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Mission Assurance for Reusable Launch Vehicles

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Introduction

- USSF has aggressively pursued reusability to achieve cost savings for National Security Space (NSS) launches, to enable greater flexibility in operations, & aid in unexpected manifest changes
- Increased reliability through post-flight inspections/ analysis
- Improved cycle time between launches and increased responsiveness
- NSSL missions since Broad Area Review have been 100% successful; need to maintain this reliability with reuse: 10-year Broad Area Review estimated launch Mission Assurance (MA) cost is 2-5% of the stack

Potential cost savings, turn-around time from launch to launch decreased and responsiveness increased

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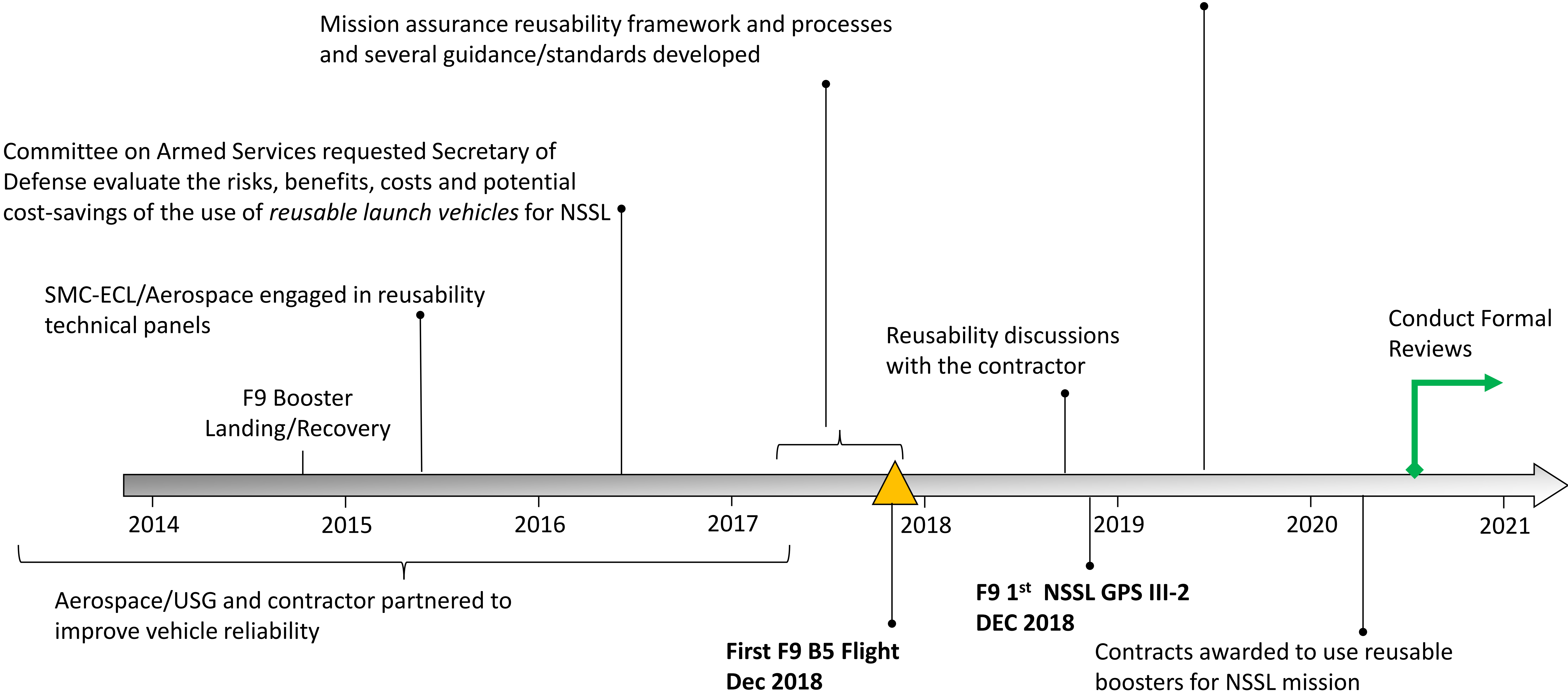
Reusability Timeline



Extensive collaboration between industry partners led to improved reliability and set foundation for USSF *reusability*

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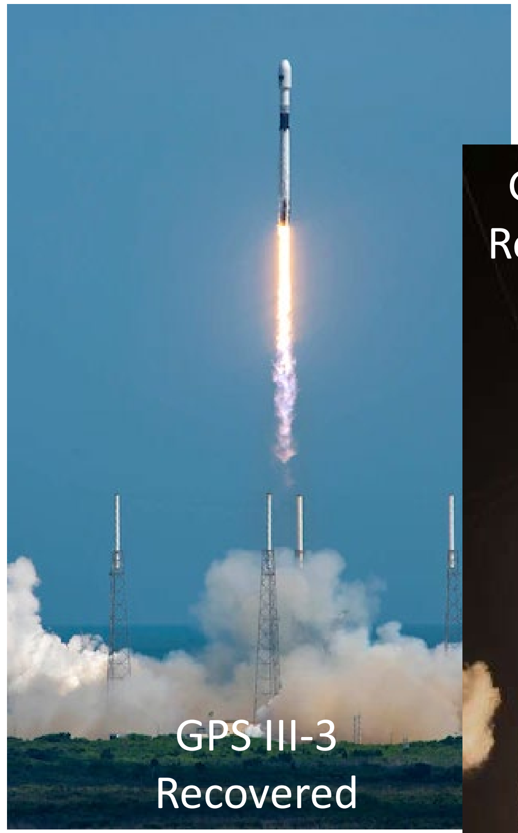
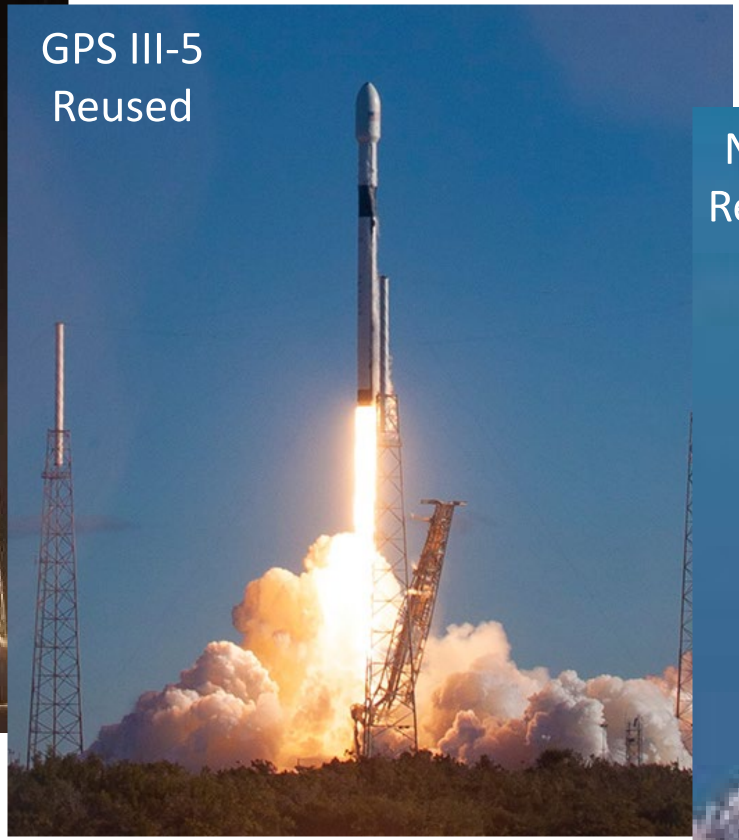
Accomplishments





Next… plan is to fly a F9 Heavy, then reuse side boosters for the following two F9 Heavy missions

Turn-around time from launch to launch decreased and responsiveness increased; potential for cost savings

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Accomplishments

- Aerospace and USSF started to develop the framework for reusability in 2016:
  - Potentially reduce cost of launch
  - Improved cycle time between launches and increased responsiveness
  - Established compliance documents/standards and NRDV process
  - Mission risk and reliability consistent with expendable vehicles

- Aerospace and USSF conducted Non-Recurring Design Validation (NRDV) to evaluate reuse
  - Completed all NRDV Review Boards (Stage 1, Engines, Avionics, …) for single stick
  - Completed all NRDV Review Boards (Stage 1, Engines, Avionics, …) for single Heavy

- NRBs resulted in acceptable risk for up to N flights

Reuse enables potentially lower cost and increased responsiveness while maintaining the same rigorous MA process to enable successful NSSL launches

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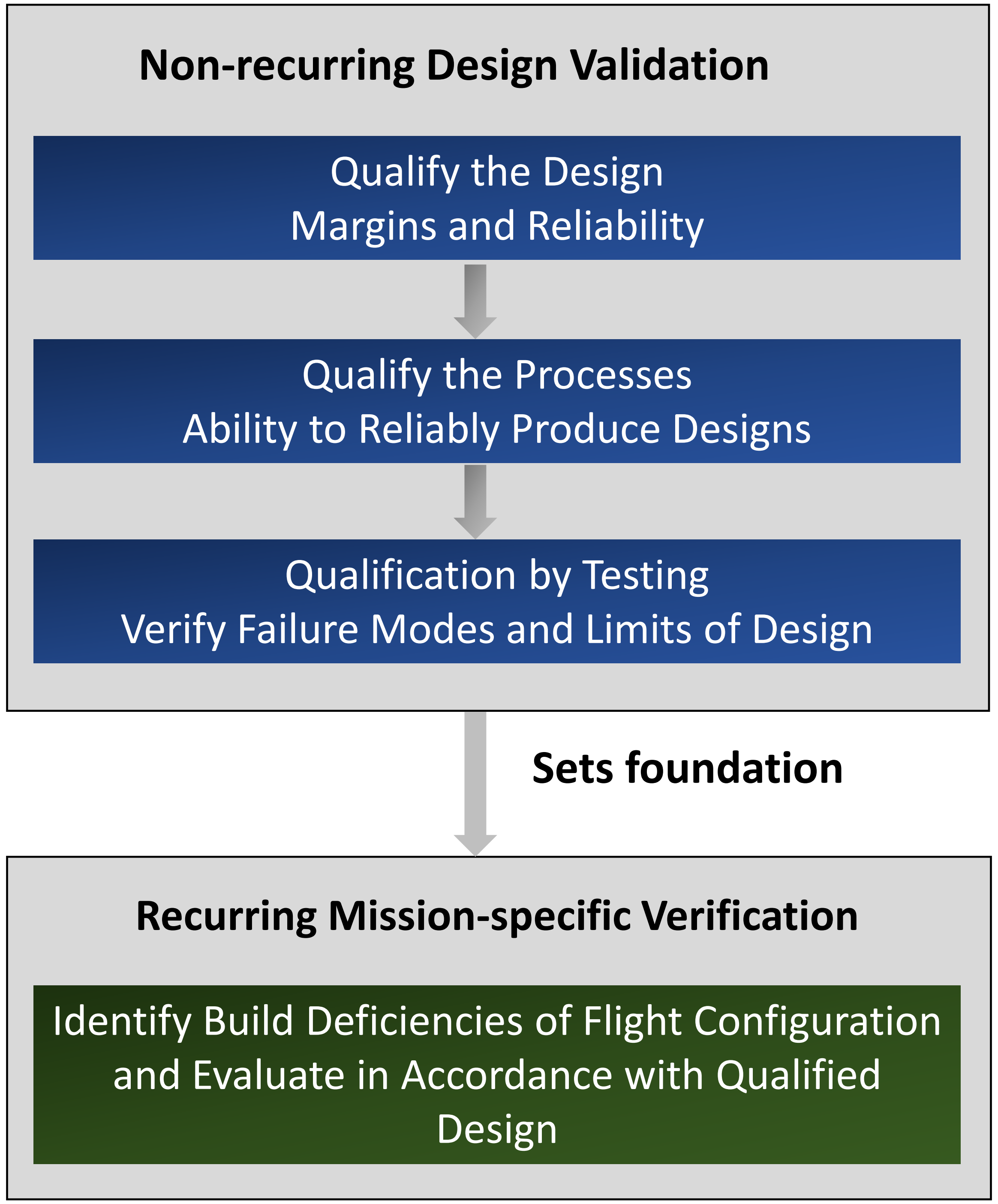
Approach for Reusability



Enablers to Tackle NRDV

- Standards, guide, and command media
- Verification and validation
- Qualification testing and anomaly resolution
- Qualification of the manufacturing process
- Qualification of inspection processes
- Analytical design margins
- Characterization of launch environments
- Formulation of acceptance testing
- Failure modes effects and analysis
- Qualification of launch parameters

Enablers to Tackle RV

- Build verification
- Evaluation of discrepant conditions
- Analysis of inspection and acceptance data
- Review of repairs and refurbishment
- Flight and post-flight support

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USSF Guidance & Compliance Docs

- Three documents generated for NSSL Phase 2 Launch Service contracts provide a guidance document and compliance documents that serve the basis for reusability
  - LE-S-010: Supplemental Requirements for Reusable Launch Systems
  - LE-T-013: Dynamic Environments Tailoring and Guidance to SMC-S-016 for Expendable and Reusable Launch Vehicles
  - LE-P-018: Guide for Reusable Launch Systems

- AIAA, SMC, NASA standards tackling structures, propulsion, avionics, etc.

- Assessment of contractor's command media against compliance and guidance documents & Independent Verification and Validation of data products are performed to establish flight risk
  - Alternate approaches are evaluated to enable flexibility through command media mapping and evaluation
  - Develop risk assessment and low-cost solutions that are low-risk or better
  - Focus on contractor's methodologies, then determine whether methodologies were applied correctly
    - Testing (qualification and acceptance), analysis, inspections, NDE methodology…

Reusability Guidance and Compliance Documents formed the basis for NRDV

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Key Aspects of LE-P-018: Guide for Reusable Launch Systems

- Process Audits
- Fleet surveillance
- Flight & Recovery Data
- Inspection Data
- Re-acceptance/Screening
- Re-design
- Re-qualification
- Refurbishment
- Integration and Checkout
- Launch Readiness Verification

Reuse involves extended service life, additional environment exposures, limited hardware inspection access during post flight maintenance, and potential for damage due to previous flight or maintenance operations

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Key Aspects of LE-S-010

- Structures & Propulsion
  - Safe life (damage tolerance) methodology based on inspection interval
  - Hardware repairs substantiated thru qual or subscale testing
  - Use proof test logic with caution in regions of high workmanship sensitivity
- Dynamics
  - Dynamic models for simulation, methodology development, or forcing function development and validation of events for RLV
  - Re-usable hardware separation events, on-orbit maneuvers, re-entry atmospheric loading, re-entry subsystem deployment, landing/retrieval loads for all recovered hardware, hoisting and transportation
- Mass Properties
  - Record of components including maintenance of mass properties change histories
  - Record mass properties of components refurbished for a new mission and verify mass after refurbishment is complete
- Mechanisms
  - Explosive systems, Moving Mechanical Assemblies (MMAs), Silicon Nitride Ball Bearings
  - Functional checkouts of units at the vehicle level conducted after each service use
- Dynamic Environments
  - Assessment of environmental exposure in terms of peak amplitude & cumulative fatigue between flights
  - Damage calculations relative to fatigue environments

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Configuration Control

- Contractor communicates which parts are on vehicle
- USG communicates life limits to the contractor based on the NRDV output
- Contractor communicates hardware swap during refurbishment to USG
  - *USG follows the refurbishment and highlight key issues to technical team*
  - *USG assesses critical issue tickets to ensure part life is within qualified NRDV life assessments*
  - *USG reviews traceability of the changes to the build*
  - *USG reviews all changes to hardware*

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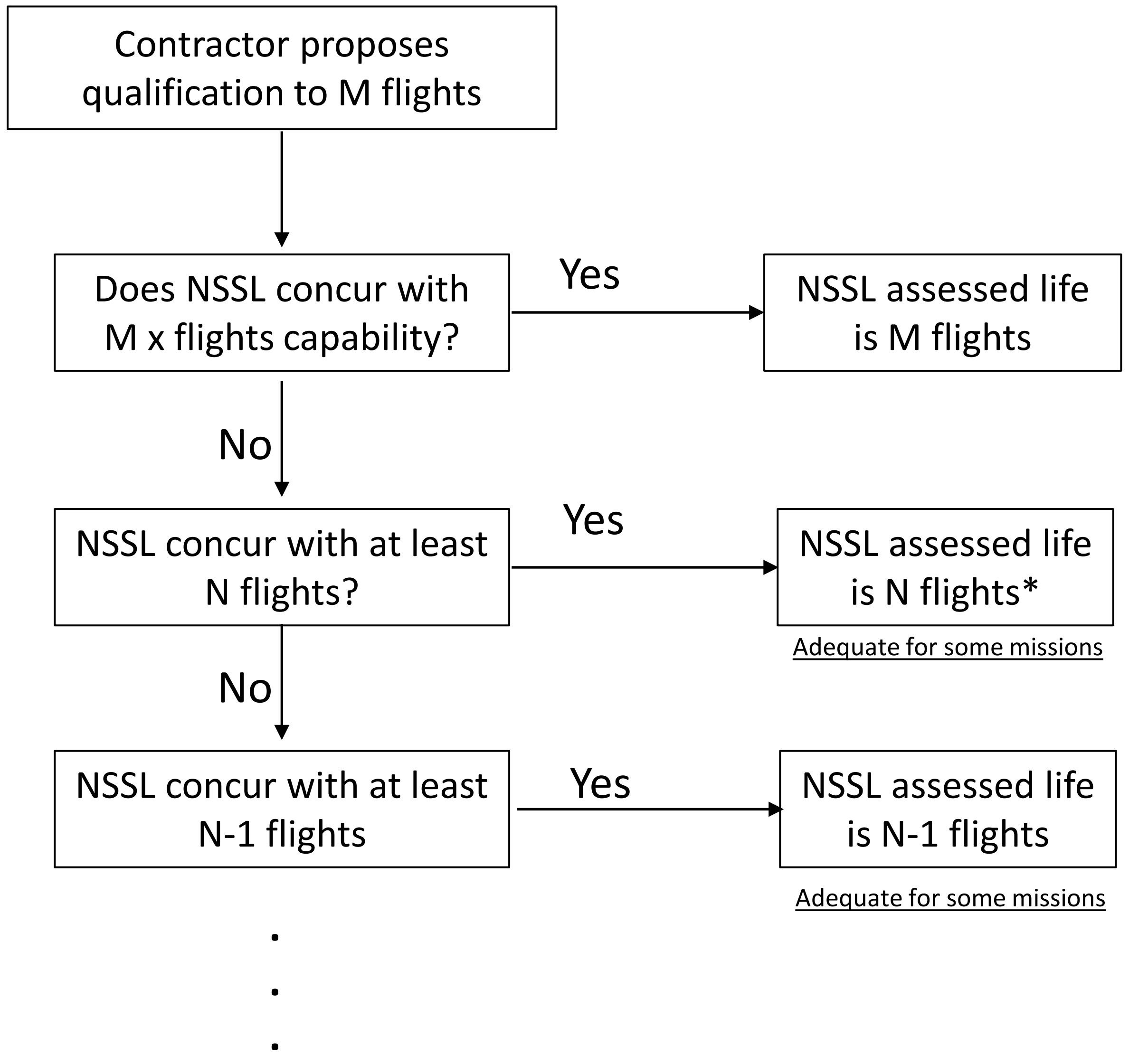
Expanded IV&V Activities Unique to Reuse

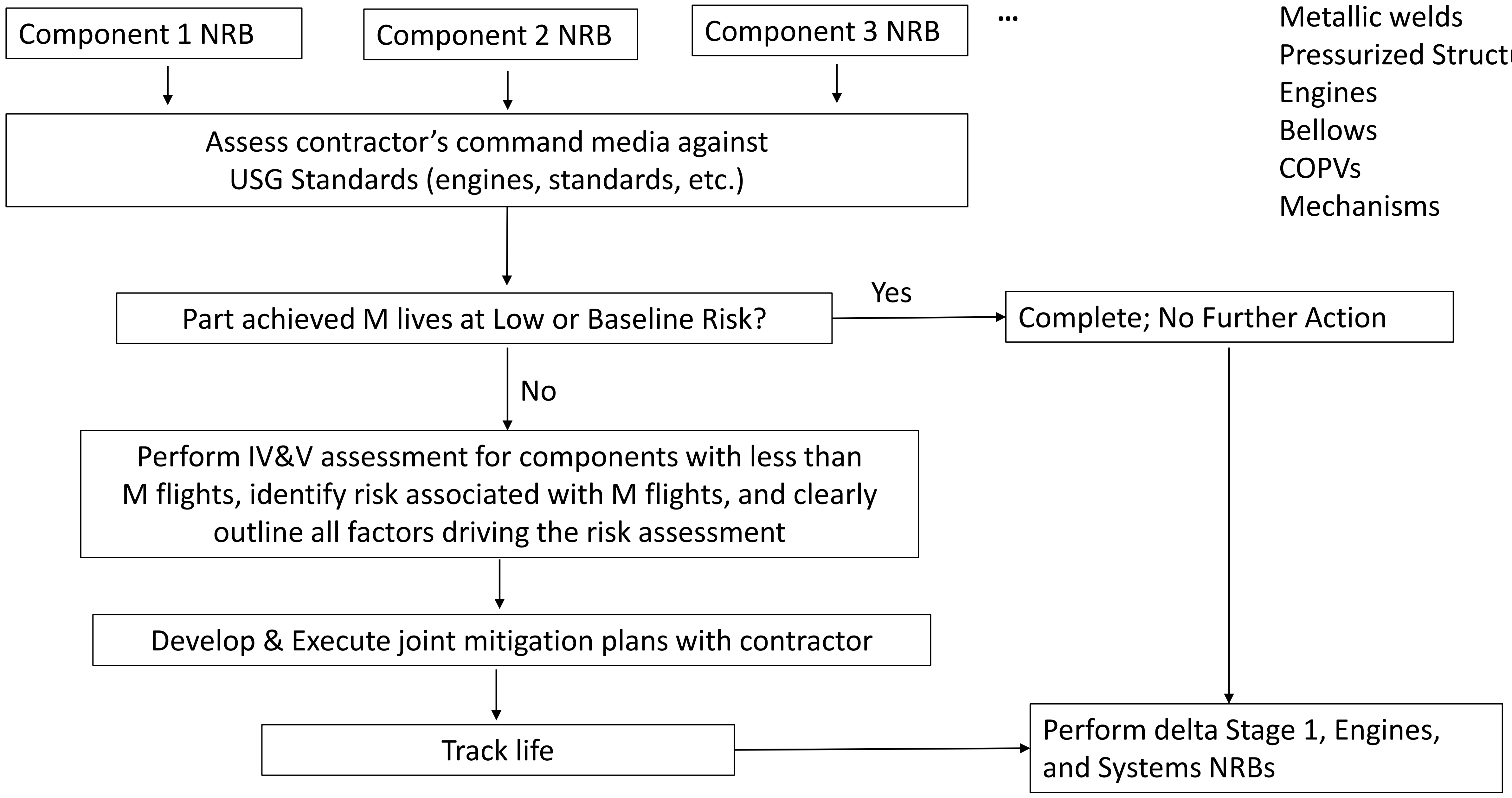
- Expanded environmental assessment
  - Verification that booster dynamic properties and excitation sources do not change on subsequent flights
  - Evaluate loads models, forcing functions, methodology, simulation and loads combination for all vehicle recovery loads events
  - Adequacy of thermal loads, dynamic environments, pressure loading, and other loads
- Expanded hardware assessment
  - Structural fatigue/fracture evaluation considering interval inspections, fatigue life spectra, and environments
  - Assessment of acceptance tests, qualification tests, analyses, and strength evaluations
  - Pedigree of new and reuse components focused on non-conformances, acceptance testing and inspections
- Evaluate previous flight data in preparation for next ascent (e.g., demonstrate dynamic environment is within fleet envelope)

Scope of the IV&V Review

- Evaluate life for the primary components on the booster targeting a min. of **N** ascents (Phase 1A) with max of **M** ascents
  - Service life/re-entry loads are considered in assessment of next ascent
  - NSSL did not perform assessment of booster recovery



Scope of the IV&V Review



Typical top issues in major rocket systems:
- Composites
- Metallic welds
- Pressurized Structures
- Engines
- Bellows
- COPVs
- Mechanisms

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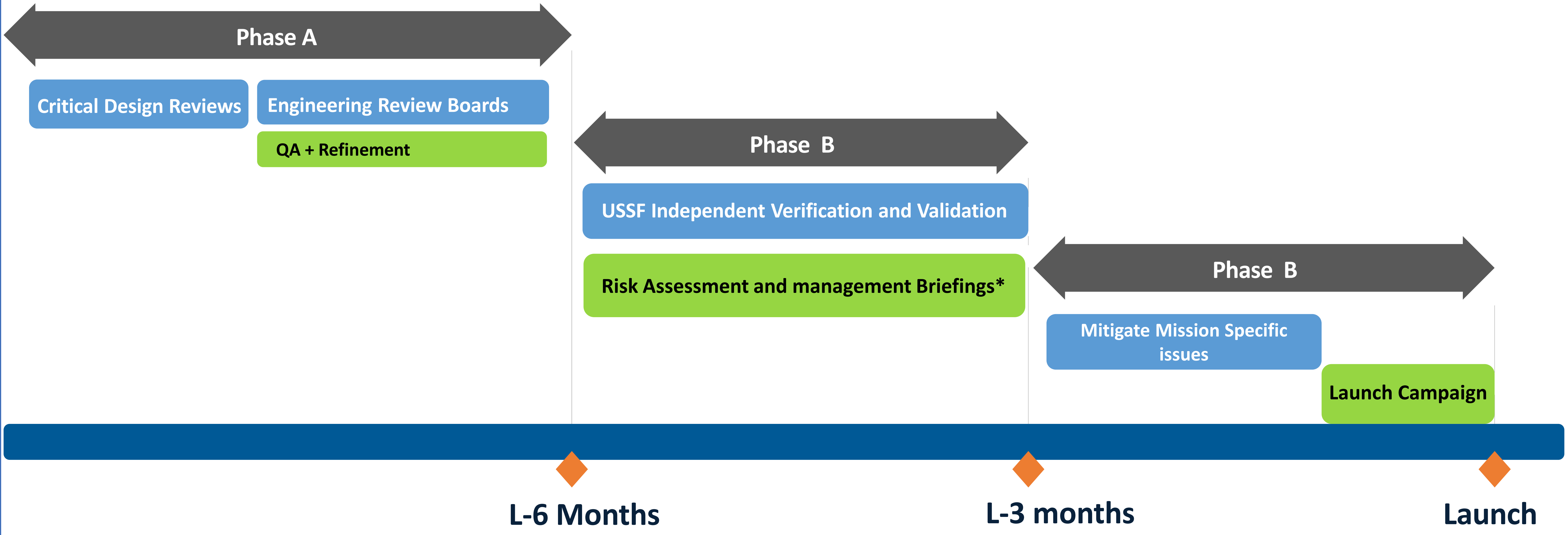
Mission Assurance Schedule for Reuse missions



** Several Non-Recurring Review Boards (NRBs) are typically conducted for NSSL Chief Engineer and Mission Director to present the result of independent assessment. NRBs cover major subsystems like engines*

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Reused Launch Vehicle Pedigree Schedule

An Estimate to begin pedigree review for new components

An Estimate to complete all new item Pedigree Reviews

An Estimate for beginning of Refurbishment Campaign

L-12 months

L-2 Months

L-45 days

Launch

Pedigree review for new Hardware

Revisit NCs that are impacted by Reuse Life

Refurbishment Pedigree

Launch Campa

Resolve late breaking issues discovered at launch sites

- Conduct an independent auditing campaign to verify Launch Vehicle provider's adequate processing prior to beginning of the pedigree process
- A list of critical components of the rocket for pedigree efforts and conduct followings:
  - Review all Supplier's Work Orders, Bill of Materials, Bill of Designs, Material Certifications, test reports, inspection reports, etc
  - Review Launch Vehicle provider's Work Orders, required inspections, drawings, test reports, etc
- Review selection of Non-conformances based on severity of events or component category

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NRDV Approach: Examples

- Composites
- Pressurized Structures
- Pressure Components
- Dynamics

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Composites

- Accelerated testing by using equivalent damage criteria
  - Composites less sensitive to strength reduction due to low load cycles
  - Equivalent damage can be calculated by trading high cycle counts at low loads for lower cycle counts at higher loads
- Equivalent damage calculations performed using Paris Law based method derived
  - Paris Law exponent, b, is typically 6-13 for graphite/epoxy composites
- Example calculations shown here demonstrate ~90 limit level cycles need to be applied to envelope the load spectra
- Method used in reverse to determine load events that can be ignored during testing
  - For example, if an event A is 10% the load level of the driving event B, then event A would have to be cycled 1,000,000 times to result in equivalent damage of 1 cycle of event B so event A can be removed from the test program
- Scatter can be applied to the equivalent cycle count to account for fatigue scatter, typically, a scatter factor of 4

Equation Used to Calculate Cycle Counts

$$N_{total} = \sum_{i}^{n} N_i \left(\frac{\Delta FL}{LL}\right)^b$$

Hypothetical Calculations of Cycle Trade-Offs (Assuming a *b*~6)

Δ(FL)/LL	# of Flight Cycles	Equivalent Cycles
1	3	3
0.9	20	11
0.8	30	8
0.7	80	9
0.6	200	9
0.5	1,000	16
0.4	5,000	20
0.3	10,000	7
0.2	15,000	1
0.1	30,000	0
Total	**61,333**	**85**

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Composites

- Composite fatigue testing provides confidence that inherent defects will not grow during structures' service life
  - Defects are common and inherent to the manufacturing process
  - Field inspections and repair are costly and may not be feasible/accessible
  - Damage tolerant structures are demonstrated through a combination of acceptance testing, inspection, and sub-scale and full-scale qualification testing

- Reuse testing enables two important aspects of structural maintenance program:
  - Assess the ability of the design to survive the minimum detectable flaws size corresponding to the NDI
  - Establish an acceptance criterion for dispositioning manufacturing flaws; the acceptable flaw size should be larger than the minimum detectable flaw size for the design to be robust

- Methodology developed to assess fatigue and fracture capability on a subscale level
  - Fracture toughness characterized by performing static testing until damage growth is observed
  - Change in fracture toughness due to fatigue loading assessed by cyclic load testing
  - Maximum acceptable flaw size calculated by comparing the fracture toughness to strain energy release rate predicted at limit load; a safety factor is added to account for uncertainties

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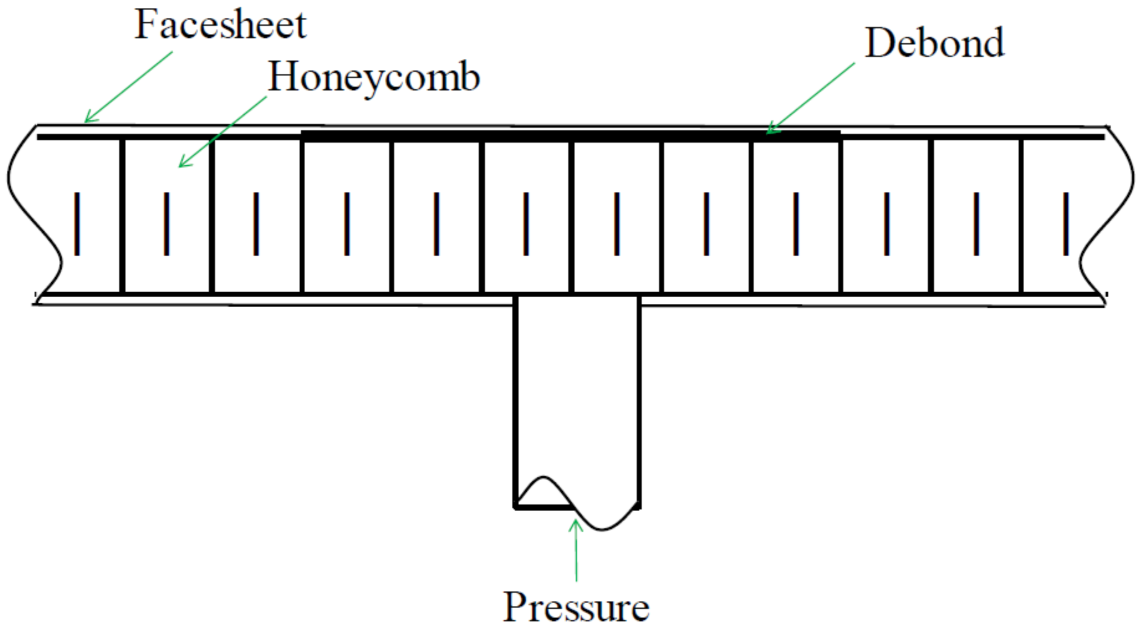
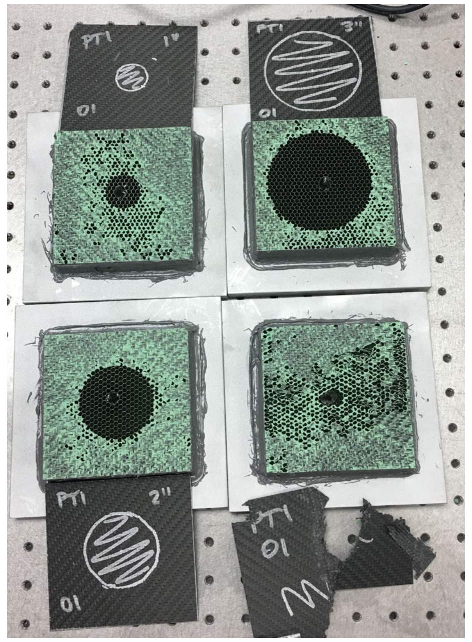
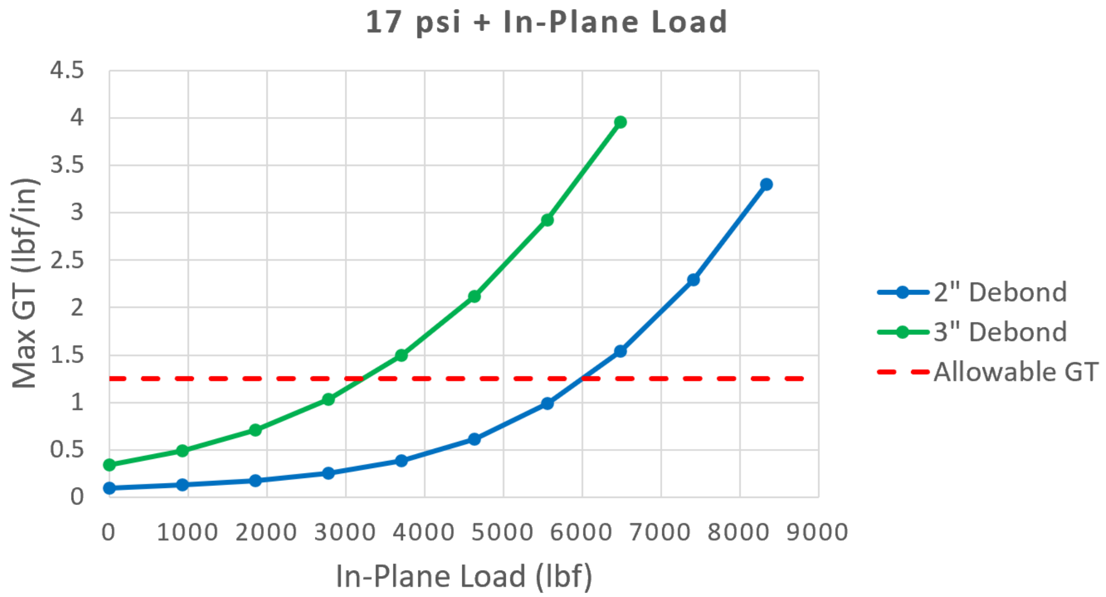
Composites



Static Test



Analysis



Fatigue Test

4" x 4" Coupons	# of Cycles
1-inch Defect	2100
2-inch Defect	1100
3-inch Defect	1400

"Composite Damage Tolerance Approach for Reusable Launch Vehicle Applications"
Vinay K. Goyal, Pavel Babuska, Dhruv Patel, Zhi Chen, Sahar Maghsoudy-Louyeh, Ignacio Maqueda and Joaquin Gutierrez: AIAA 2021-1166

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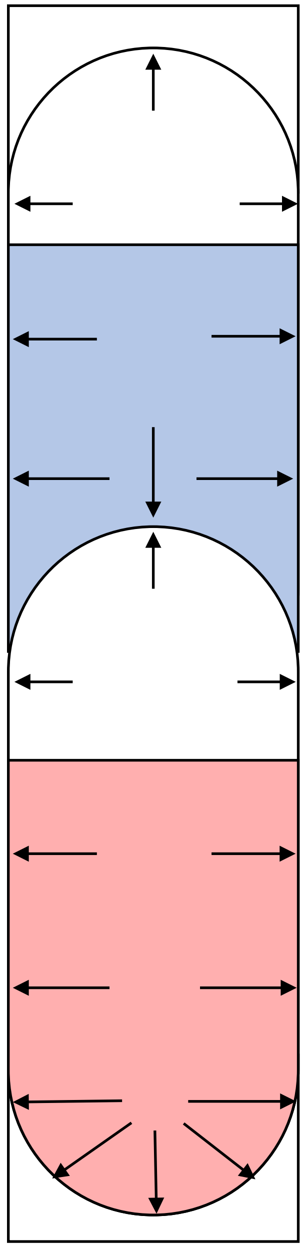
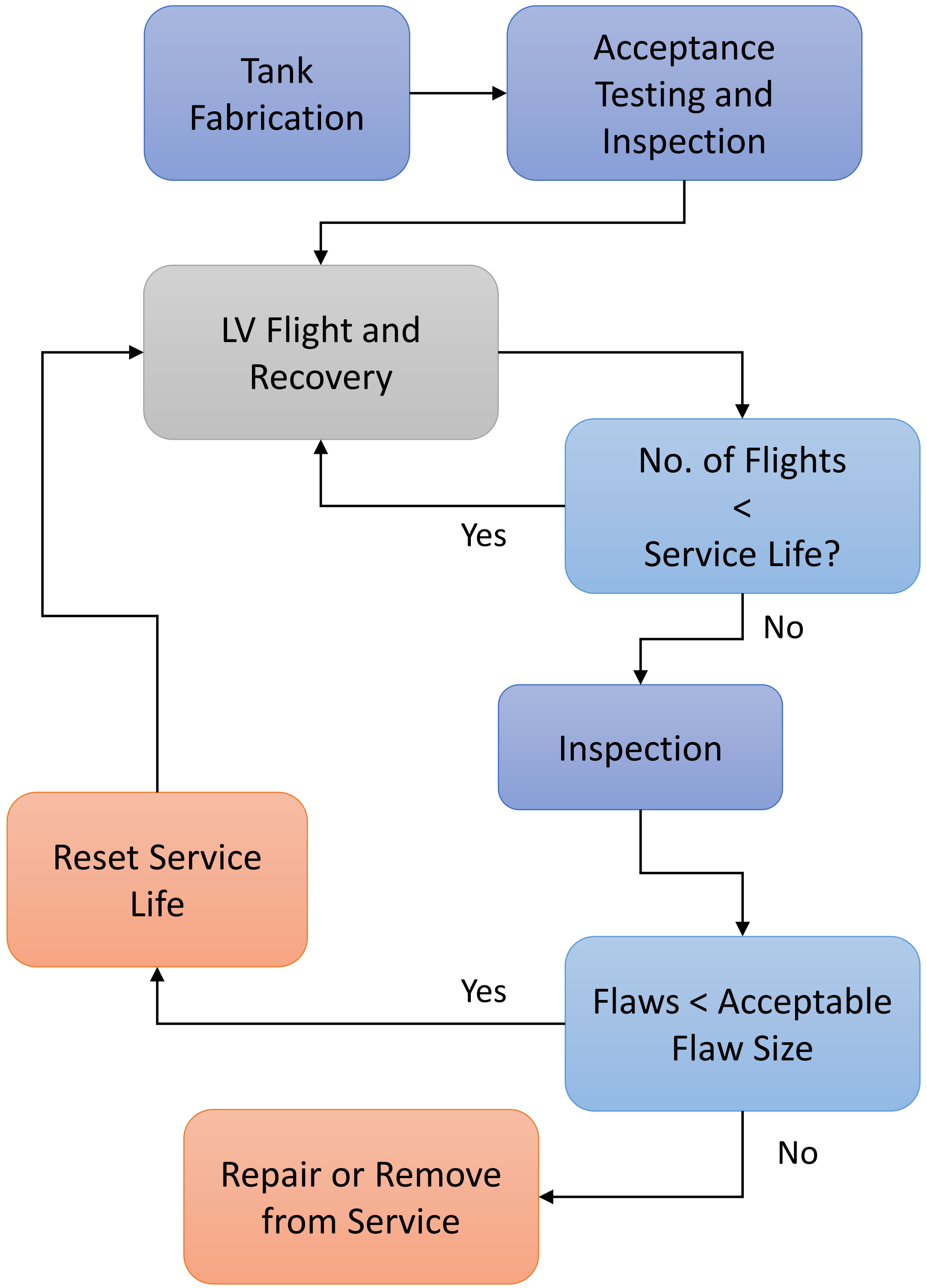
Pressurized Structure

- Pressurized structures, such as stage tanks, are qualified for life and strength regardless of reuse vs. single flight applications
- Pressurized structure loading driven by external forces/pressures
  - External forces predicted by CLA and confirmed with flight data
  - Pressures driven by tanking, detanking, and mission profiles
- Safe life verified by ensuring minimum detectable or maximum acceptable flaw size will survive service life
  - Verification methods may include "Fast Fracture" check (see section on Lines and Fittings), conventional LEFM analysis (e.g., NASGRO), coupon tests with initial flaws, or a full-scale test with initial flaws
- Interim inspections may extend usable life
  - By verifying no surface or internal flaws exceed allowable flaw size, service life may be "reset"
  - May not be feasible if critical locations are not inspectable

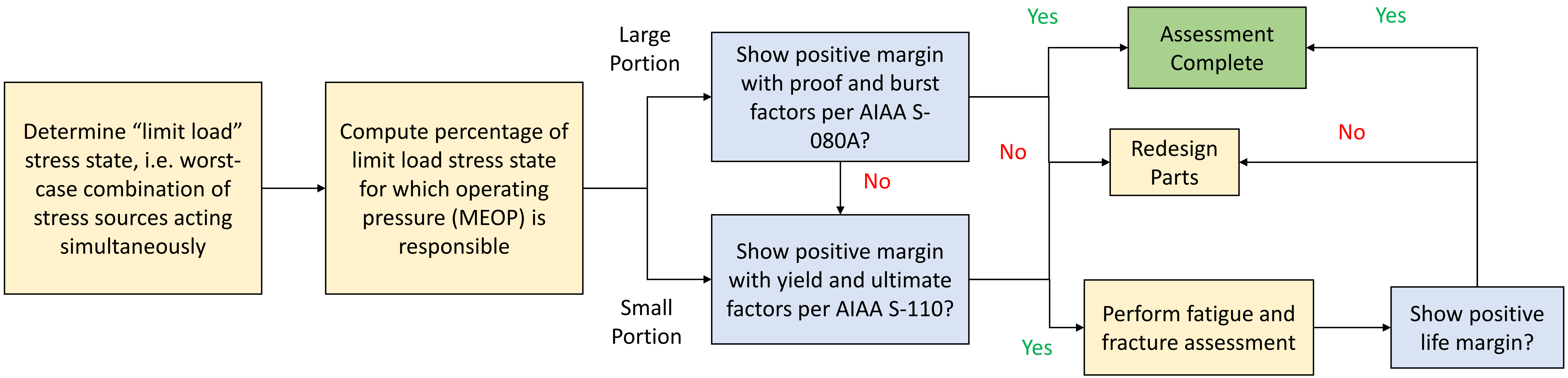




Pressure Components

- Assumption that hardware is "designed largely by internal pressure" meaning portion of total stress in the part is large portion due to pressure alone (not external mechanical loads, thermal loads, etc.)
  - AIAA S-080A-2018 Proof and Burst Factors (pressure-specific safety factors) provide adequate coverage against needing to perform any fatigue or fracture (safe-life) assessments

- When pressure components carry significant non-pressure loads, either (1) the Proof and Burst factors must be adjusted to cover the total stress state or (2) structural yield and ultimate safety factors (per AIAA S-110) are applied to the total stress state, but hardware must receive additional fatigue and/or fracture (safe-life) assessments



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Loads and Dynamics - Overview

- Design for descent, reentry, and landing loads is based on a combination of analysis and flight data
- Loads simulations are based on several conservative design descent trajectories that are intended to envelope potential descent environments
  - Loads are calculated for all critical events for each trajectory including separation events, engine startups, engine shutdowns, atmospheric loading, landing, and transportation
  - Loads analyses use ascent CLA derived launch vehicle models and test/flight data based forcing functions
- Flight data from descent, recovery, and transportation is compared to the design descent trajectories to ensure that predicted loads envelope flight loads
- Flight data from multiple missions is monitored and compared to ensure that system dynamics are not changing from one flight to the next

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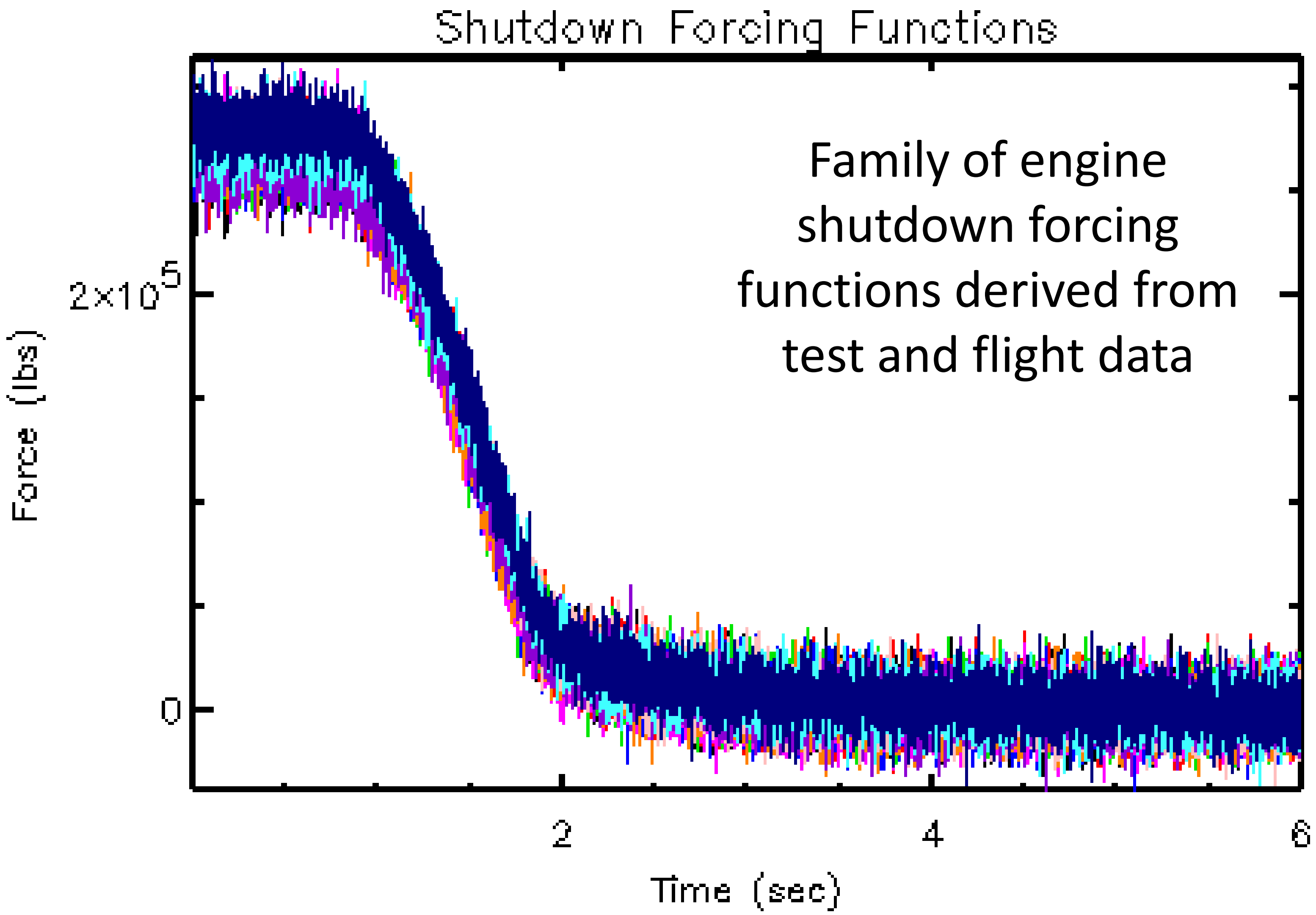
Loads and Dynamics - Simulations

- Loads are calculated for all critical events
  - Separation events, engine startups, engine shutdowns, atmospheric loading, landing, and transportation
- Loads analyses use ascent CLA derived launch vehicle models and forcing functions based on test and/or flight data

Engine Thrust Forcing Functions

Hypothetically derived forcing functions



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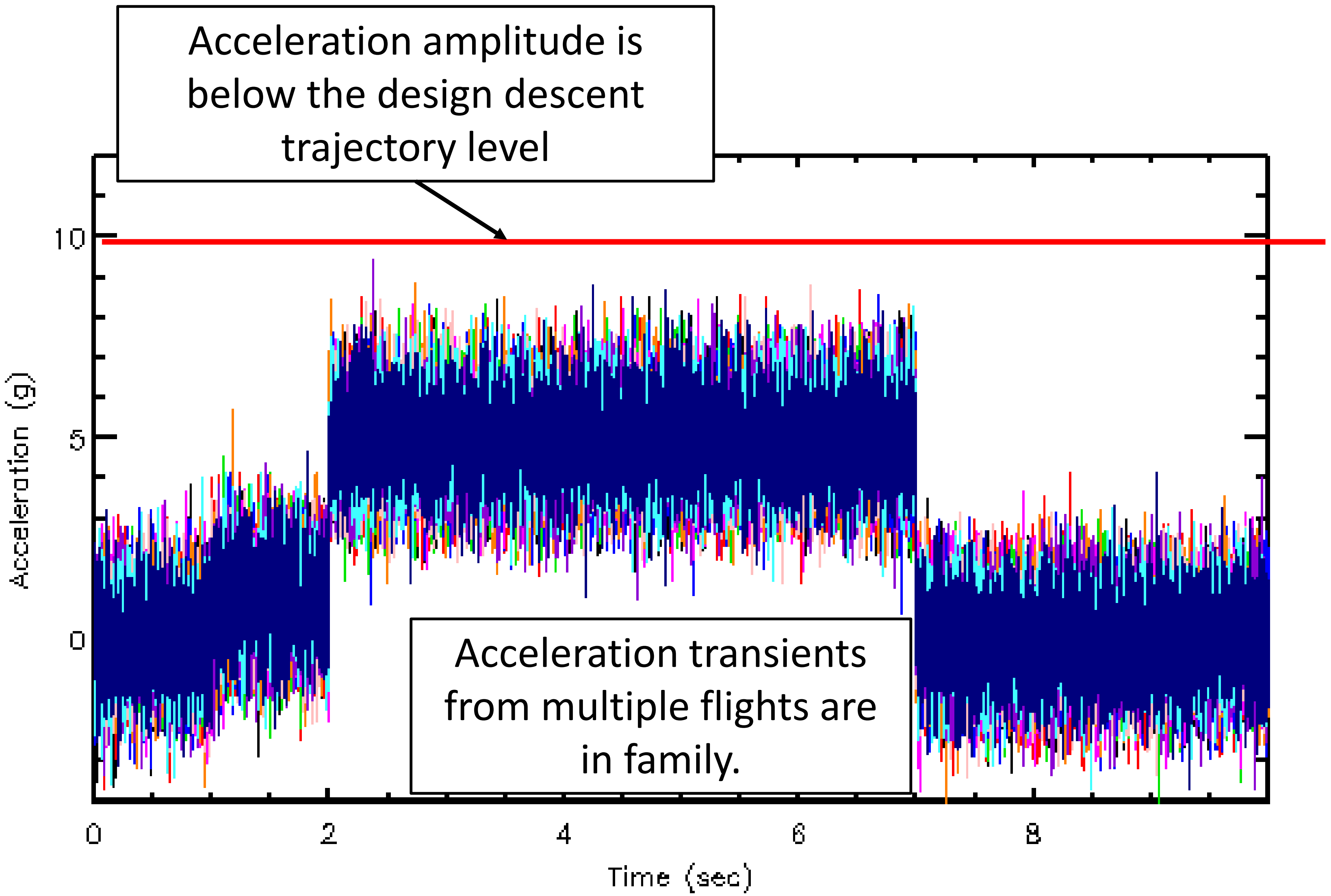
Loads and Dynamics – Flight Data

- Flight data from descent, recovery, and transportation is compared to the design descent trajectories to ensure that predicted loads enveloped flight loads

- Flight data from multiple missions is monitored and compared to ensure that system dynamics are not changing from one flight to the next



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Typical Challenges

- Damage tolerance and fatigue life limitations
- Propensity to corrosion and other detrimental effects from environments
- FOD propulsion systems
- Inadequate inspections
- Inspection limitations due to accessibility
- Insufficient design load validation from the dynamics perspective
- Qualification/acceptance of hot structures and engine components
- Random vibration qualification of avionics or workmanship sensitive electronics

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Keys to Success: Launch is a Team Sport

- Reusable launch vehicle contractor
  - Strong qualification and acceptance program that considers inspections
  - Interval inspections
  - Redesigns to overcome challenges with life-limiting hardware
  - Use flight learning to make incremental changes to the hardware
  - Use flight data to increase confidence in the environments

- USSF team
  - Robust standards, flexible and cost-effective
  - Reusability allows a reduction in efforts expended in hardware reviews
  - Follows refurbishment process to increase confidence in the decision-making progress
  - Determine if inspections and criteria for refurbishment are adequate
  - Risk identification, mitigation, and partnership to ensure that all issues are addressed

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Looking Ahead

- Team is in the process of developing a structured, repeatable and sustained process for assessing criticality of each mission assurance task based on **confidence** in contractor processes
- Informs how deep of an effort is required to achieve confidence threshold for flight certification
- Surveillance-driven, limited reassessment following major process changes, anomalies, etc.
- Key factor to the **confidence factor concept**:
  - Design Management
  - Margins & Conservatism
  - Process Management
  - Tools & Methodology
  - Flight Experience
  - Test Adequacy & Results

Confidence factor being developed to ensure right-sized recurring IV&V while maintaining vigilance and capability

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Technological Needs

- To achieve highly reusable systems, the development of liquid rocket engines that are robust to fatigue as well as extreme environments is a requirement

Advanced Engineering Materials

Advanced Turbine Engine Technologies

Advanced Manufacturing

Materials by design and material genomics

Materials with new properties

Materials with substantial improvements over existing properties

Material property characterization and lifecycle assessment

Clean, sustainable manufacturing

Smart manufacturing

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Technological Needs

- Materials able to resist adverse environmental conditions
  - Corrosion
  - Hydrogen embrittlement
  - Hydrogen assisted cracking

- Materials able to resist extreme environmental conditions
  - High temperatures in nozzles (e.g., GRC using CMC in aircraft engines)
  - High temperatures in thrust chambers
  - Creep

- Materials able to resist wear behavior due to extreme dynamic environments
  - Fatigue and fracture in turbine wheels
  - Durability
  - Wear/Frictional issues from material contact
  - Seals

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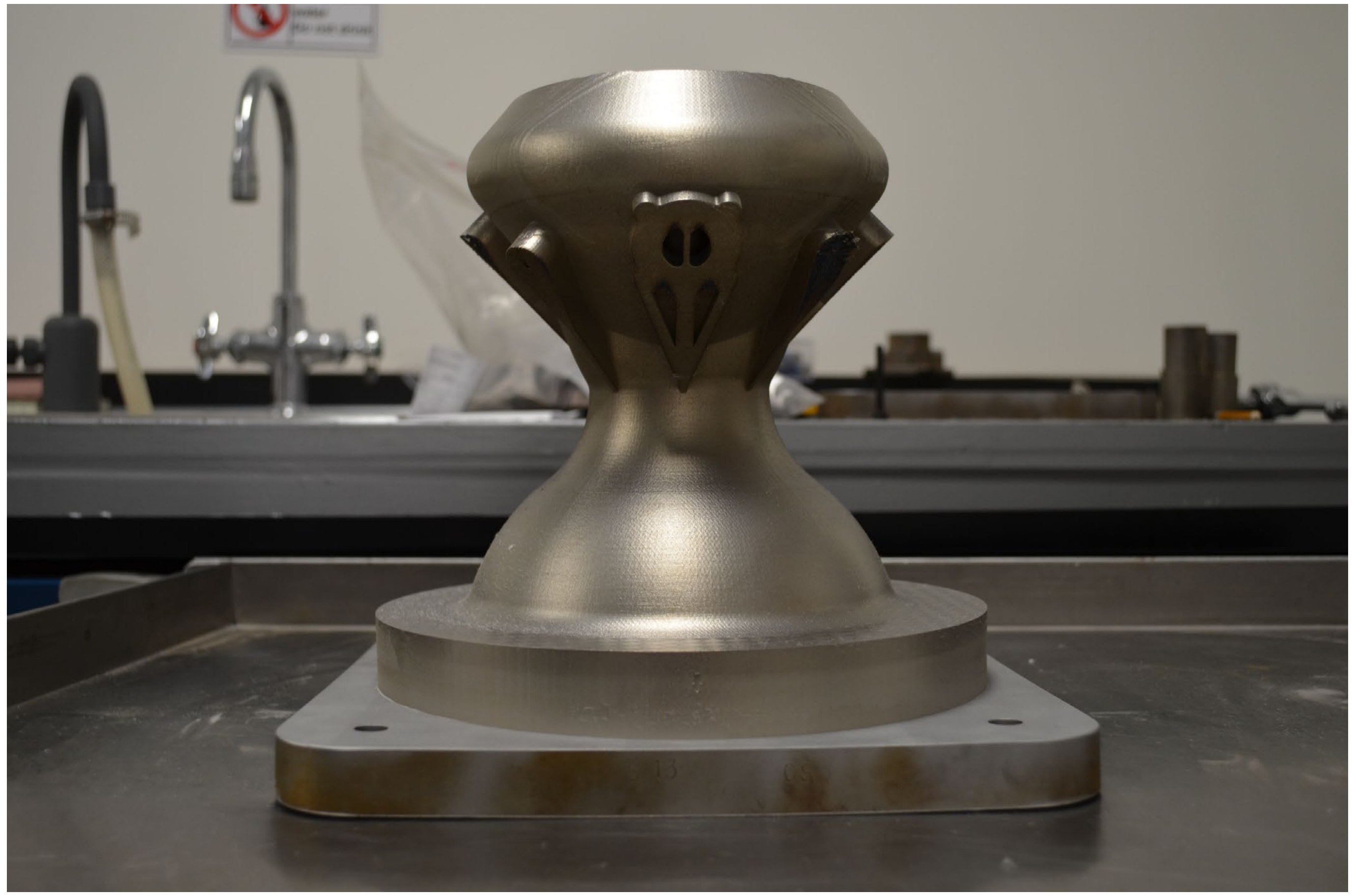
Technological Needs

- Structural health monitoring to reduce inspection times
- Additive manufacturing to accelerate production and increase production times
  - New Materials with greater capabilities
  - Improve Joining methods of dissimilar materials to overcome structural limitations
  - Optimize Processing methods to reduce part count and integration
- Adoption of composite materials in engine components to increase fatigue performance and increase survivability to high thermal gradients



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Summary

- RLV's present numerous new challenges for conducting non-recurring design validation and recurring verification activities
- Adapted and modified several considerations from the commercial civil aviation industry to address challenges unique to RLV's
- Developed system-level considerations for RLV's to achieve equivalently rigorous levels of mission assurance and acceptable risk as currently achieved with EELV (NSSL) missions
- Excellent progress towards increasing the use of reusable launch vehicles
- Potential for cost savings

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