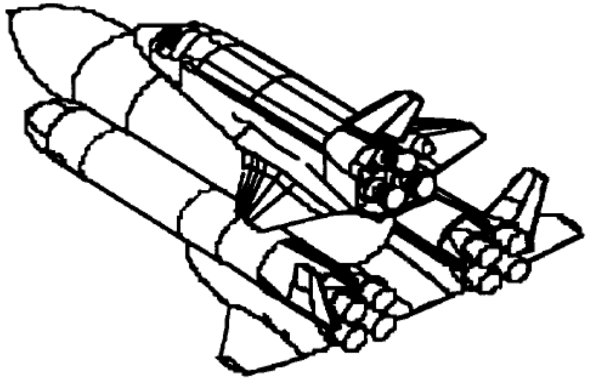
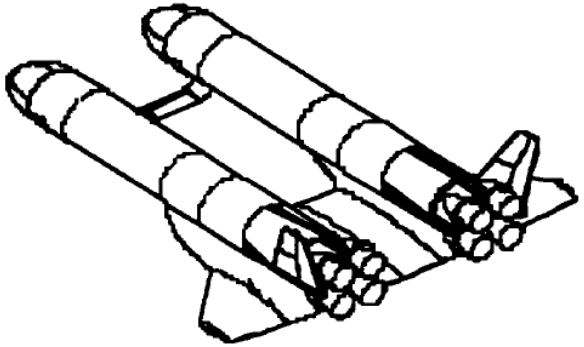




Reusability in NASA Crewed Spaceflight

Dan Dorney
NASA Tech Fellow for Propulsion

Overview

- **Goals of reusability**
- **NASA programs incorporating reusability**
- **Space Shuttle**
- **Launch Services Program**
- **Commercial Crew Program (CCP) and the Falcon 9**
- **Summary**

Goals of Reusability

- **Cost**
  - **Less expensive to re-fly than build new**
- **Reliability**
  - **Greater flight time can help uncover design flaws**
- **Safety**
  - **Inspection of recovered boosters increases knowledge of the systems/components**
- **Increased launch rate**
  - **As inspection criteria/cadences are refined, launch rates can be increased**

A Sample of Reusability in NASA Programs

- Space Transportation System (STS) → Space Shuttle
  - Orbiter, solid rocket booster (SRB) reuse
- Shuttle Growth Study → Late 1970s
  - Flyback boosters
- Advanced Launch System (ALS) → 1987-1990
  - Flexible, modular, heavy-lift, high launch rate
- Liquid Rocket Booster (LRB) → 1987-1989
  - Alternative to solid rocket boosters (SRBs) on the Space Shuttle
- Liquid Fly Back Booster (LFBB) → 1993-1998
  - Liquid propellant Booster Main Engine (BME) for the Space Shuttle
- Constellation/Ares
  - SRB reuse
- Commercial Crew Program (CCP) → Falcon 9 booster

All these programs had the goals of reduced costs and increased launch rates

Space Shuttle

Shuttle Reuse - Background

- The Space Shuttle had ~2.5 million moving parts → complexity is the nemesis of reusability

- All components/systems of the Space Shuttle were designed for reuse except for the External Tank
  - Orbiter
  - Space Shuttle Main Engines (SSMEs)
  - Solid Rocket Boosters (SRBs)

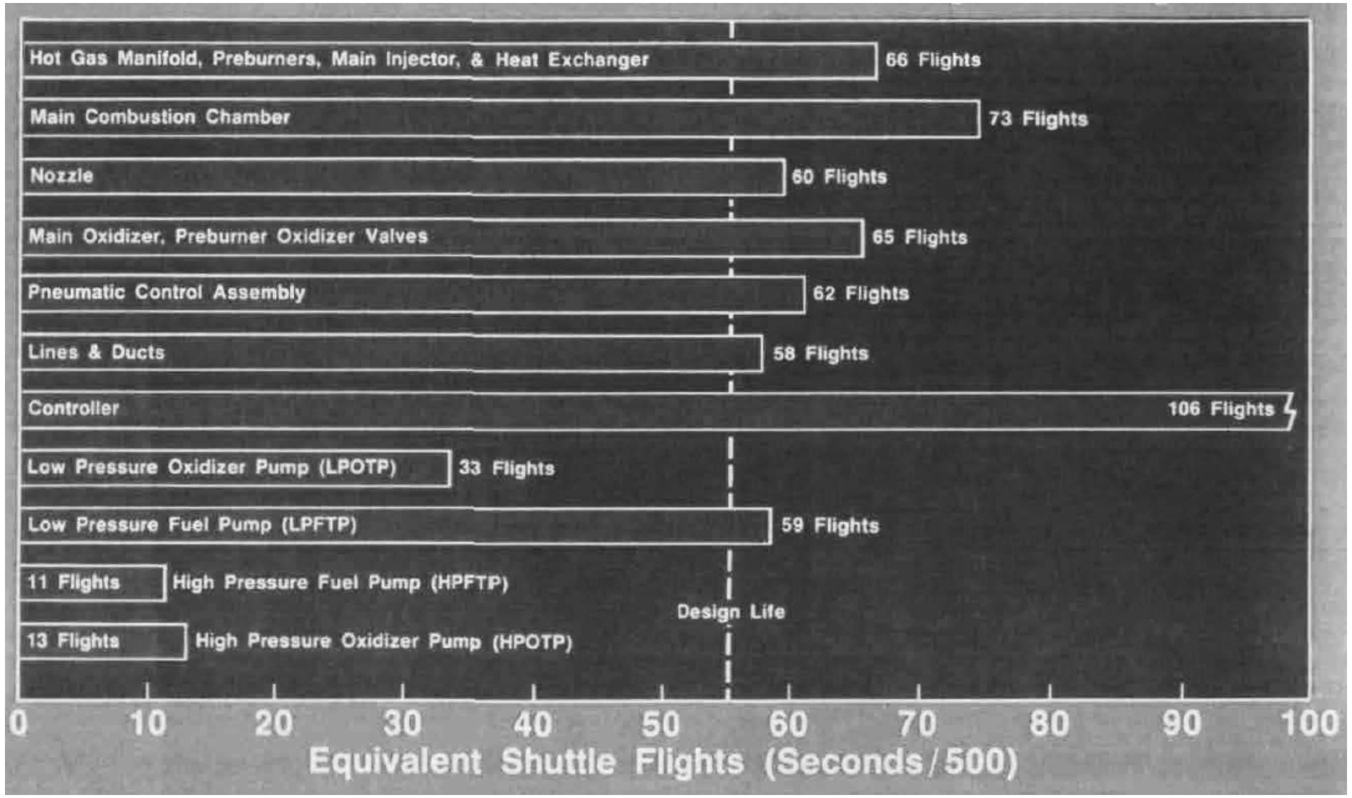
- Space Shuttle turnaround time designed to be two weeks → shortest turnaround time was 55 days

- Many design and construction (D&C) standards were used during Shuttle Program, although some of the NASA D&C standards used today had not been codified. For example,
  - NASA-STD-5012 – Strength & Life Assessment Requirements for Liquid Fueled Space Propulsion System Engines - June 13, 2006
  - NASA-STD-5019 – Fracture Control Requirement for Spaceflight Hardware – January 7, 2008
  - NASA-STD-6016 – Standard Materials & Processes Requirements for Spacecraft – July 11, 2008

- The Shuttle Program implemented the fleet leader approach to mitigate unexpected issues that periodically occurred during flight, despite the use of the D&C standards and testing. The objective of this process for the Space Shuttle SSME was to provide margin for flight against demonstrated life.

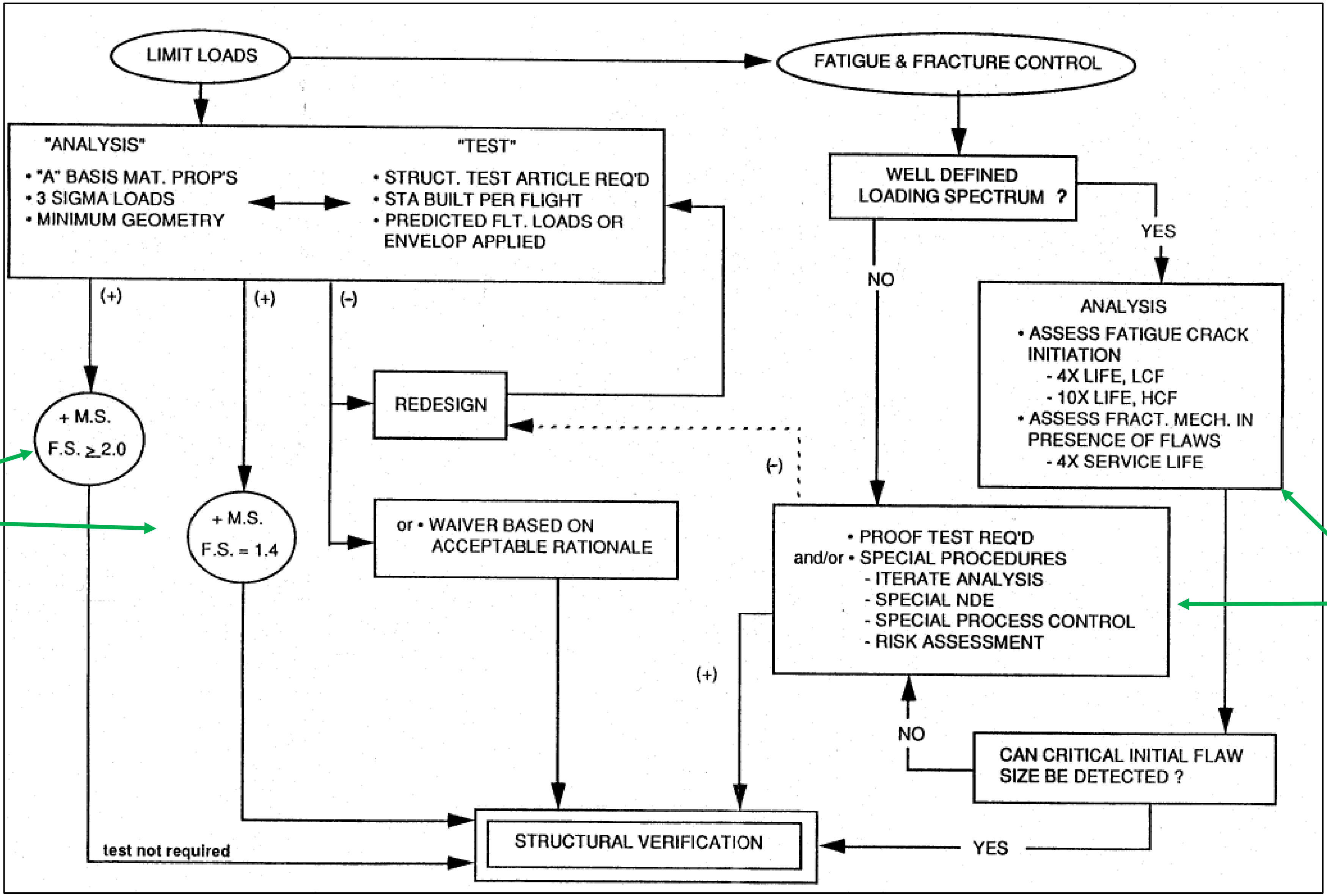
Fleet Leader Concept

- The Shuttle Fleet Leader Program was introduced in 1989 → used to extend system and component life, expand operating limits, and detect, predict, and prevent life-dependent failures before they impacted the fleet
- The use of hardware is governed by the fleet leader in terms of run time and/or starts
- The Shuttle application used a Weibull distribution → $F = 1 - \exp[-(T/\eta)^{\beta}]$ where
  - T = run time or starts
  - F = fraction of parts that will fail by time/starts T
  - η = characteristic life
  - β = distribution shape parameter
- All units used in the estimate of η must be of the same population:
  - Same basic configuration, geometry, etc.
  - Tested in the same environment
- All factors which influence life (ideally) remain constant/consistent from unit to unit



SSME Review to the Aerospace Safety Advisor Panel, Rocketdyne, September 20, 1988.

Design and Reuse of Shuttle Structures



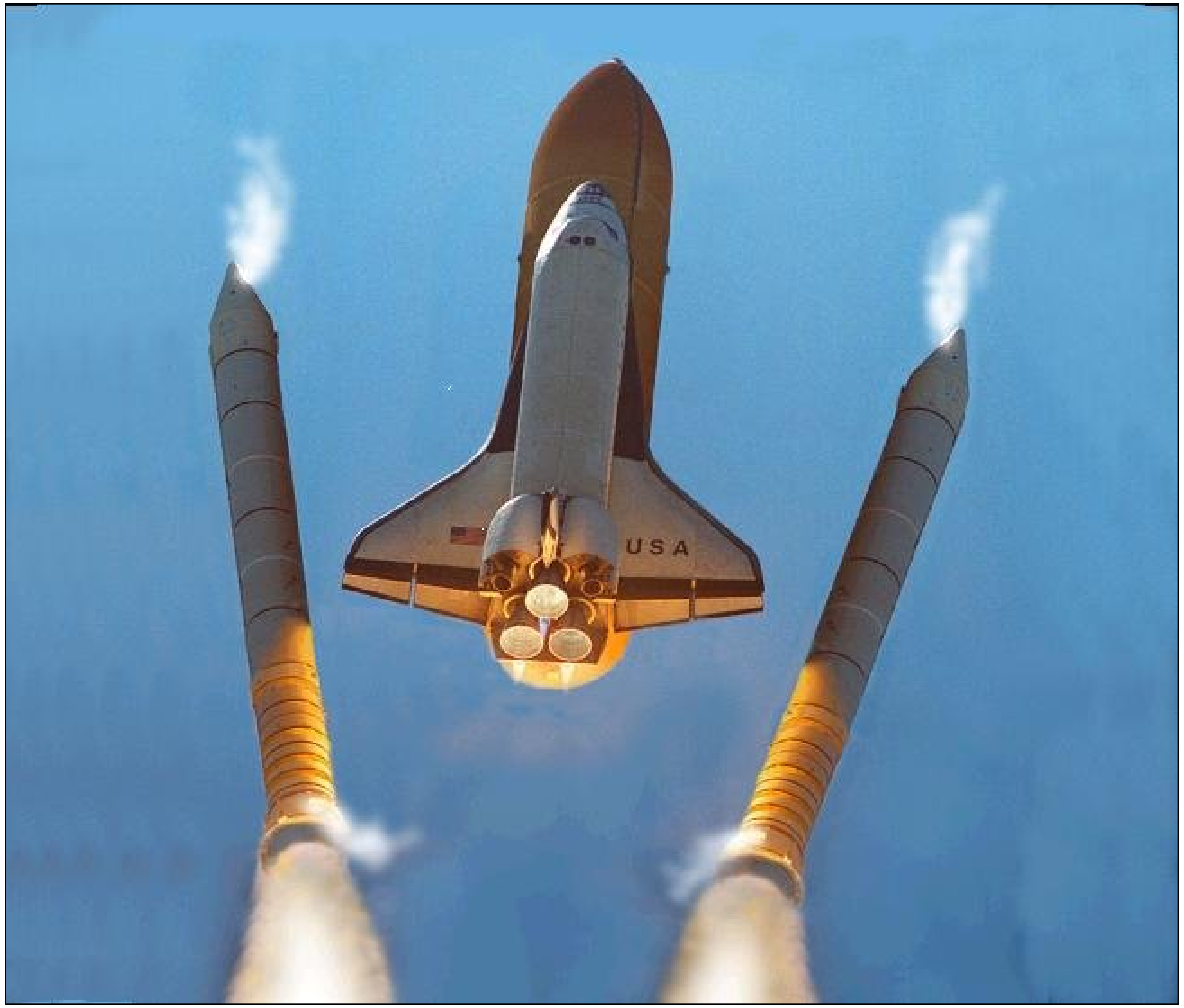
Later part of JSC 65828

Well-defined Process for evaluating structural Components for reuse

Later part of NASA-STD-5012, NASA-STD-5019

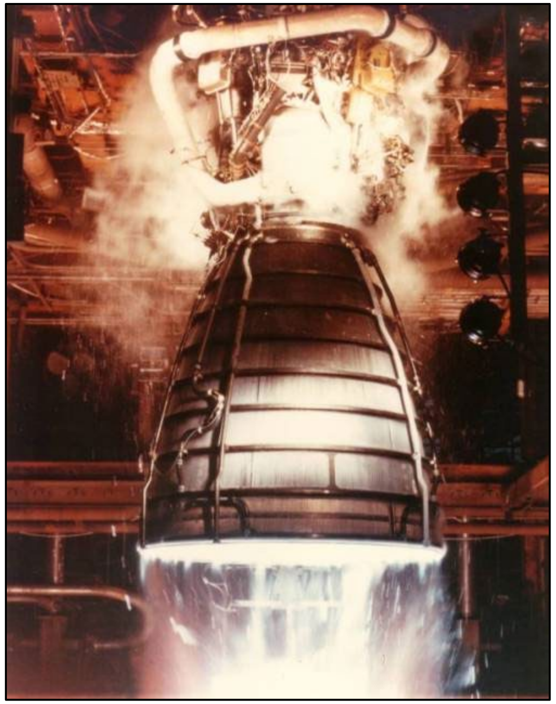
R. Jewell, NASA MSFC, ED21, January 1990

Solid Rocket Motor Minimum Reusability Design Objectives



	Component	Number of Reuses
1.	Case cylindrical segments	19
2.	Case stiffener segments	19
3.	Case attach segments	19
4.	Case forward and aft closures	19
5.	Case stiffener rings	19
6.	Stiffener ring attach fasteners	TBD
7.	Case clevis joint pins	19
8.	Nozzle metal parts	19
9.	Nozzle flex seal reinforcement shims and end mounting rings	19
10.	Nozzle flex seal assembly	9
11.	Nozzle boss attach bolts	19
12.	S&A device	19
13.	Igniter chamber	19
14.	Igniter adapter	19
15.	Chamber pressure transducers	19
16.	Igniter port special bolts (for mounting chamber pressure monitoring operational pressure transducers (OPTs))	5
17.	Pin retainer band	TBD

Design Data Book for Space Shuttle Redesigned Solid Rocket Motor (RSRM), Morton Thiokol, Inc., TWR-16881.



SSME Reusability

- The Space Shuttle Main Engine (SSME) was designed for performance, not reusability → higher performance normally equates to more complexity and failure modes

- The SSME was relatively heavy because of the need for robust structures and thermal protection to survive harsh reentry environments (for reuse)

- Reuse of SSME components based on the fleet leader concept

- After each flight the SSMEs were removed for maintenance → required more than 20,000 hours of direct and indirect labor (~2 months) to service the engines
  - Originally, the SSMEs were left on the Orbiter for maintenance, but operational impacts and relative ease of SSME removal made it more effective to take the SSMEs offline for maintenance

Childress-Thompson, R. and Thomas, D., A Framework for Assessing the Reusability of Hardware (Reusable Rocket Engines), JANNAF 9th Liquid Propulsion Meeting/8th Spacecraft Propulsion Meeting, Phoenix, AZ, December 5-8, 2016.

Aging Orbiter Lessons Learned

- After about 10 years of service an increased frequency of corrosion related issues led to the formation of the Corrosion Control Review Board (CCRB).
  - The lessons learned from the CCRB are documented in 4 volumes of reports. The main areas of concerns documented are:
    - Galvanic barriers
    - Development and training of inspection techniques
    - Use of Corrosion Preventative Compounds (CPCs)
    - Cleanliness/Washing Exposed surfaces
    - Depainting/repainting intervals
    - Development of NDE
    - Electrical bonding techniques
    - Proper Drainage
- Other lessons learned from reuse are the early development of Standard Repair Procedures and Fair, Wear and Tear criteria.
- Hardware inspection and replacement cycles need to be developed based on age life as well as time and cycle requirements.
  - These intervals may need to be adjusted based on inspection results.

The lessons learned were shared with commercial partners early in the development of the CCP vehicles and to date the number of aging/corrosion related issues has been minimal. However, there are certain areas that need to be followed closely with the possibility of additional test and inspections introduced.

Orbiter Maintenance Requirements

- Subsystem maintenance and testing was based on component and function criticality
- Critical maintenance was performed every flow
  - Critical components and functions tested, and limited life items replaced
- Less critical maintenance was conducted on intervals depending on subsystem requirements
  - Typical intervals were every other flight; every third flight; every fifth flight; or every tenth flight.
  - Additional time in the processing schedule was added to accommodate those interval requirements.
- With experience the program created Orbiter Maintenance Down Periods where periodic, designated maintenance periods were set aside for many interval requirements to be combined and worked in one flow.

Shuttle Costs and Launch Rate

- Costs (derived from several sources)
  - Payload to LEO → 27,500 kg
  - Average cost per flight → $1.4B
  - Actual cost to LEO → ~$43,650/kg
  - 1972 estimated cost to LEO (2012 $) → ~$2400/kg

- Launch rate
  - Peak launch rate → 9/yr
  - Average launch rate → ~4.5/year
  - 1982 estimated launch rate – 24/year

- Estimated costs and launch rate not achieved but significant knowledge gained that has informed subsequent programs

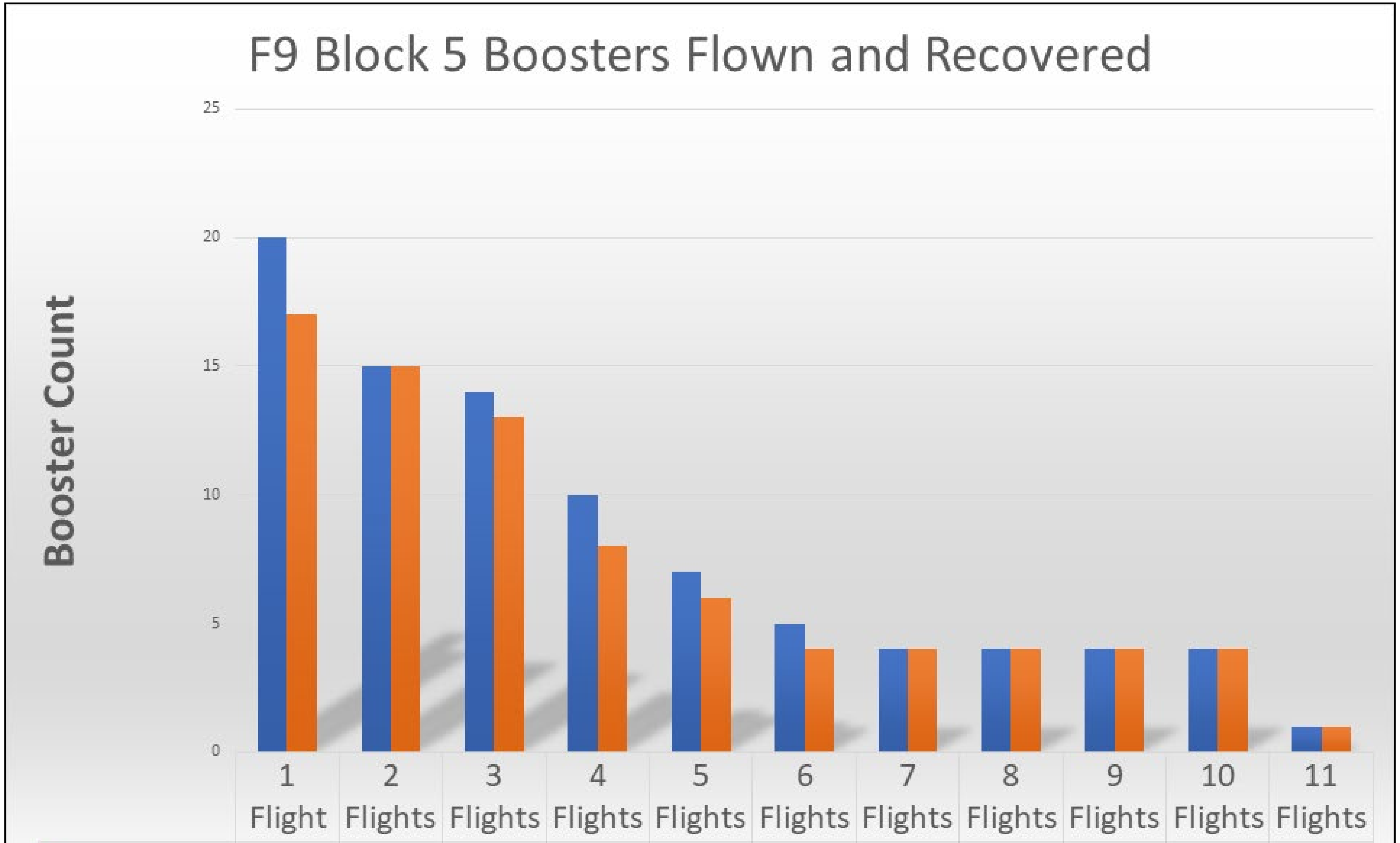
Launch Services Program

Launch Services Program (LSP)

- LSP collects fleet data for NASA and provides assessments of booster reuse
- The LSP reuse assessment focuses on independently verifying the qualified service life of flight critical components and ensuring the reuse processes and IT systems are robust and capable.
- LSP has accepted Falcon 9 booster reflight within qualified hardware service life
  - IXPE and DART utilized reused boosters

Sentinel 6-MF launch and landing. Photo: SpaceX

Falcon 9 Fleet Recoveries as of 2/1/22



	1 Flight	2 Flights	3 Flights	4 Flights	5 Flights	6 Flights	7 Flights	8 Flights	9 Flights	10 Flights	11 Flights
Flights	20	15	14	10	7	5	4	4	4	4	1
Recoveries	17	15	13	8	6	4	4	4	4	4	1

LSP Approach

- Expanding capability of an existing certified launch vehicle
  - Reuse was assessed similarly to any other component that is expanding its capability, just a much larger scope (i.e., not a formal NASA certification effort per NPD 8610.7)
- Use a phased approach that first allowed reuse on more risk tolerant missions (e.g., missions flying on Cat 1 or 2 LVs and non-planetary)
- Fleet Leader methodology acceptable to expand qualified service life → fleet leader here refers to life leader and is different from Shuttle
- Reflight on a LSP mission should not pose any increase in baseline risk
  - Will not fly fleet leaders
  - Hardware expected to be qualified for the entirety of its service life
  - Verification that processes and systems are robust and able to track reused components including service life expended
- Ascent is mandatory – entry, descent and landing(EDL) are optional
- Standard LSP processes for assessing design changes, process changes, first flight items, anomalies, etc., have not changed

Standards/Requirements/Processes

- LSP does not assess to any particular government reuse standard or NASA design and construction standards
  - None levied as requirements on LSP Commercial NASA Launch Services (NLS) contracts
  - Review Launch Service Contractors internal documentation for compliance and adequacy.
  - IXPE and DART contractual language added which required NASA LSP approval of any changes to reuse processes

LSP Recurring Work

- Standard LSP fleet insight and assessment processes used for recurring work on reuse missions.
  - Pedigree reviews (nonconformances, acceptance test data, work orders, inspections, etc.)
  - Engineering Review Boards (ERBs) on technical problems
  - First flight/first use assessments
  - Qualified service life expansion assessments
  - Surveillance of refurbishment and inspections
  - Fleet insight
  - Assessment/verification of changes to reuse processes and IT systems

Commercial Crew Program (CCP)
Falcon 9

CCP Approach to Launch Vehicle Reusability

- **The Falcon 9 booster must still meet all CCP design and construction (D&C) standard requirements**

- **Perform review for at least 1X reuse, and identify any gaps or constraints needed for additional flights**

- **Document and recommend reuse certification closure for any hardware >1X reuse if sufficient evidence is supplied → approximately 30% of the design units have been approved for >1X reuse**

- **CCP LV Engineering prefers only 1X reuse (2 total flights) for the Falcon 9 booster**
  - **1X reuse certification through the Crew-3 mission → now reviewing 5x reuse**
  - **Crew-4 (~4/2022) will use a multiple-reuse booster**

- **Fleet leader logic has been proposed in certain cases to develop specific reuse criteria for specific hardware**
  - **Being used for turbine wheels**

- **Any new changes, risks, fleet anomalies, nonconformances, etc., will follow the same process for CCP review and disposition**

Butt, A., Ruggles, R., and Vega, K., SpaceX Booster Reuse Certification Beyond 2X - Falcon 9 Reuse, Life Assessments, CCP ERB-21-00977, March 2, 2020.

CCP Design and Construction Standards - I

Document Number	Revision	Title and CCT-REQ-1130 Requirement	CCT-STD-1140 Reference	CCT-STD-1140 Description
20M02540	Rev. E	*Assessment of Flexible Lines for Flow-Induced Vibration* (R.CTS.303)	7.5.2	Fluid Systems
ANSI/ESD S20.20	Edition 07	*For the Development of an Electronic Discharge Control Program for Protection of Electrical and Electronic Parts, Assemblies and Equipment (Excluding Electrically Initiated Explosive Devices)* (R.CTS.286)	7.1.8.2 7.2.2	Avionics and Electrical Systems EEE Parts Management
FAA AC 20-136A	Rev. A	*Aircraft Electrical and Electronic System Lightning Protection* (R.CTS.290)	7.1.7.2	Avionics and Electrical Systems
GEIA-STD-0005-1	Baseline	*Performance Standard for Aerospace and High Performance Electronic Systems Containing Lead-Free Solder* (R.CTS.277)	7.1.5.2	Printed Wiring Boards Technical Assessment
GEIA-STD-0005-2	Baseline	*Standard for Mitigating the Effects of Tin Whiskers in Aerospace and High Performance Electronics* (R.CTS.278)	7.2.2	EEE Parts Management
IEC 61000-4-2	Edition 2.0	*Electromagnetic Compatibility (EMC) Testing and Measurement Techniques-Electrostatic Discharge Immunity Test for Human Body Model (HBM) Subassemblies, Assemblies and Equipment Discharge Levels* (R.CTS.371)	7.1.8	Electrostatic Controls

Document Number	Revision	Title and CCT-REQ-1130 Requirement	CCT-STD-1140 Reference	CCT-STD-1140 Description
IPC J-STD-001E	Rev. E	*Requirements for Soldered Electrical and Electronic Assemblies* (R.CTS.275 and R.CTS.276)	7.1.5.2	Avionics and Electrical Systems
IPC J-STD-001ES Amendment 1		*Space Applications Electronic Hardware Addendum to J-STD-001E, Requirements for Soldered Electrical and Electronic Assemblies* (R.CTS.275 and R.CTS.276)	7.1.5.2	Avionics and Electrical Systems
IPC-2152	Baseline	*Standard for Determining Current Carrying Capacity in Printed Circuit Board Design* (R.CTS.270)	7.1.5.2	Avionics and Electrical Systems
IPC-2220 Series	2221: A 2222: A 2223: B 2224: BL 2225: BL 2226: BL	*Family of Printed Board Design Documents* (R.CTS.268)	7.1.5.2	Avionics and Electrical Systems
IPC-6010 Series	6011: BL 6012: C 6013: B 6015: BL 6016: BL 6017: BL 6018: A	*Family of Printed Board Performance Documents* (R.CTS.269)	7.1.5.2	Avionics and Electrical Systems
IPC-CM-770E	Rev. E (1/1/04)	*Component Mounting Guidelines for Printed Boards* (R.CTS.284)	7.1.5.2	Avionics and Electrical Systems
JSC 20793	Rev. B	*Crewed Space Vehicle Battery Safety Requirements* (R.CTS.282)	7.1.4	Avionics and Electrical Systems
JSC 62809	Rev. D	*Human-Rated Spacecraft Pyrotechnic Specification* (R.CTS.294)	7.1.3 7.3.2	Interconnecting Cable and Harnesses Pyrotechnics
JSC 65827	Baseline	*Thermal Protection System Design Standard for Spacecraft* (R.CTS.293)	7.4.3.1	Thermal Protection Systems

Document Number	Revision	Title and CCT-REQ-1130 Requirement	CCT-STD-1140 Reference	CCT-STD-1140 Description
JSC 65828	Rev. A	*Structural Design Requirements and Factors of Safety for Spaceflight Hardware* (R.CTS.295)	7.4.3.1 7.4.1 7.5.2 7.6.2	Thermal Protection Systems Structures Fluid Systems Propulsion Systems
JSC 65829	Baseline	*Loads and Structural Dynamics Requirements for Spaceflight Hardware* (R.CTS.297)	5.2.2 5.3.1 5.3.2 7.5.2 7.6.2	Structural Dynamics Int. Vehicle Dynamics Fluid Systems Propulsion Systems
JSC 65985	Rev. A	*Requirements for Human Spaceflight for the Trailing Deployable Aerodynamic Decelerator (TDAD)* (R.CTS.291)	7.7.2	Trailing Deployable Aerodynamic Decelerator
MIL-STD-461	Rev. F	*Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment* (R.CTS.287)	7.1.6.2	Avionics and Electrical Systems
MIL-STD-464	Rev. C	*Electromagnetic Environmental Effects Requirements for Systems* (R.CTS.288)	7.1.6.2	Avionics and Electrical Systems
MIL-STD-981	Rev. C	*Design, Manufacturing and Quality Standards for Custom Electromagnetic Devices for Space Applications* (R.CTS.289)	7.1.6.2	Avionics and Electrical Systems
NASA-STD-4003	Baseline	*Electrical Bonding For NASA Launch Vehicles, Spacecraft, Payloads, and Flight Equipment* (R.CTS.281)	7.1.9.1	Avionics and Electrical Systems
NASA-STD-4005	Baseline	*Low Earth Orbit Spacecraft Charging Design Standard* (R.CTS.285)	7.1.10	Avionics and Electrical Systems

- These D&C standards are on contract with the commercial partners
- The standards (meet/meet intent) are contained in CCT-STD-1140

CCP Design and Construction Standards - II

Document Number	Revision	Title and CCT-REQ-1130 Requirement	CCT-STD-1140 Reference	CCT-STD-1140 Description
NASA-STD-5012	Baseline	*Strength and Life Assessment Requirements for Liquid Fueled Space Propulsion System Engines* (R.CTS.304)	7.4 7.6.2	Structures Propulsion Systems
NASA-STD-5017	Baseline	*Design and Development Requirements for Mechanisms* (R.CTS.292)	7.3 7.5.2	Mechanisms Fluid Systems
NASA-STD-5018	Baseline	*Strength Design and Verification Criteria for Glass, Ceramics, and Windows in Human Spaceflight Applications* (R.CTS.296)	7.4	Structures
NASA-STD-5019	Baseline	*Fracture Control Requirements for Space Flight* (R.CTS.307)	7.4 7.5.2 7.6.2 8.1	Structures Fluid Systems Propulsion Systems Fracture Control
NASA-STD-5020	BL (3/12/12)	*Requirements for Threaded Fastening Systems in Spaceflight Hardware* (R.CTS.298)	7.4	Structures
NASA-STD-6016	Baseline	*Standard Materials and Processes Requirements for Spacecraft* (R.CTS.260)	7.4.4 7.5.1 7.6.2 8.2	Structures Fluids Propulsion TDAD Materials and Processes
NASA-STD-7009		*Standard for Models and Simulations*	5.1.1 5.2.3 9.1.3	Models and Simulations Structures Software
NASA-STD-8739.1	Rev. A, change 2	*Workmanship Standard for Polymeric Application on Electronic Assemblies Wiring Boards and Electronic Assemblies* (R.CTS.274 and R.CTS.283)	7.1.5.2	Avionics and Electrical Systems
NASA-STD-8739.4	Rev. R, change 6	*Crimping, Interconnecting Cables, Harnesses, and Wiring* (R.CTS.313 and R.CTS.279)	7.1.3	Avionics and Electrical Systems

Document Number	Revision	Title and CCT-REQ-1130 Requirement	CCT-STD-1140 Reference	CCT-STD-1140 Description
NASA-STD-8739.5	Rev. R, change 2	*Fiber Optic Terminations, Cable Assemblies, and Installation* (R.CTS.273)	7.1.3	Avionics and Electrical Systems
NPR 7150.2A	Rev. A (11/19/09)	*NASA Software Engineering Requirements* (R.CTS.262)	9.1	Flight and Ground Software
SAE ARP 5412A	Rev. A	*Aircraft Lightning Environment and Related Test Waveforms* (R.CTS.290)	7.1.7.2	Avionics and Electrical Systems
SAE ARP 5414A	Rev. A	*Aircraft Lightning Zoning* (R.CTS.290)	7.1.7.2	Avionics and Electrical Systems
SAE ARP 5577	Basic	*Aircraft Lightning Direct Effects Certification* (R.CTS.290)	7.1.7.2	Avionics and Electrical Systems
SMC Standard SMC-S-016 (2008)		*Test Requirements for Launch, Upper-Stage, and Space Vehicles* (R.CTS.315)	5.6.2 7.1.2 7.3.1.2 7.5.2 7.6.2	Thermal Control Analysis Avionics Mechanisms Fluid Systems Propulsion Systems
SMC Standard SMC-S-010	Baseline	*Space and Missile Systems Center Standard, Parts, Materials, and Processes Technical Requirements for Space and Launch Vehicles* (R.CTS.319)	7.2.1	EEE Parts Management

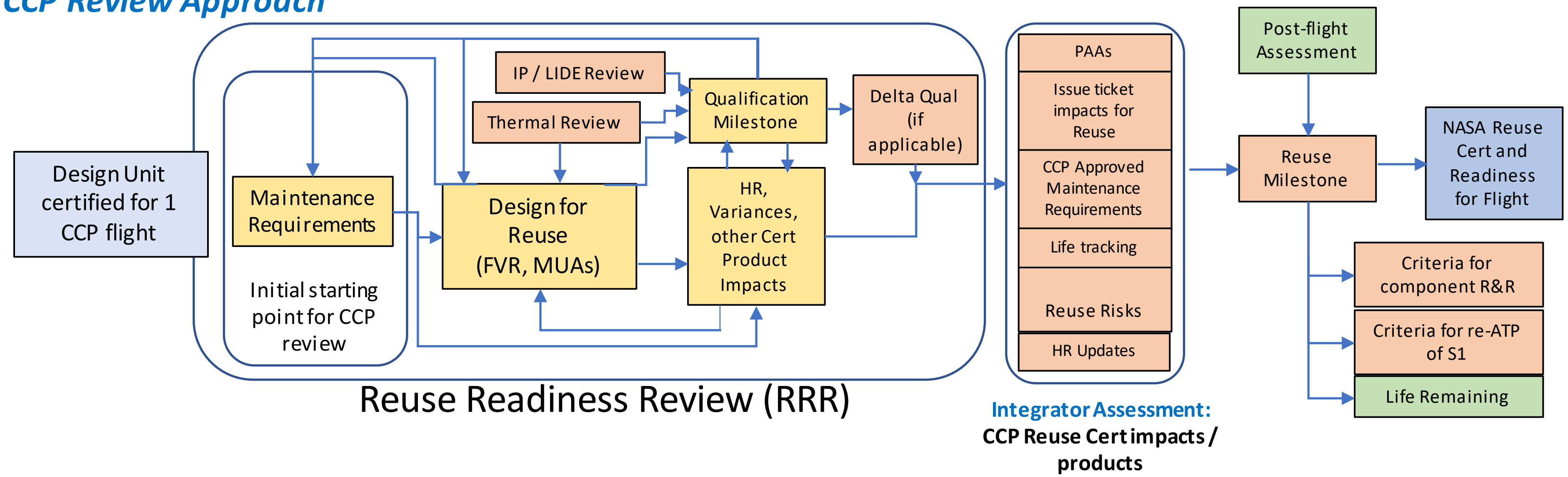
CCP Reusability – LV Ground Rules and Assumptions

- **Assess LV booster for multiple flights**
  - Engine Certified Service Life will be updated
- **Will use a booster flown on a previous CCP or CRS mission**
- **Will not fly fleet leader hardware**
- **Landing the booster successfully is not a requirement**
  - Priority ratings of components shouldn't change
  - Minimal changes to hazard reports
  - Recovery hardware will not be subject to fault tolerance requirements
- **Booster will have product assurance activities (PAAs) performed**
  - Existing PAAs and additional ones for reuse
- **LSP requirements will be used as a starting point for CCP reuse baseline**
- **Design changes will go through the same review process as for a first flight**
- **First flight and refurbishment issue tickets will be reviewed by CCP**
  - Combination of current Materials Review Board (MRB) and LSP processes
- **All risk tickets will be reviewed and dispositioned by CCP**
- **Will not use a booster that has landed in the water**
- **Booster must have a nominal landing**
  - Includes boosters landing on barges
- **Assume no failures of hardware or qualification exceedances on initial flight**
- **Identify a backup booster as a contingency**

Butt, A., Ruggles, R., and Vega, K., SpaceX Booster Reuse Certification Beyond 2X - Falcon 9 Reuse, Life Assessments, CCP ERB-21-00977, March 2, 2020.

CCP Approach to Reusability – Crew-2

CCP Review Approach



Individual Reviews

- Initial Maintenance Requirements
- FVRs/MUAs
- Variances
- Hazard Reports
- Qual
- Nonconformances (CoFR)
- Other products – CCP risks

Integrator Assessment:

- Final Maintenance Requirements
- PAA impacts
- Integrated Performance life assessment
- Gap assessment if agreements aren't reached with the commercial provider:
  - Recommendations for baseline
  - Risk(s) if no change

FVR – Final Verification Review
MUA – Material Usage Agreement
PAA – Product Assurance Action
ATP - Acceptance Testing Program
CoFR – Certification of Flight Readiness
HR – Hazard Report
IP – Integrated Performance
LIDE - Loads and Induced Dynamic Environments

Schrock, K. and Whittaker, J., F9 Booster Reuse – Maintenance Timeline Proposal, CCP ERB-20-0317, September 11, 2020.

F9 Costs and Launch Rate

- Costs (derived from several sources)
  - Payload to LEO
    - ~22,800 kg (booster expended)
    - ~15,600 kg (booster recovered)
  - Average cost per flight
    - New Falcon 9 booster → ~$65m
    - Reused Falcon 9 booster → ~$50M
  - Actual cost to LEO
    - New booster, booster expended → ~$2850/kg
    - New booster, booster recovered → ~$4200/kg
    - Reused booster, booster expended → ~$2200/kg
    - Reused booster, booster recovered → ~$3200/kg

- Launch rate (included crewed and uncrewed)
  - Peak launch rate → 31/yr
  - Average launch rate → 22/yr (last 4 years)

Summary

- **Reusability has been a recurring theme in NASA crewed spaceflight programs**
- **Reusability has evolved over the past 50 years**
- **The costs and launch rates of reusable launch vehicles are starting to meet the intended goals**