# Considerations for Proliferated Space Vehicle Qualification 34th Aerospace Testing Seminar

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**Abstract**

The processes to build, qualify, and test traditional, high-value, bespoke space vehicles has served National Security Space (NSS) customer needs very well for the past 60+ years. Contractors have relied on craft manufacturing methods and rigorous industry-standard environmental qualification and acceptance testing requirements for individual and small batches of space vehicles. As a result, a very high percentage of space vehicles have operated well past their design lifetimes. A paradigm shift is now needed as NSS space systems move to more resilient architectures, and space vehicle production volumes that will be substantially scaled-up for proliferated systems.

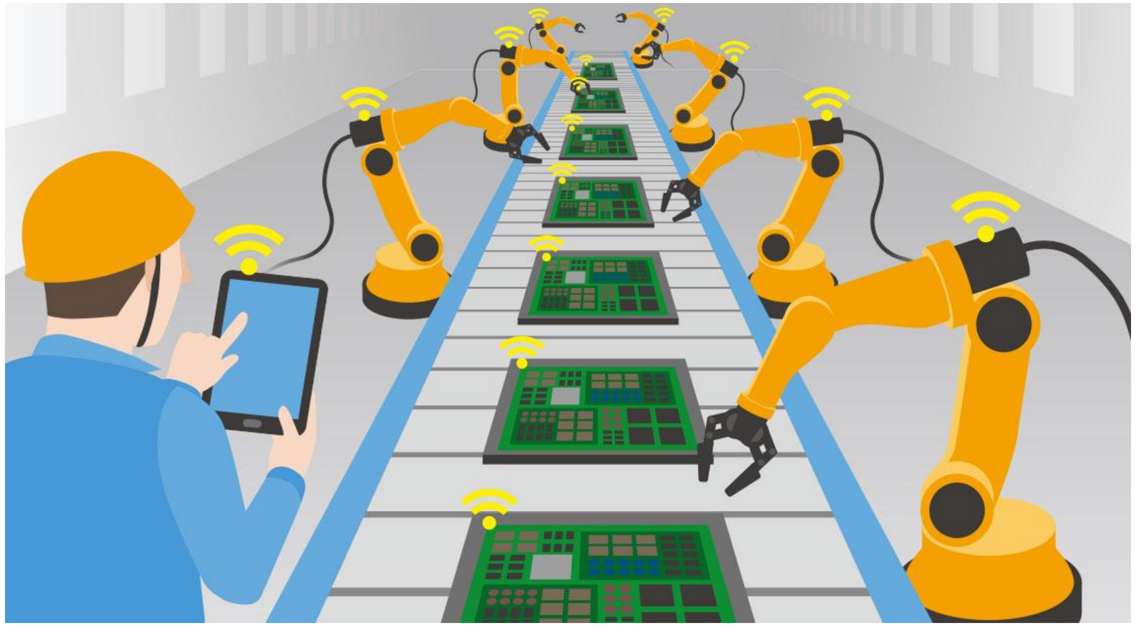
Up until very recently, space vehicles have not been produced in significant quantities for NSS space systems. New thinking and adoption of proven methods from other high-volume manufacturing industries are necessary to successfully design, qualify, manufacture, test, and launch constellations with potentially hundreds of space vehicles. Starting with space vehicle design processes – producibility, standardization, simplification, and cost targets must be integrated into product designs and processes that result in mature, robust space vehicles that are dramatically less costly to produce. Investment in HALT™ and other test approaches should be used during the development phase to ruggedize circuit performance and product design and reduce the likelihood of latent defects in flight hardware. A robust unit level qualification program also demonstrates tolerance for unit-to-unit variability. Early-on, before high-volume production begins, an assembly-line approach should be adopted that focuses on ease of production and efficiency. Pathfinders are used to proof the production system and validate engineering designs with early on-orbit testing. If discovered on-orbit, feedback can be incorporated into designs prior to ramping up production. Finally, with successful early risk mitigation testing and pathfinder on-orbit mission success, TR-RS-2014-00016/S-016 can be adapted to gradually reduce acceptance testing. These efforts will ensure a robust, repeatably produced space vehicle that is intrinsically less costly without over-specifying and over-testing.

This presentation provides insights into some of the considerations that will help transition from traditional space vehicle qualification to high-volume proliferated space vehicle qualification.

# Considerations for Proliferated Space Vehicle Qualification

## Agenda

- Where We Were >>>  Where We Want to Be
- Proliferated Space Vehicle High-Volume Product Life Cycle
- Environmental Test Guidance
- Proliferated Space Vehicle Qualification
- Summary



# Where We Were …

## Considerations for Constellation Space Vehicle Qualification

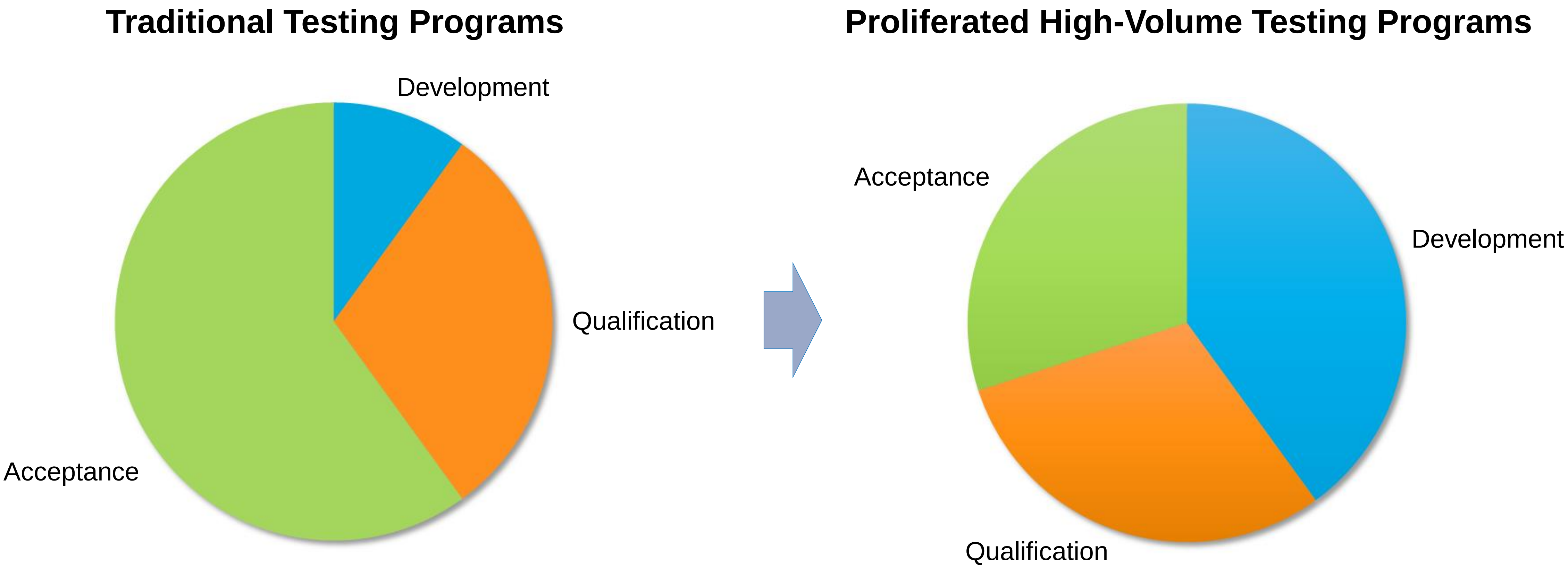
- Traditional, exquisite space vehicles have long design cycles and high-reliability requirements
  - 8 - 10-year development cycles
  - Production quantities < 10 space vehicles/system (GPS is an exception)
  - Class A missions “have to work”
- Craft manufacturing processes unique to each vehicle
  - Even commercial buses tend to be heavily modified for each mission
    - Processes not consistent enough to invest NRE to characterize and monitor
  - Hard to maintain repeatable processes; extensive tribal knowledge, touch labor, and high technician skill levels required
- TR-RS-2014-00016/S-016 standard defines qualification and acceptance test programs for units, subsystems, and vehicles
  - Qualification demonstrates design margin, covers for test tolerances, and unit-to-unit variability
  - Acceptance testing validates that flight hardware performs in mission environments and screens out workmanship defects
- Accepting RE in test and workmanship screening rather than investing NRE to develop a manufacturable design with qualified, characterized, and monitored processes
- Extensive testing of all hardware required to screen for inevitable defects
- Resulting vehicles support long, 10+ year missions, frequently overachieving their life requirements

James Webb Space Telescope being prepared for vibration testing.
Photo credit: NASA/Chris Gunn

**Exquisite vehicles drive long development timelines, which drives extensive testing to support long missions to recoup the cost**

RE – Recurring Engineering
NRE – Non-Recurring Engineering

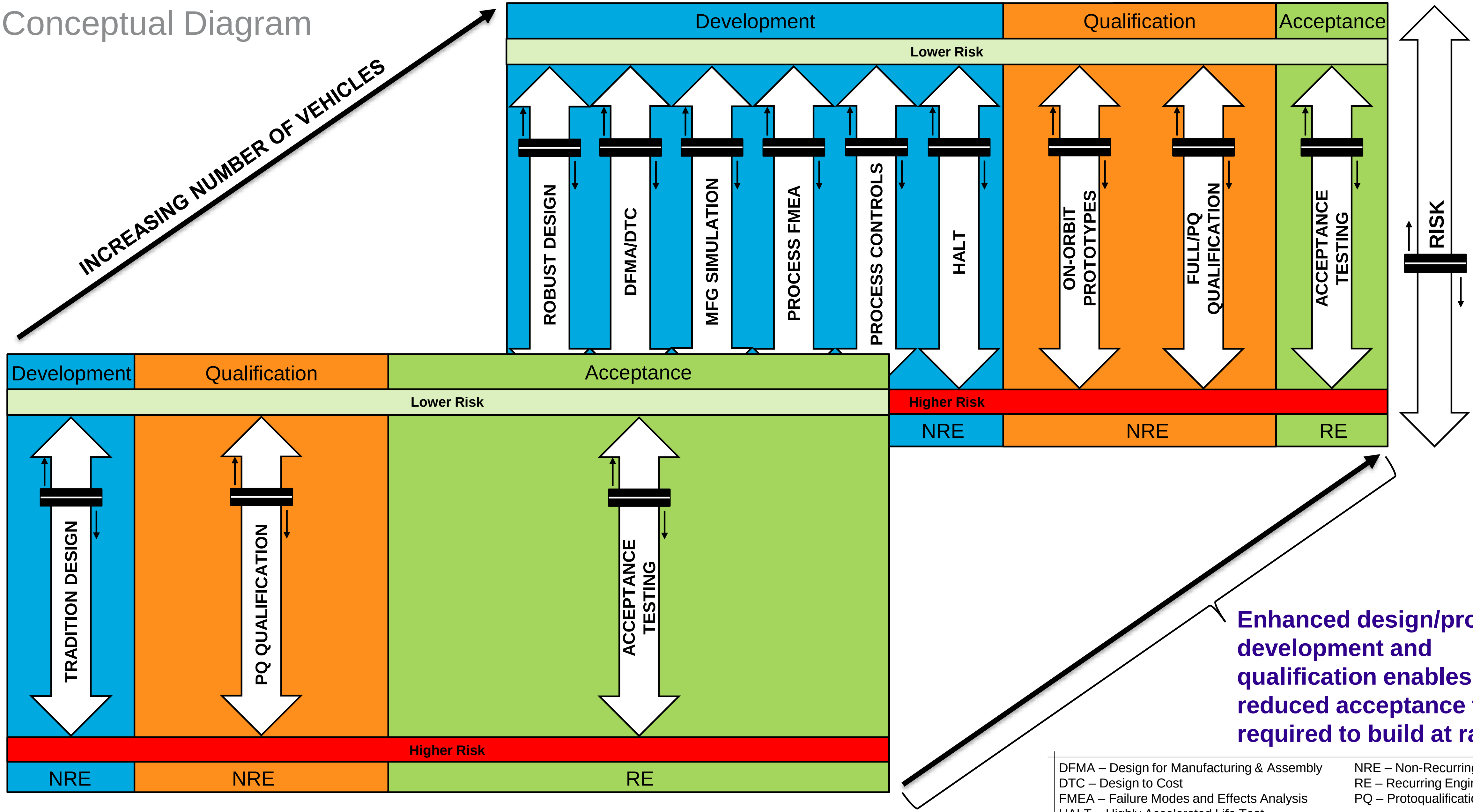
# Notional Representation of Cost and Schedule Commitments for Environmental Testing of Traditional and Proliferated Space Programs




**Increased development and qualification efforts on high-volume programs will enable reduced acceptance testing**

# Proliferated Space Vehicle Qualification

## Conceptual Diagram




Slider Bars change the relative risk

**Enhanced design/process development and qualification enables reduced acceptance testing required to build at rate**

DFMA – Design for Manufacturing & Assembly
DTC – Design to Cost
FMEA – Failure Modes and Effects Analysis
HALT – Highly Accelerated Life Test

NRE – Non-Recurring Engineering
RE – Recurring Engineering
PQ – Protoqualification

# Where We Want to Be (for Many Capabilities)

## Considerations for Proliferated Space Vehicle Qualification

- Proliferated systems with short development cycles, relying on re-use of commercial technology wherever possible

- Standardized, high-volume manufacturing processes used for all vehicles

- Investing NRE in hardware and manufacturing process qualification reduces overall life cycle cost

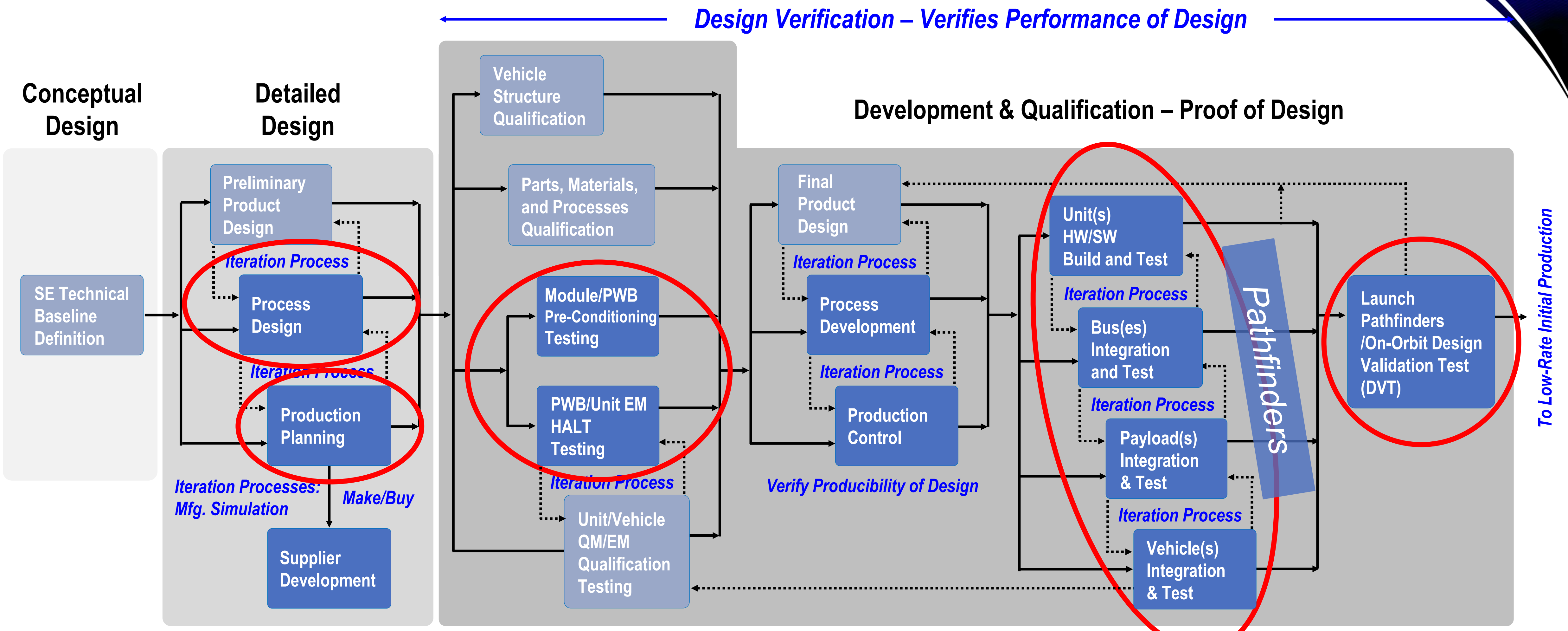
- TR-RS-2104-00016/S-016 standard is *adapted* to accommodate constellation, space vehicle design, and contractor capabilities
  - Adaptive S-016 addresses the unique testing needs of proliferated systems

- Resulting vehicles support required constellation functional availability

**Leverage high-volume production techniques to build constellation space vehicles quickly, with few defects, reducing the need to perform full environmental acceptance testing on each vehicle**

NRE – Non-Recurring Engineering

# Proliferated Space Vehicle High-Volume Product Life Cycle




*Legend*

| Typical Activities for Traditional Space Vehicles | Additional Activities for Proliferated Space Vehicles |
|---|---|

**<u>Hardware</u>**

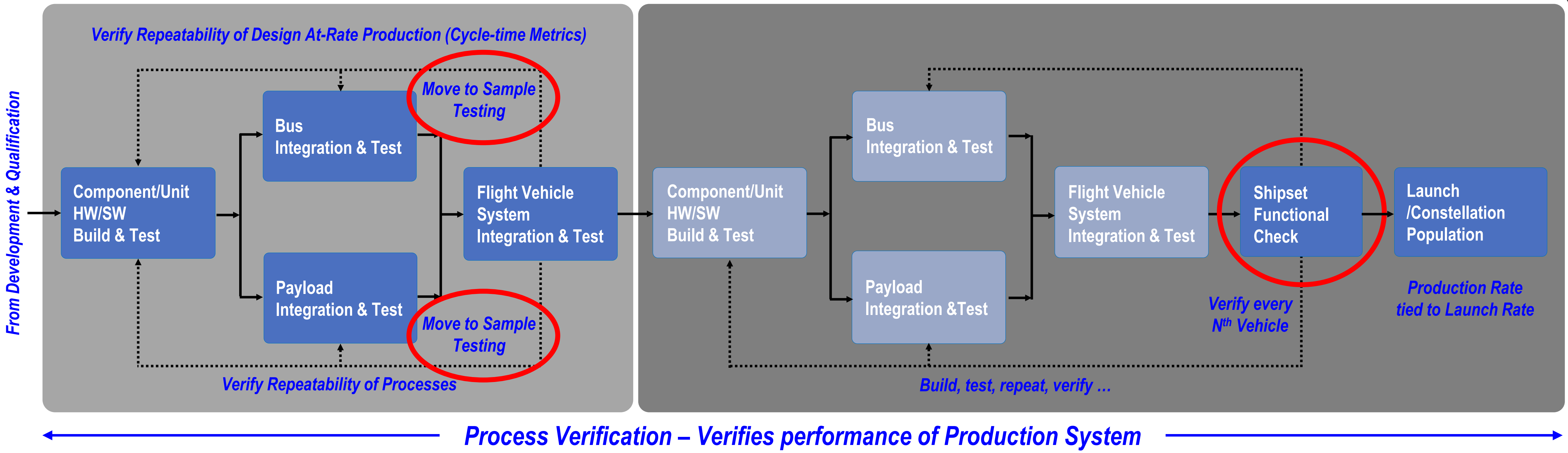
**Prototypes – Functional Models**
**EM – Engineering Models**
**QM – Qualification Models**
**Pathfinders – DVT Vehicles**
**Vehicle – Space Vehicle**

HALT – Highly Accelerated Life Test
PWB – Printed Wiring Board

# Proliferated Space Vehicle High-Volume Product Life Cycle (Con’t.)

**Low-Rate Initial Production – Proof of Manufacturing**

**Full-Rate Production**




***Legend***

| Typical Activities for Traditional Space Vehicles | Additional Activities for Proliferated Space Vehicles |
| --- | --- |

**<u>Hardware</u>**

**Prototypes – Functional Models**
**EM – Engineering Models**
**QM – Qualification Models**
**Pathfinders – DVT Vehicles**
**Vehicle – Space Vehicle**

HW – Hardware
SW – Software

# Environmental Test Guidance

## Considerations for Proliferated Space Vehicle Qualification

- All programs can start with TR-RS-2014-00016/S-016, *Test Requirements for Launch, Upper-Stage, and Space Vehicles* standard as a baseline
- Adaptive considerations to S-016 ensure efficient production for high-volume programs:
  - Enhanced design processes like DFMA result in producible, cost-effective designs – make qualification models affordable and supports testing to full qualification levels
  - Manufacturing process characterization and monitoring identify and remove sources of variation to ensure repeatability
  - Development test methods such as HALT play a critical role in ruggedizing designs and identify latent defects
  - Qualification establishes design margin over application requirements
  - Use of pathfinders and early on-orbit testing validate vehicle design – complementary with S-016
  - Acceptance testing screens for workmanship defects and validates performance – leading to sample testing
  - Shipset functional check ensures confidence that production processes are stable over time

Blue text – correlates with S-016

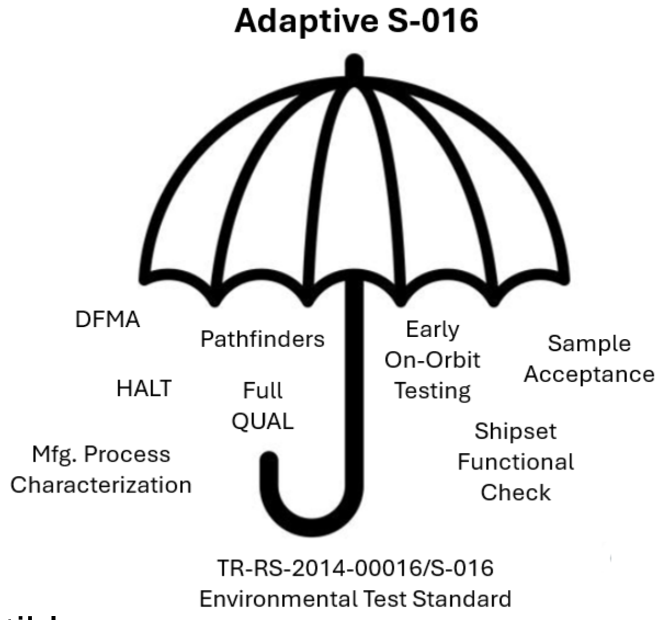
**Adaptive S-016 considers all relevant factors in determining the development, qualification, and acceptance test program**

DFMA – Design for Manufacturing & Assembly
HALT – Highly Accelerated Life Test

# Summary

## Considerations for Proliferated Space Vehicle Qualification

- Proliferated constellations represent a paradigm shift in how space vehicles are built, qualified, and tested
  - If traditional design, qualification, and testing approaches are used, there is a concern that flight vehicle production issues (and associated troubleshooting and rework) could cause significant cost overruns and schedule delays when producing large quantities of space vehicles
- Higher production volumes support expending more NRE on the upfront design and manufacturing processes such as DFMA
- Investment in HALT™ and other test approaches should be used during the development phase to ruggedize circuit performance and product design and reduce the likelihood of latent defects in flight hardware
- Acceptance testing can be reduced (Adaptive S-016) if a robust qualification is demonstrated, and manufacturing is repeatable
- Environmental test must be planned and executed within the context, constraints, and goals of the program
  - Full acceptance testing of every flight unit, subsystem, and vehicle is likely not compatible with the expected development timelines, cost constraints, and launch cadence for proliferated constellations




**Adaptive S-016 goes beyond the environmental test standard – it represents a collection of approaches/tools used throughout the product lifecycle to support high-volume production of proliferated systems**

# Thank you

# Back-up

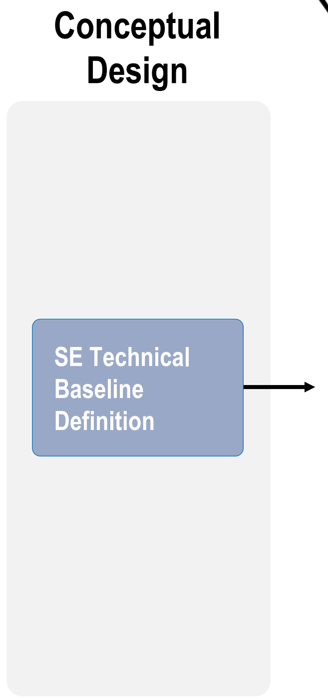
# Conceptual Design Phase

*Legend*

| Typical Activities for Traditional Space Vehicles | Additional Activities for Proliferated Space Vehicles |
|---|---|

- Systems Engineering (SE) Technical Baseline Definition:
  - Definition of Mission Objectives (WHAT's)
    - Define Preliminary Requirements and Constraints
  - Mission Characterization (HOW's)
    - Identify Applicable Mission Concepts
  - Mission Evaluation and Selection
    - Perform System-level Trades of multiple architectures
  - Identify Alternative Mission Concepts
    - Mission Analysis Hierarchy
  - Define Requirements
    - Allocate requirements to System elements

Mission Needs
*Gov't/Contractor Collaboration*




- SE Technical Baseline and Trades
  - Define Mission Life/Space Vehicle Design Life Trade-offs: *Individual Space Vehicle reliability; Functional availability; etc.*
  - Define Orbit/Constellation Design Trade-offs: *No. of space vehicles; Sparing strategy; Launch cadence; etc.*
  - System Cost Implications Trade-offs: *Reduced requirements; COTS parts; DFMA/Cost targets; etc.*
  - Consensus on Mission/Program Risk Posture Trade-offs: *Standards Tailoring; CDRL quantity/authority; etc.*

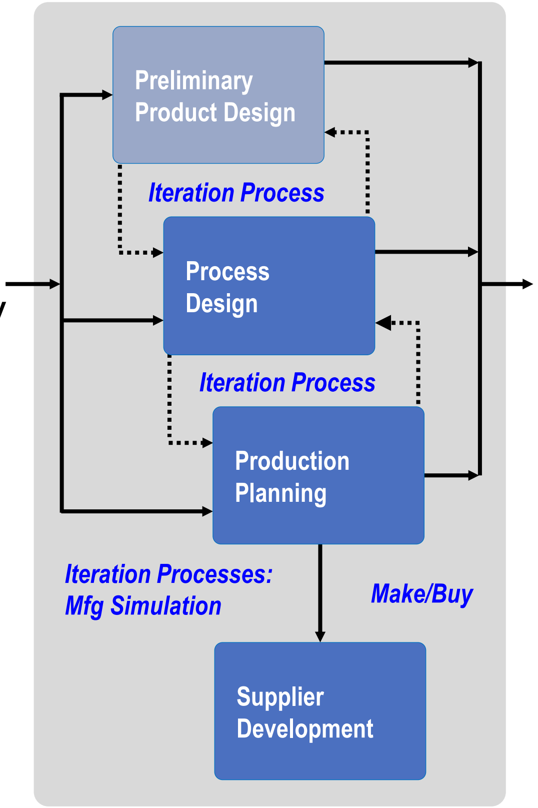
CDRL – Contractor Data Requirements List
COTS – Commercial-off-the-Shelf
DFMA – Design for Manufacturing & Assembly

# Detailed Design Phase

Legend
- Typical Activities for Traditional Space Vehicles
- Additional Activities for Proliferated Space Vehicles

- Preliminary Product Design
  - Preliminary design is created that meets technical requirements defined in A/B/C specs
  - Baselined design is improved and iterated through planned DFMA workshops
  - Performance may be traded to reduce variability and enhance producibility
  - Informed by USG approval of Producibility Design Plan CDRL
- Process Design – *“How to produce the product”*
  - Motorola 4-phase model used to characterize manufacturing processes for high-repeatability
  - Selection of processes is traded-off with product design features (e.g., tolerances, etc.) to error-proof and to create a “producible design”
- Production Planning – *“How much to produce” and “When are products needed”*
  - Volume production techniques, like “Pull” and “Batch” production are traded-off/planned
  - Manufacturing simulation used to test cost/schedule/facility options and maximize efficiency
  - Factory layout/flow, inventory levels, available resources are defined – culminates with Capacity Plan model that defines process yields and production rates
  - Informed by USG approval of Production Plan CDRL
  - Make/Buy decisions determined
- Supplier Development
  - Supply base rated by TRL and MRL assessments, and active support to meet production rates

Detailed Design




CDRL – Contract Data Requirements List
DFMA – Design for Manufacturing & Assembly
MRL – Manufacturing Readiness Levels
TRL – Technology Readiness Levels

# Development and Qualification – Proof of Design (1 of 3)

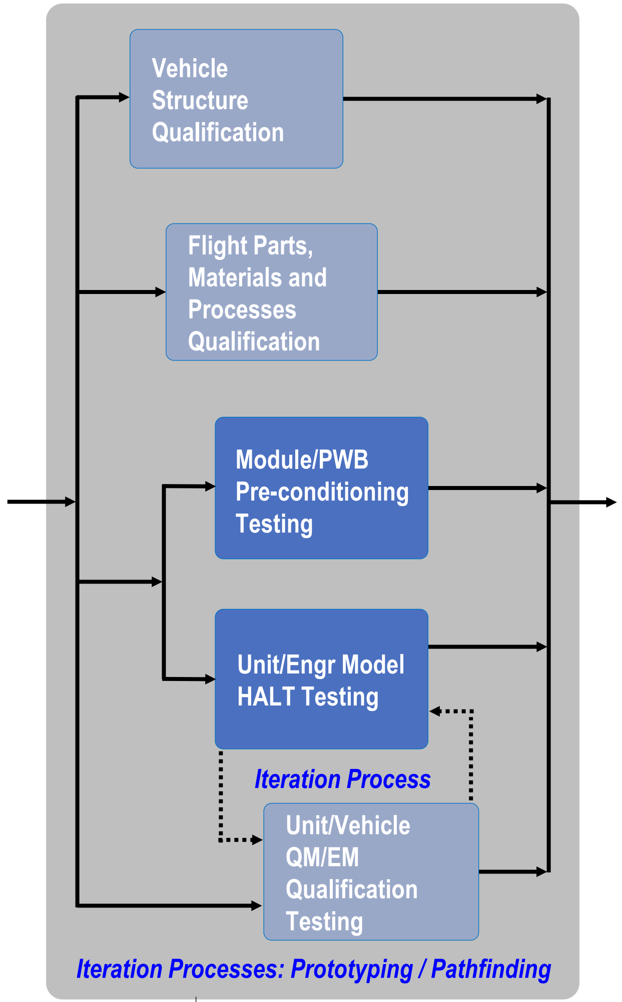
*Legend*

| Typical Activities for Traditional Space Vehicles | Additional Activities for Proliferated Space Vehicles |
|---|---|

- Vehicle structure is qualified early-on with analytical models and physical testing
  - Models are correlated to physical tests (e.g., Quasi-static loads; Coupled loads; Mode survey, etc.)
- Flight parts, materials, and processes are qualified – but parts/components selected from a standard catalog that designers don't deviate from
  - Greater use of COTS electronic parts significantly brings down costs
  - COTS parts enables earlier brassboard/prototype/engineering model testing – allowing for multiple design iterations in a short period
- Heavy focus on development activities distinguishes key differences between constellation space vehicles from traditional space vehicles
  - Module Pre-conditioning is a thermal cycling test performed below the Unit-level where testing is cheapest at the lowest hardware level
  - HALT testing ruggedizes the design, reducing latent defect rate
    - Weakest link typically solved with process or part change; more mass not typically required
- Once development testing has been completed the product (unit/subsystem /vehicle) is more robust – it is ready for formal Qualification testing
  - Qualification-levels are recommended if affordable

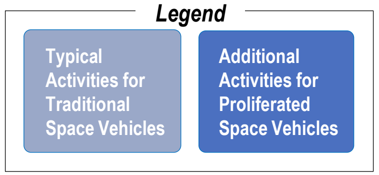
**Greater emphasis on EMs, brassboards, and development testing like HALT to reduce life cycle costs**

**Development & Qualification – Proof of Design**

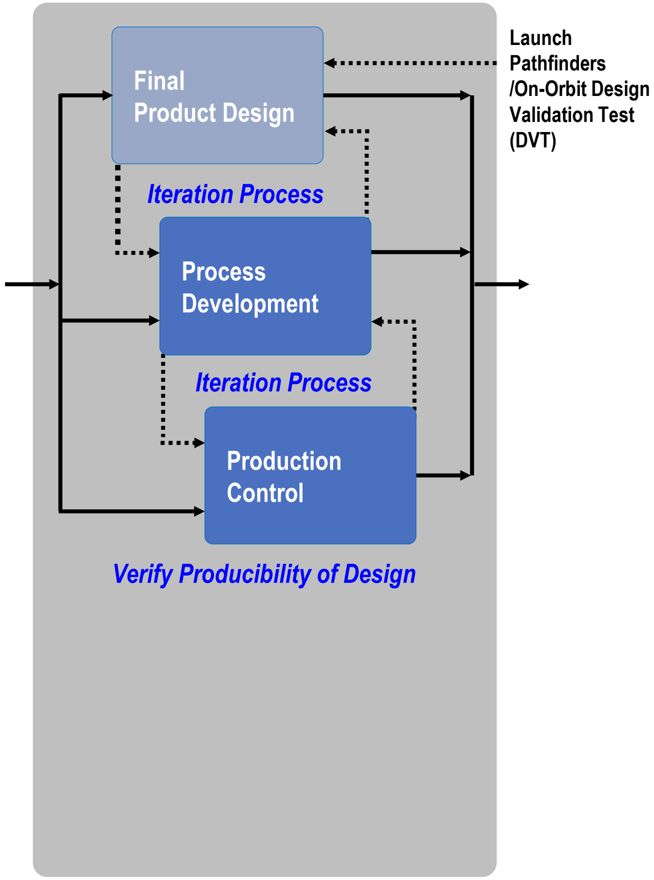



COTS – Commercial-off-the-Shelf
EM – Engineering Models
HALT – Highly Accelerated Life Test

# Development and Qualification – Proof of Design (2 of 3)



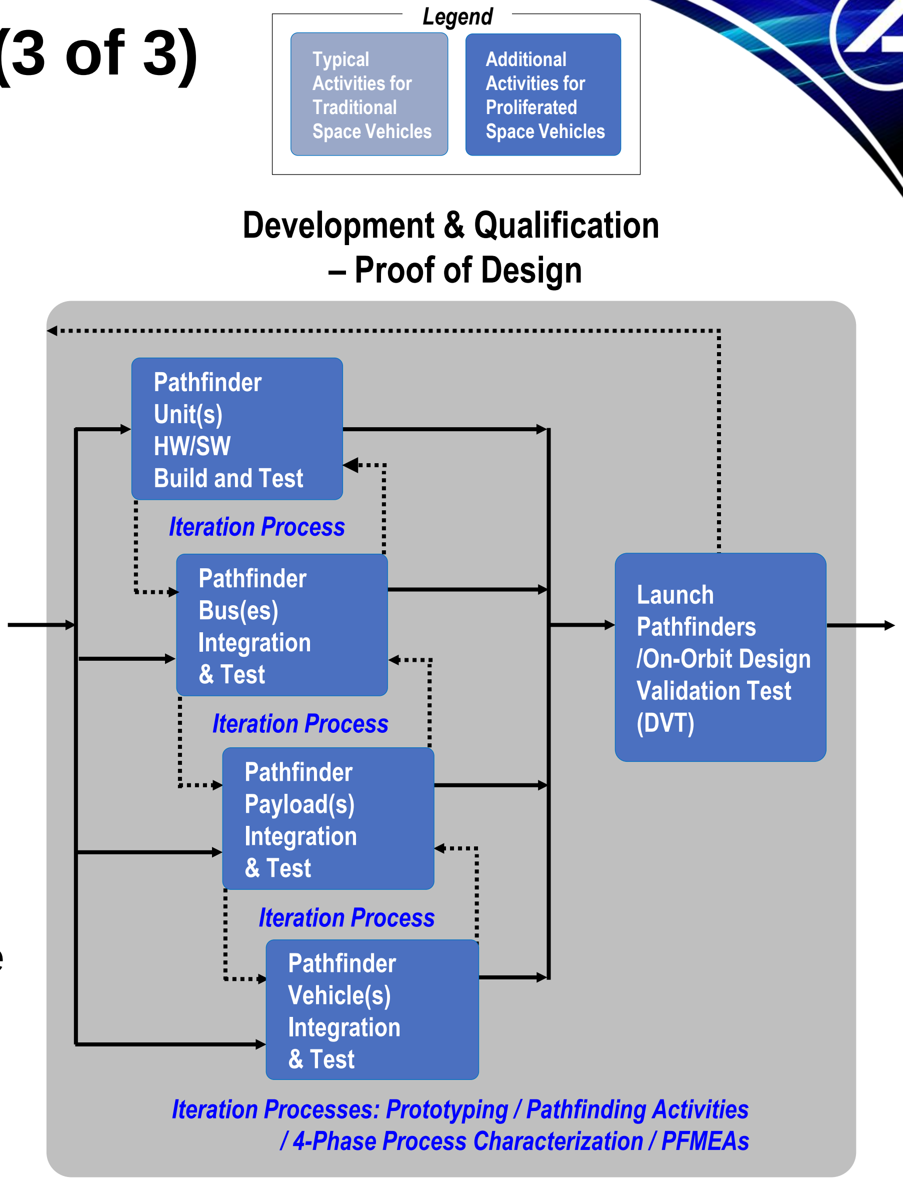

- Final Product Design
  - At conclusion of Development & Qualification testing – final design changes are made to incorporate fixes/improvements from development activities (e.g., HALT, etc.)
  - Potential to carry design trades into pathfinder build to evaluate on-orbit and develop hardware sooner
  - Feedback loop into process development and final product design
    - Test ports, witness samples/test features, and fixturing built into the design
- Process Development
  - In-process optimization and measurements ensure defect free hardware
  - Can provide feedback into product design to create a more repeatable, efficient product
  - Ideally, product is processed “in equal chunks of time” – work instructions define operational steps (i.e., manufacturing execution)
  - Automation opportunities are identified (e.g., “one-button” SV test automation)
- Production Control
  - Master production scheduling (MPS) lead-times defined
  - ERP order quantities and inventory requirements defined
  - Equipment/Facility layouts defined




**Process Development and Production Control is significantly more iterative and in-depth for constellation space vehicles**

ERP – Enterprise Requirements Planning
SV – Space Vehicle

# Development and Qualification – Proof of Design (3 of 3)

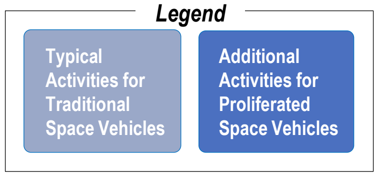



- Pathfinder Unit(s) HW/SW Build & Test
  - Depending on make/buy considerations, unit-level HW/SW first articles are be built in-house or external
  - Focus is on understanding initial manufacturability concerns and anomaly resolution (5-Why's)
    - Emphasis is on ensuring manufacturing/test repeatability of first articles
- Pathfinder Bus(es) Integration & Test
  - Engineering drawings released
  - Manufacturing work instructions integration & test procedures baselined
  - ERP system loaded – all parts/materials received and in stores
  - Testability issues/anomalies addressed
- Pathfinder Payload(s) Integration & Test
  - Depending on make/buy considerations, Payload HW/SW first articles are built in-house or external
  - Integration and test flow are baselined
- Launch/On-Orbit Design Validation Test
  - Uncover design escapes and validate design prior to full-rate production

**Pathfinder lessons learned are incorporated into process optimization and process controls …**

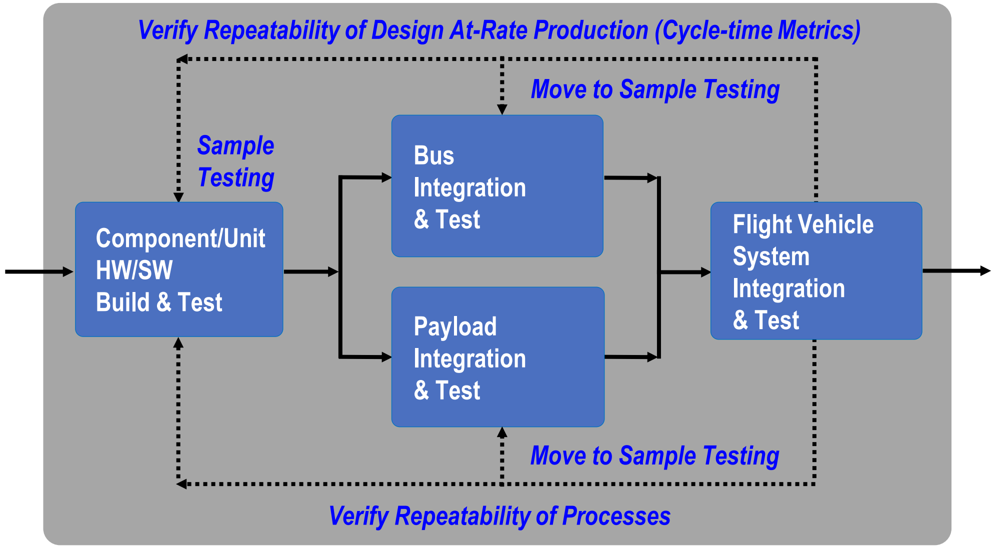
HW – Hardware
SW – Software
PFMEA – Process Failures Modes & Effects Analysis

# Low-Rate Initial Production (LRIP)




- Component/Unit HW/SW Build & Test
  - Production of flight components/units starts
  - Designs were optimized for ease of production, simplified, and standardized to meet cost targets
  - Parts, components, and units were ruggedized during development to ease qualification testing and verify anomalies are “designed-out” to ensure high process repeatability
  - Acceptance testing is performed initially, and gradually moved to sample testing as cycles/durations are reduced
  - Production rates are incrementally increased to meet weekly and monthly cumulative delivery requirements

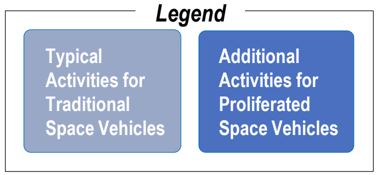
Low-Rate Initial Production – Proof of Manufacturing




- Bus Integration & Test
  - Same as component/units – verify Subsystem anomalies are “designed-out” to ensure high process repeatability
- Payload Integration & Test
  - Supplier Development activities utilized during development to ensure Payload-providers ship robust products
- Flight Vehicle System Integration & Test
  - Feedback loops ensure “safety valve” to decouple occasional troubleshooting offline and keep production flowing

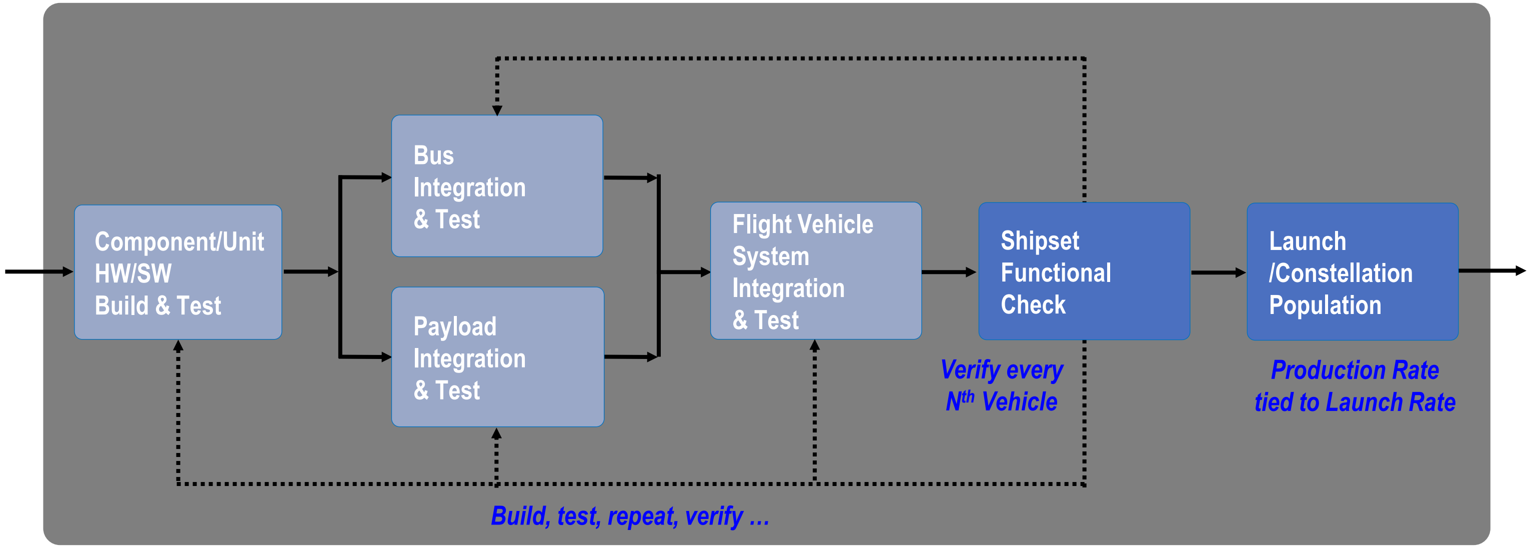
**Processes are monitored to ensure defect rate remains low; selected acceptance testing confirms**

# Full-Rate Production (FRP)




- Full-Rate Production
  - Supported by on-time delivery of components and units to Bus/Payload Integration & Test, and Flight Systems Integration & Test
  - Verifies manufacturing processes are capable of sustained production of components and units that meet quality requirements consistently
  - Assembly-line is running at required capacity to support launch cadence

**Full-Rate Production**




Note: First four boxes are the same as on LRIP.

- Shipset Functional Check
  - Spot-checks manufacturing processes to ensure no process shifts have occurred and stay in statistical control
    - Shipset = Max quantity required that can be launched (fits under the Fairing)
  - Feedback loops ensure "safety valve" to decouple occasional troubleshooting offline and keep production flowing
- Launch/Constellation Population
  - Space vehicle output is matched to launch vehicle cadence to maximize efficiency and ensure vehicles/spares meet operational capability requirements

**Amount of rework typical of a traditional space vehicle would quickly bring a constellation assembly line to a stop …**

# Product Design & Development Testing

# Design for Manufacturing and Assembly (DFMA)

## Robust Design Methods

**Design for Manufacturing and Assembly**

- *Design for Manufacturing and Assembly (DFMA)* is a set of design principles that allows a product to be easier to manufacture while minimizing the product cost
  - Considers operations that can be designed for automation
- DFMA minimizes the total product costs:
  - Reduced product design costs through fewer parts and less complex parts (optimizes part for assembly)
  - Reduced assembly costs through fewer number of assembly operations and less complex operations (optimizes manufacturing process)

DFMA Principles:

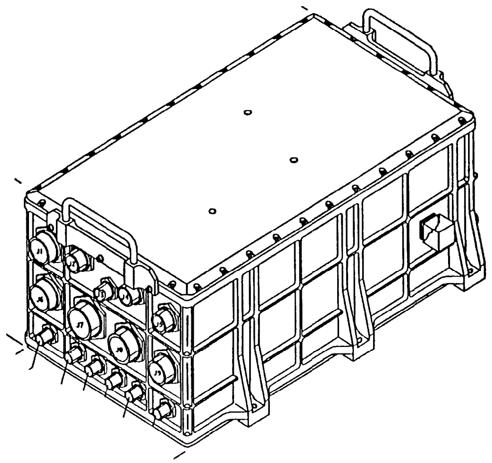
- ✓ Simplify and minimize number of parts
- ✓ Minimize levels of assembly
- ✓ Mistake-proof product features for assembly (e.g., only one way for parts to fit together)
- ✓ Minimize fasteners – use snap-fit parts (when possible)
- ✓ Standardize and use common parts/sizes
- ✓ Design parts for ease of fabrication
- ✓ Minimize reorientation of parts during assembly
- ✓ Develop modular designs as building blocks

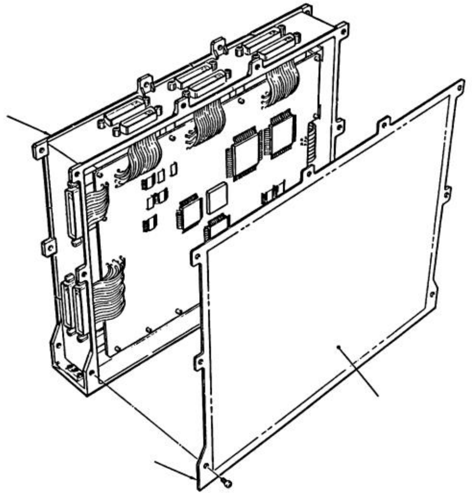
**Most of all production costs are determined in the early stages of design**

# Pre-conditioning Testing

## Development Test Methods

- Pre-conditioning Testing
  - Performing thermal cycle testing on individual slices or units prior to formal unit-level thermal cycle testing
    - Detect problems early
    - Testing over a very wide temperature range
- Aerospace Assessment
  - As part of tailoring the number of unit cycle requirements, consideration is given for pre-conditioning testing
    - All slices/boards in the unit are pre-conditioned
    - Slices/boards are powered-on
    - Functional testing performed in a manner consistent with unit testing
    - Anomalies and defects are reported and tracked
  - Credit may be given for an equivalent screening environment up to half the required unit cycle count
    - Applicable for Qualification, Protoqualification, and Acceptance hardware
- An option called-out in TR-RS-2014-00016/S-016





# Highly Accelerated Life Testing (HALT)

## Development Test Methods

- HALT philosophy:
  - Understand product margins and design limits by stimulating failure modes
  - Improve product robustness prior to starting production to reduce production and field failures
- HALT process:
  - Determine maximum operating and destruct limits
  - Determine root cause of observed failure modes
  - Correct root causes to improve product robustness, prior to entering flight unit production
- Typical HALT environment stimulus:
  - Vibration step stress
  - Hot and cold temperature step stress
  - Rapid thermal cycling
  - Combined environments: Vibration step stresses simultaneous with rapid thermal cycling
- HALT implementation:
  - First phase of HALT is performed at the lowest practical level
  - Subsequent phases of HALT are performed at higher levels of assembly (where possible)
    - Testing at higher levels of assembly allows interface problems to be identified and corrected
    - Subsequent phases validate effectiveness of earlier corrective actions

**HALT is a viable way to improve product circuit & mechanical robustness to reduce production and on-orbit issues**