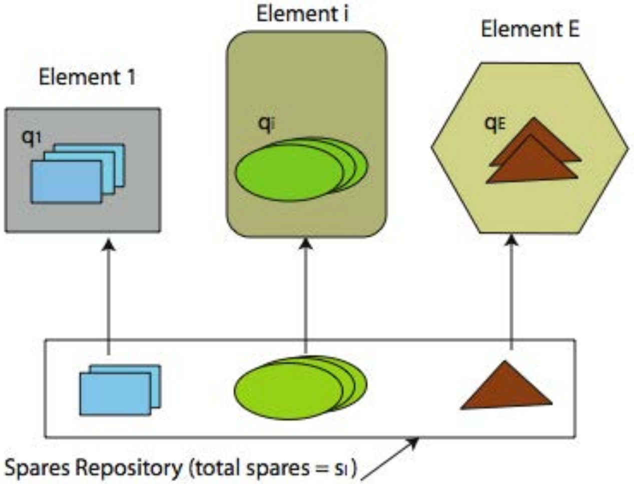
Spares from elements are function of time (operation profile)

$$s_E(t_i) = \sum_{e=1}^{E} q_e[\neg\Gamma_e(t_i)]$$

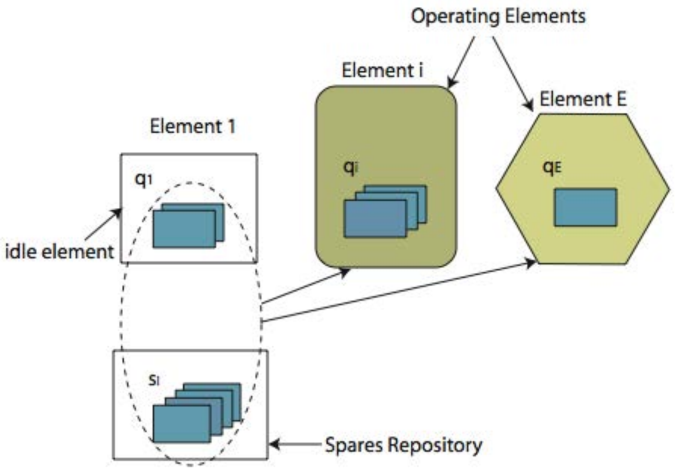
$$s(t_i) = s_I + s_E(t_i) - n_F$$

q: quantity per application (QPA)
λ: mean failures
n_f: # of failures
p(n): probability of n failures
l : failure rate
Γ: binary variable for operation
s_E : spares from elements
s_I : spares from repository
s: total spares

Dedicated Parts



Reconfigurable Parts



Spare Parts Requirements Model - II

Number of failures is limited by total parts due to no re-supply and repair:

$$0 \leq n_F \leq N$$

$$N = s_I + \sum_{e=1}^{E} q_e$$

For independent failures, the probability of no outstanding part order is:

$$A(t_i) = \left(1 - \frac{\overline{B}(t_i)}{Q}\right)^Q$$

Expected backorder level is function of available spares (and therefore of time):

$$\overline{B}_c(s,t_i) = \sum_{n_F = s+1}^{N} (n_F - s)\, p(n_F)$$

$$\overline{B}(t_i) = \sum_{s=0}^{S} \overline{B}_c(s,t_i) P(s)$$

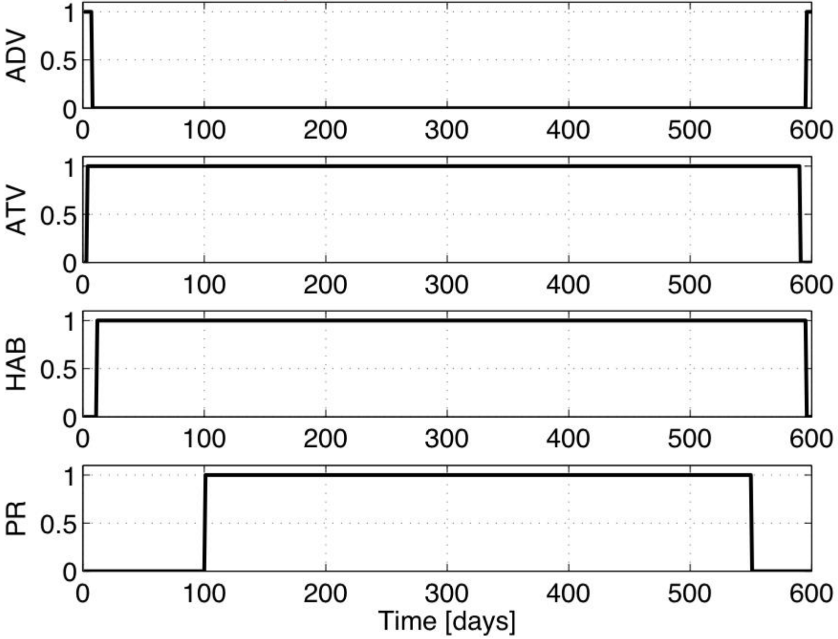
$$A_{sys} = \min\left[A(t_i)\right] \quad t_i \in T$$

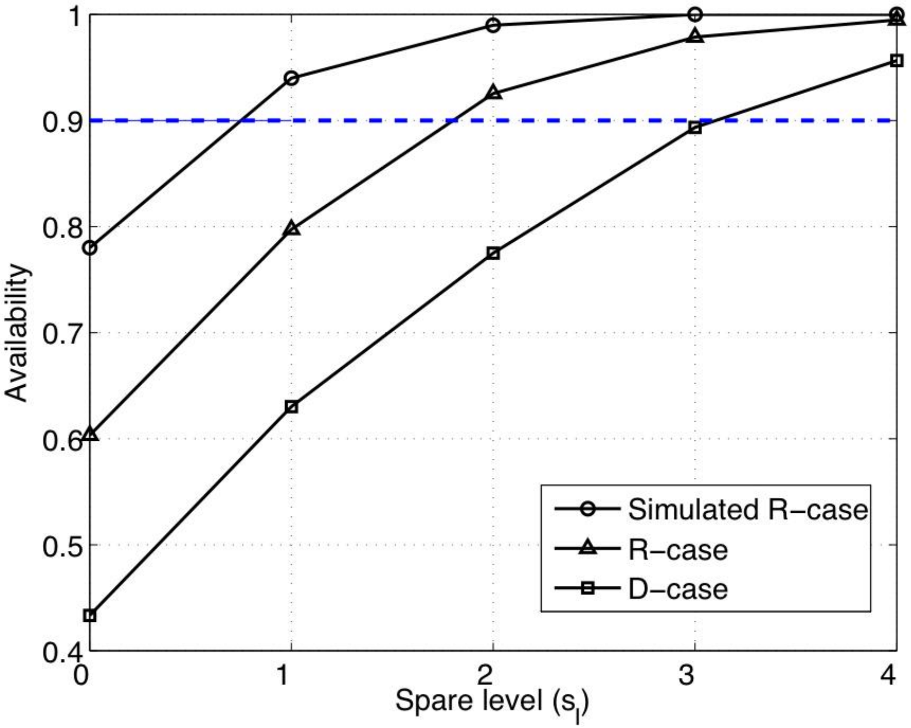
N: total number of parts
$B_C(s,t)$: conditional backorder at spares level s
P(s): probability of s spares being available
$A(t_i)$: Availability at time t_i

Quantifying the Impact of Reconfigurability

- Define co-located mission elements
- Define operational time profile, QPA *etc.*
- An Electronic Control Unit (ECU) with 100,000 hrs MTTF was used as an example

Operational Profiles

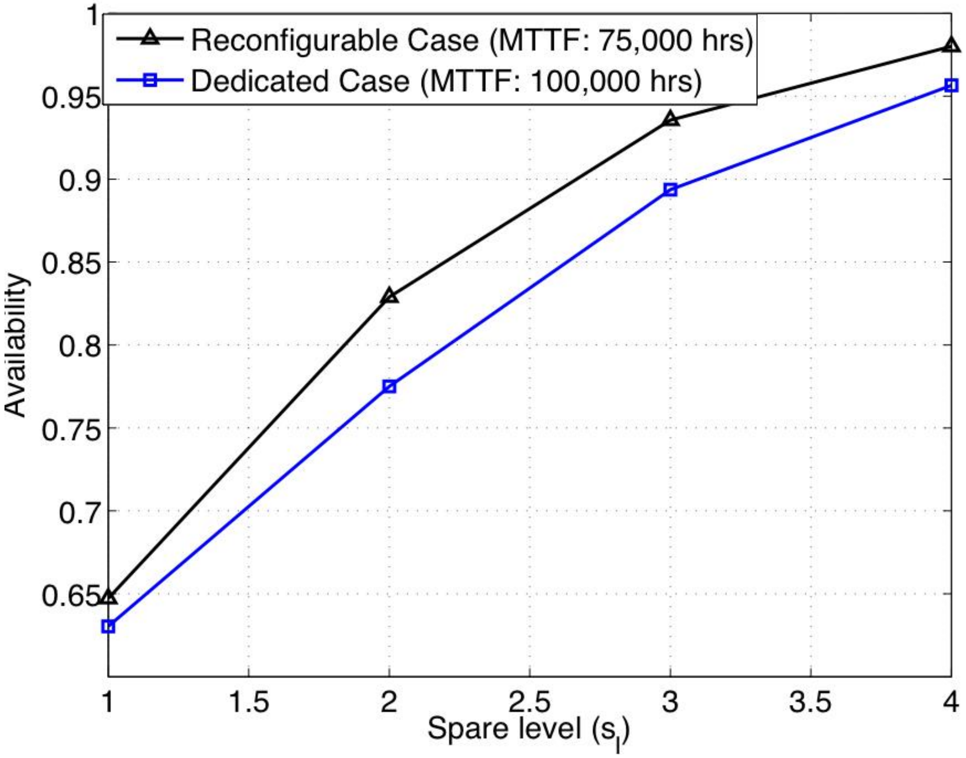


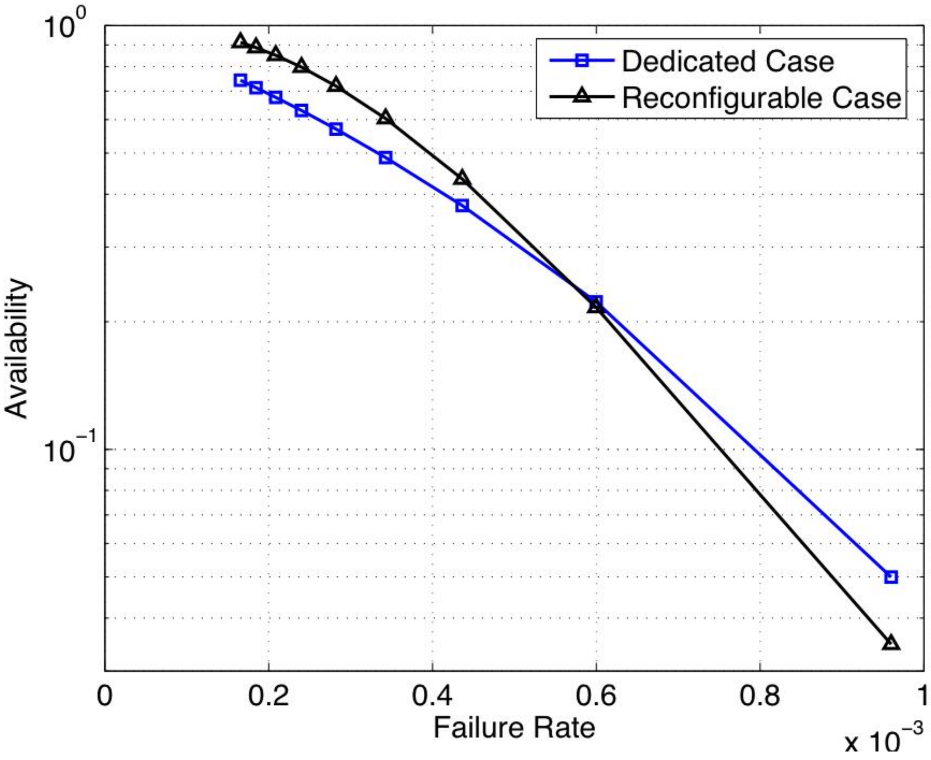


- Reconfigurable parts allow for 33-50% reduction in number of required spares for 90% Availability level

Benefits and Limitations

Increase in availability may be traded for reduced reliability (to affect component cost)



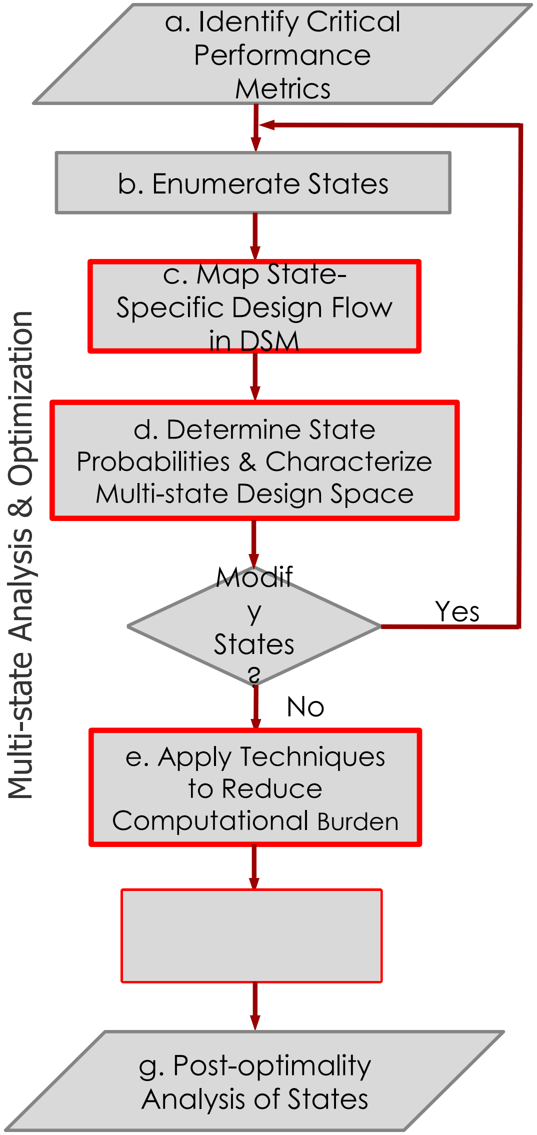


There is an eventual tradeoff between reconfigurable and dedicated parts if failure rates become high enough

Robustness of degraded aircraft (USAF)

- Aerospace systems spend significant time operating in **degraded or off-nominal states**
  - Yet current early-stage design focuses on improving performance in the nominal or most-likely state.
  - Future ultra long endurance vehicles require more attention to robustness in off-nominal states

Robustness – ability to perform under a variety of circumstances; ability to deliver desired functions in spite of changes in the environment, uses, or internal variations that are either built-in or emergent


Multi-state Analysis & Optimization

a. Identify Critical Performance Metrics

b. Enumerate States

c. Map State-Specific Design Flow in DSM

d. Determine State Probabilities & Characterize Multi-state Design Space

Modify States?

Yes

No

e. Apply Techniques to Reduce Computational Burden

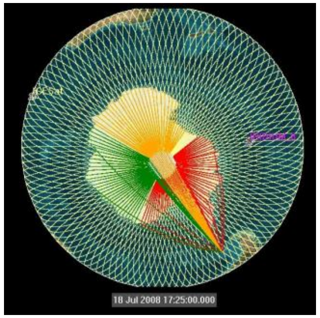
g. Post-optimality Analysis of States

PhD Thesis of J. Agte

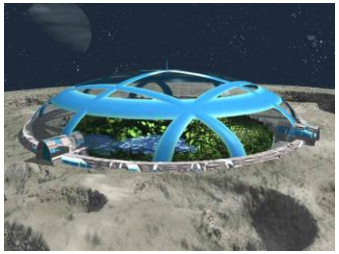
DARPA – Vulture

Vulture – stay aloft 5 years
No landing + repair allowed

NASA Antarctica UAV mission



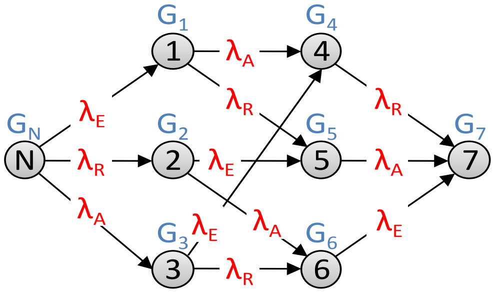
5 years, 50kft, map ice sheets
Replace or complement IceSat



Space Colonization

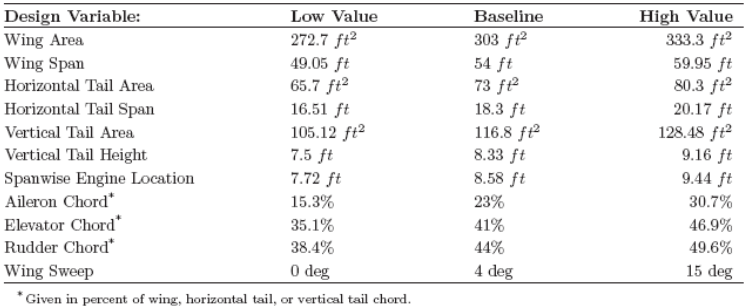
King Air Twin Engine Case Study

C12-C Aircraft



State	Left Engine	Rudder	Ailerons	Turn control
N				ailerons
1	failed			ailerons
2		failed		ailerons
3			failed	rudder
4	failed		failed	rudder
5	failed	failed		ailerons
6		failed	failed	diff. thrust
7	failed	failed	failed	none

Aircraft Design Space



Design Variable:	Low Value	Baseline	High Value
Wing Area	272.7 ft^2	303 ft^2	333.3 ft^2
Wing Span	49.05 ft	54 ft	59.95 ft
Horizontal Tail Area	65.7 ft^2	73 ft^2	80.3 ft^2
Horizontal Tail Span	16.51 ft	18.3 ft	20.17 ft
Vertical Tail Area	105.12 ft^2	116.8 ft^2	128.48 ft^2
Vertical Tail Height	7.5 ft	8.33 ft	9.16 ft
Spanwise Engine Location	7.72 ft	8.58 ft	9.44 ft
Aileron Chord*	15.3%	23%	30.7%
Elevator Chord*	35.1%	41%	46.9%
Rudder Chord*	38.4%	44%	49.6%
Wing Sweep	0 deg	4 deg	15 deg

* Given in percent of wing, horizontal tail, or vertical tail chord.

Expected Availability

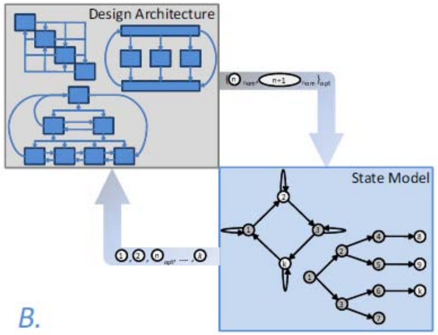
$$E_A = \sum_{m=1}^{M} A(W_M)\frac{T_M}{T} \quad \text{where} \quad A(W_M) = \sum_{G_k \geq W_M} p_k$$

$$E_G = \sum_{k=1}^{K} p_k G_k$$

Expected Performance

$$\begin{aligned}
&\textit{given} \quad \text{parameters, } \mathbf{c} \\
&\textit{minimize} \quad -E_G(\mathbf{x},\mathbf{c}) = -\sum_{k=1}^{K} p_k G(\mathbf{x},\mathbf{c})_k \;\; \textit{or} \;\; -E_A(\mathbf{x},\mathbf{c}) = -\sum_{m=1}^{M} A(W_M)\frac{T_M}{T} \\
&\quad s.t. \quad \mathbf{h}(\mathbf{x},\mathbf{c}) = 0 \\
&\qquad\quad \mathbf{g}(\mathbf{x},\mathbf{c}) = \mathbf{G}_{N,req}/\mathbf{G}_N(\mathbf{x},\mathbf{c}) - 1 \leq 0 \\
&\qquad\quad x_{i,LB} \leq x_i \leq x_{i,UB}
\end{aligned}$$

Agte J., Borer N., de Weck O., "Multistate Design Approach to the Analysis of Performance Robustness for a Twin-Engine Aircraft", *Journal of Aircraft,* 49(3), 781-793, May-June 2012

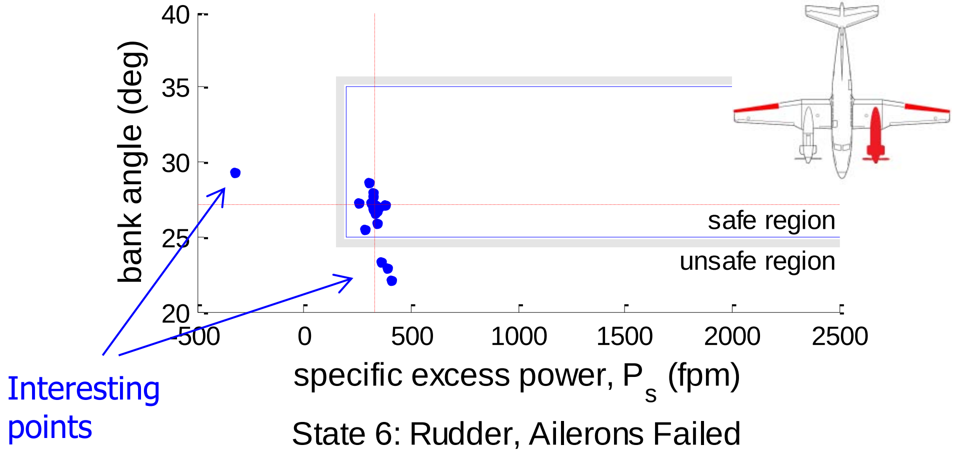


Actual (non-weighted) performance in each Markov state for the 23 geometry cases
Loss if P_s < 200 fpm, bank angle not held within 10 degrees

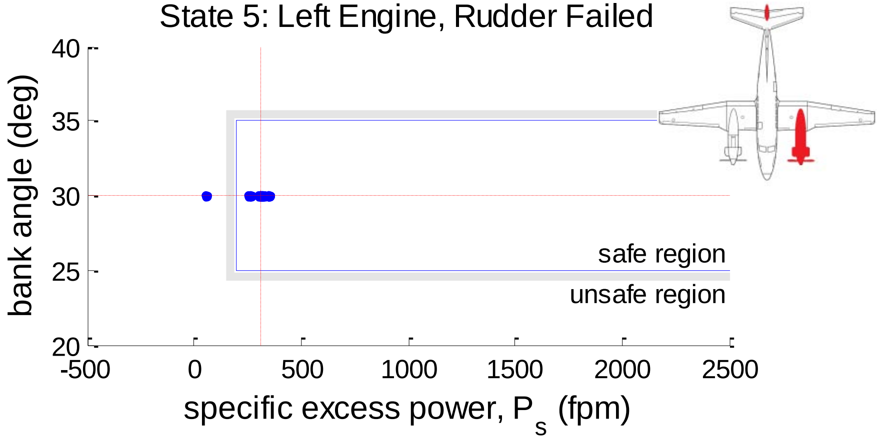
specific excess power, P_s (fpm)

specific excess power, P_s (fpm)

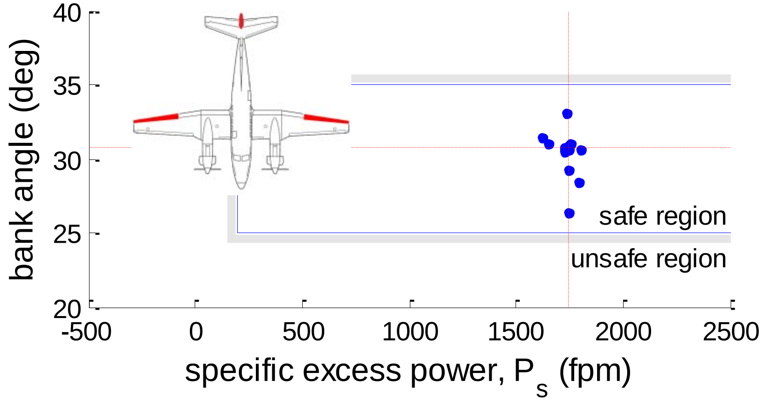
State 4: Left Engine, Ailerons Failed



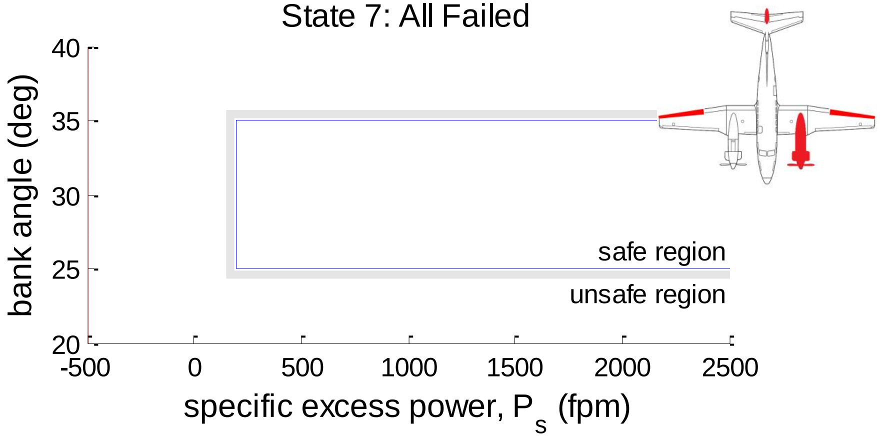
State 5: Left Engine, Rudder Failed



State 6: Rudder, Ailerons Failed



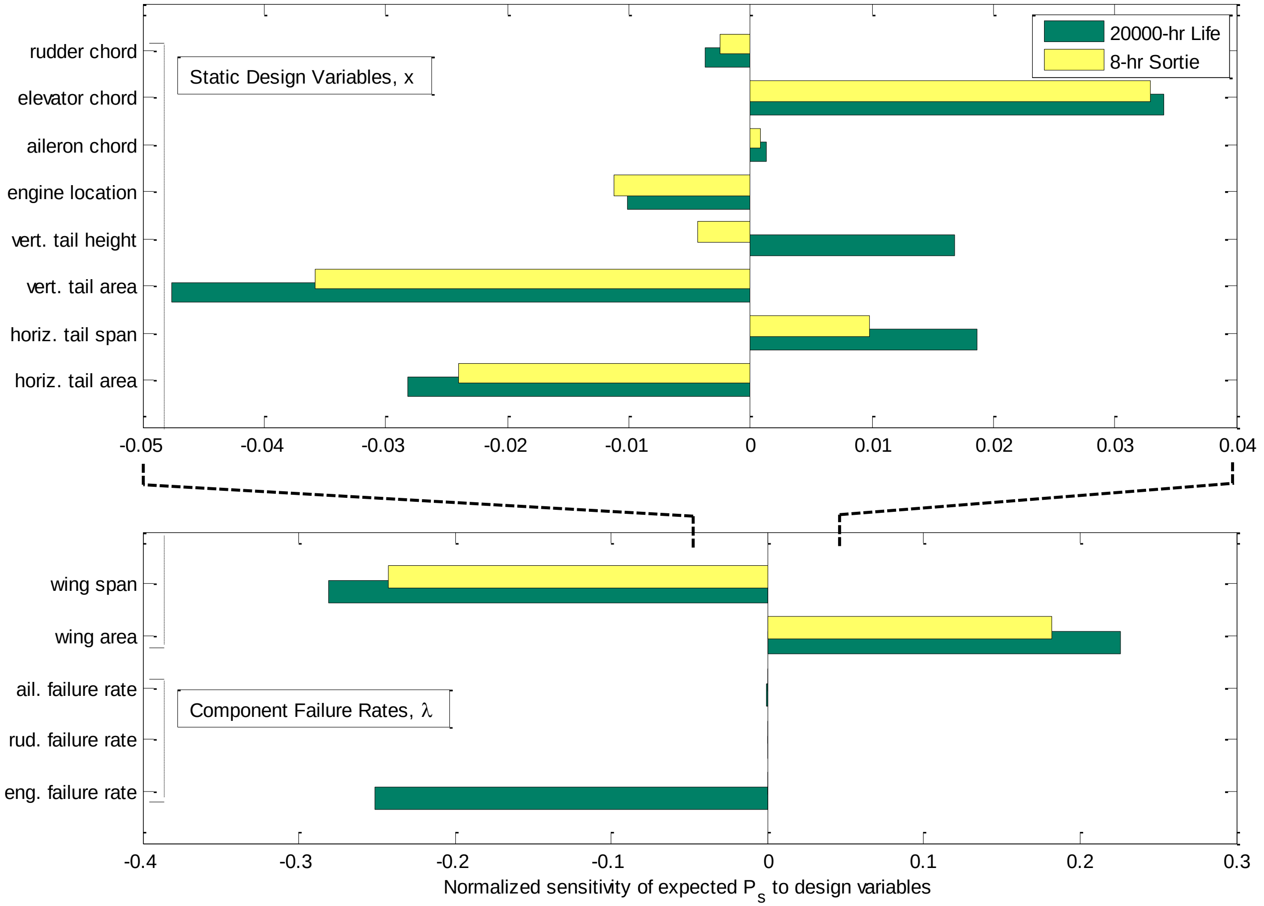
State 7: All Failed

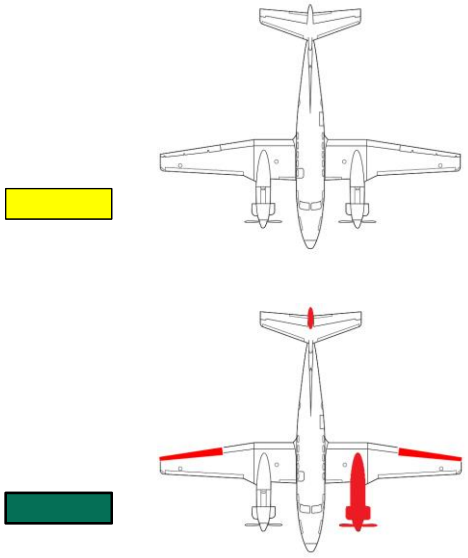


Robustness requires off-nominal design optimization

Key result: aircraft geometry influences long-duration performance robustness more than component failure rates λ_i. Off-nominal control needed.

$$E_G(\mathbf{x}) = \sum_{k=1}^{8} p_k(\mathbf{x}) P_s(\mathbf{x})_k = \sum_{k=1}^{8} p_k(\mathbf{x})[\dot{h}(\mathbf{x}) + \frac{V(\mathbf{x})}{g}\dot{V}(\mathbf{x})]_{avg,k}$$





Design sensitivities when considering only nominal state (yellow) differ from those when considering expected performance across multiple states (green) → guidance towards robustness must include off-nominal states

Outline for Today

- Operational Considerations
- Commissioning
- Research into Operations
  - Reconfigurability and Common Sparing for Mars Missions
  - Designing Systems for Operations in Partially Failed States
- Post-Flight Review (PFR)

Post Flight Assessment Review (PFR)

- Also known as Post Launch Review (PLR)
  - Review telemetry from flight
  - Compare against predictions (e.g. from simulation)
  - Find / repair any failures
  - Secure data for later use
  - Initiate detailed commissioning / handover to operators
- A PFR-like review is part of the 2016 Cansat Competition

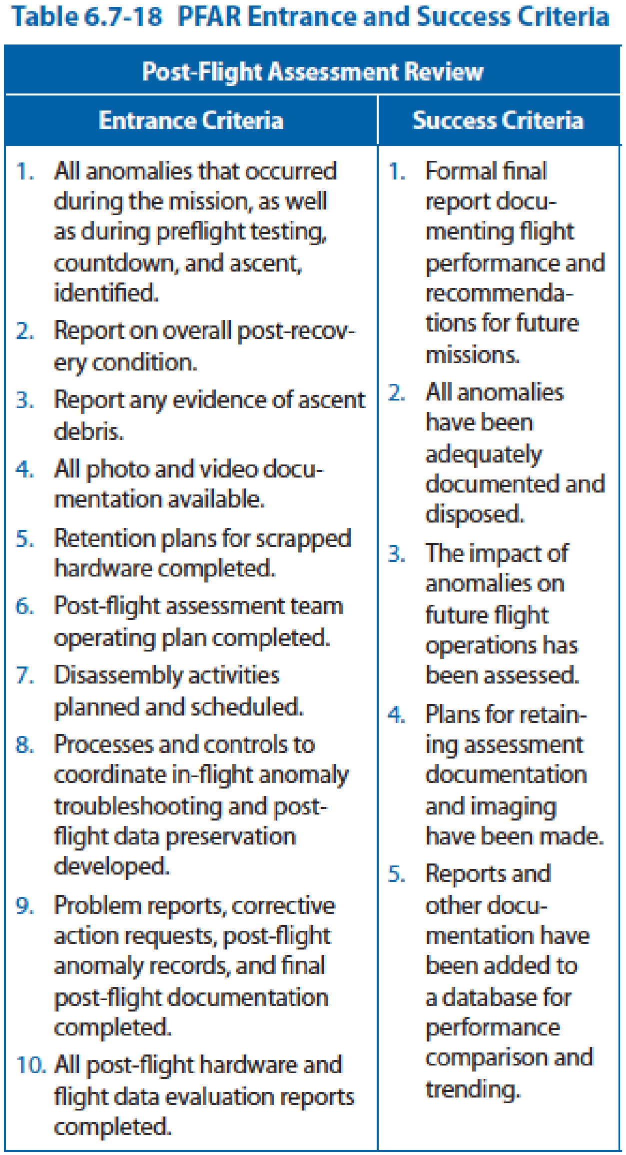


Table 6.7-18 PFAR Entrance and Success Criteria

Post-Flight Assessment Review	
Entrance Criteria	**Success Criteria**
1. All anomalies that occurred during the mission, as well as during preflight testing, countdown, and ascent, identified.	1. Formal final report documenting flight performance and recommendations for future missions.
2. Report on overall post-recovery condition.	2. All anomalies have been adequately documented and disposed.
3. Report any evidence of ascent debris.	3. The impact of anomalies on future flight operations has been assessed.
4. All photo and video documentation available.	4. Plans for retaining assessment documentation and imaging have been made.
5. Retention plans for scrapped hardware completed.	5. Reports and other documentation have been added to a database for performance comparison and trending.
6. Post-flight assessment team operating plan completed.	
7. Disassembly activities planned and scheduled.	
8. Processes and controls to coordinate in-flight anomaly troubleshooting and post-flight data preservation developed.	
9. Problem reports, corrective action requests, post-flight anomaly records, and final post-flight documentation completed.	
10. All post-flight hardware and flight data evaluation reports completed.	

This image is in the public domain.

Summary: Ops Checklist

- System checkout in lab/hangar/field; everything working OK?
- Bring sufficient consumables (batteries, fuel, lubricants etc…), including reserves
- Spare parts and tools to repair
- Other support equipment (remote control, telemetry, cameras …)
- Training operators and support personnel
- Checklist for normal operations and emergency/contingencies
- Transportation logistics (forward and reverse)
- Plan in enough time for commissioning → before operations

Reminders for PDR (next week)

- Check Schedule – be on time
- Upload slide deck beforehand
- 30 min PDR presentation
- Followed by up to 30 min Q&A

Questions?

16.842 Fundamentals of Systems Engineering
Fall 2015