Recommended Verification Approach for Human Spaceflight Vehicles

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Introduction

- Human spaceflight necessitates increased scrutiny because of the risks to human life.
- Requirement and hardware verification is the way that this scrutiny is satisfied.
- A Program must be able to provide verification that is convincing, cohesive, and coherent.
- This paper provides a model for verification planning and execution based on lessons learned during a development program.

Application Of This Presentation

- New Government Development Programs
  - Commercial Crew Development
  - Shuttle retirement and replacement
  - Planetary exploration goals
- Space Tourism
- Applications outside of Aerospace Industry where public safety paramount or where strict performance measures must be satisfied.

About The Authors

- Systems Engineering Team from Orbital Sciences Corp. for the Orion Launch Abort System (LAS)
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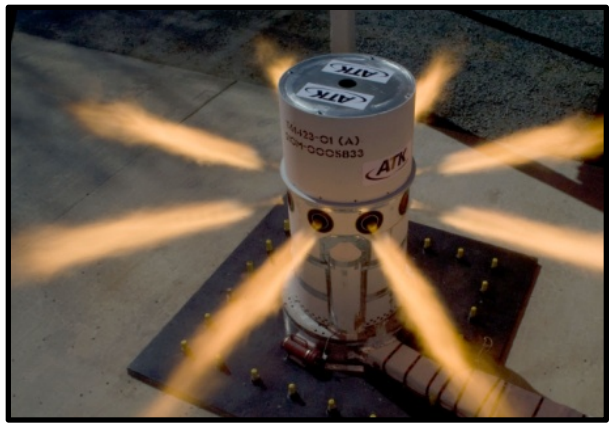
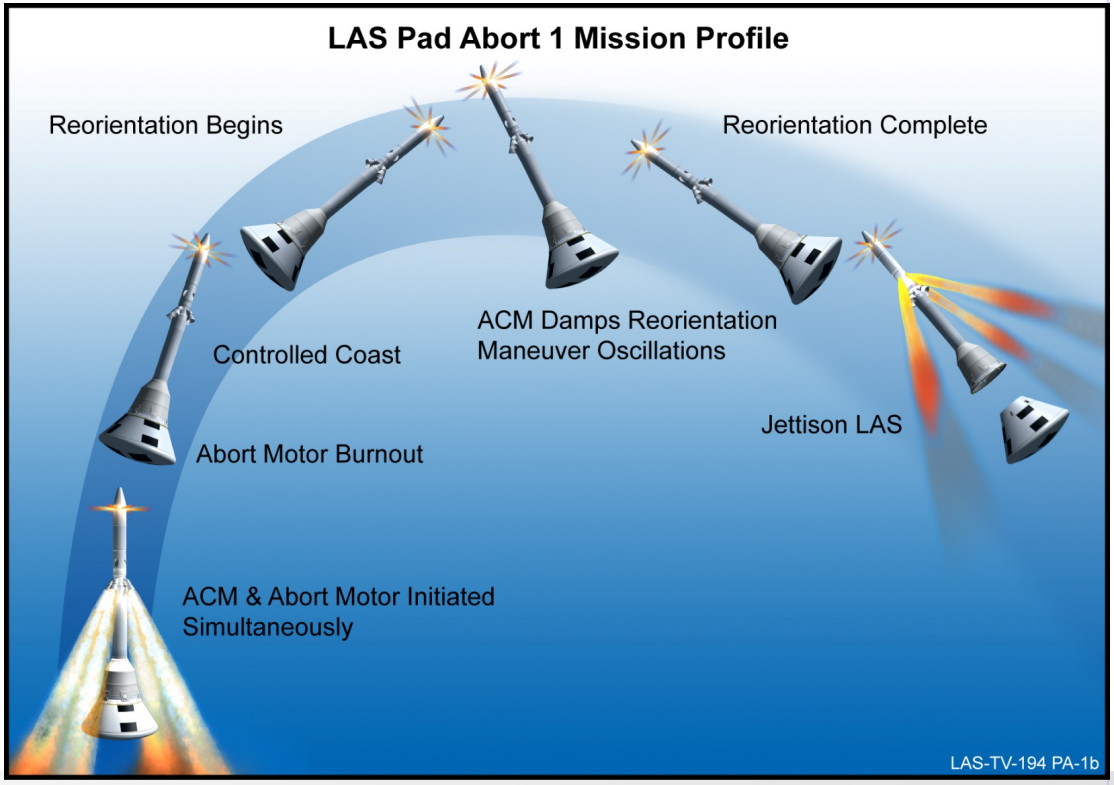
Launch Abort System Overview

- LAS is designed to remove the crew during a launch vehicle failure while on the pad and up to a nominal jettison at approximately 300 kft
- LAS accomplishes this mission using
  - Three solid motors
  - Trajectory optimization during the abort
  - Lightweight composite structures





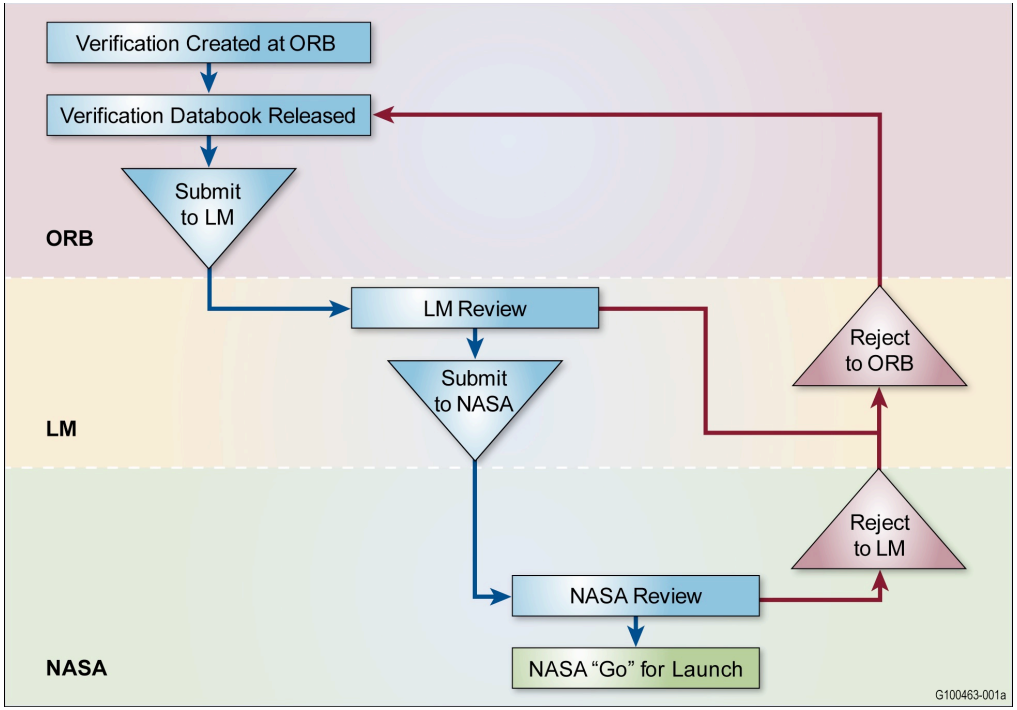
Standard Commercial Approach to Verification

- To date, commercial spacecraft have been uncrewed systems that are usually variations on an existing design.
- Commercial verification is usually based on addressing changes from previously flown or qualified vehicles.
- Greater risks are accepted to reduce cost in absence of a risk to human life.

Human Spaceflight Requires More Rigor

The PA-1 Verification Approach

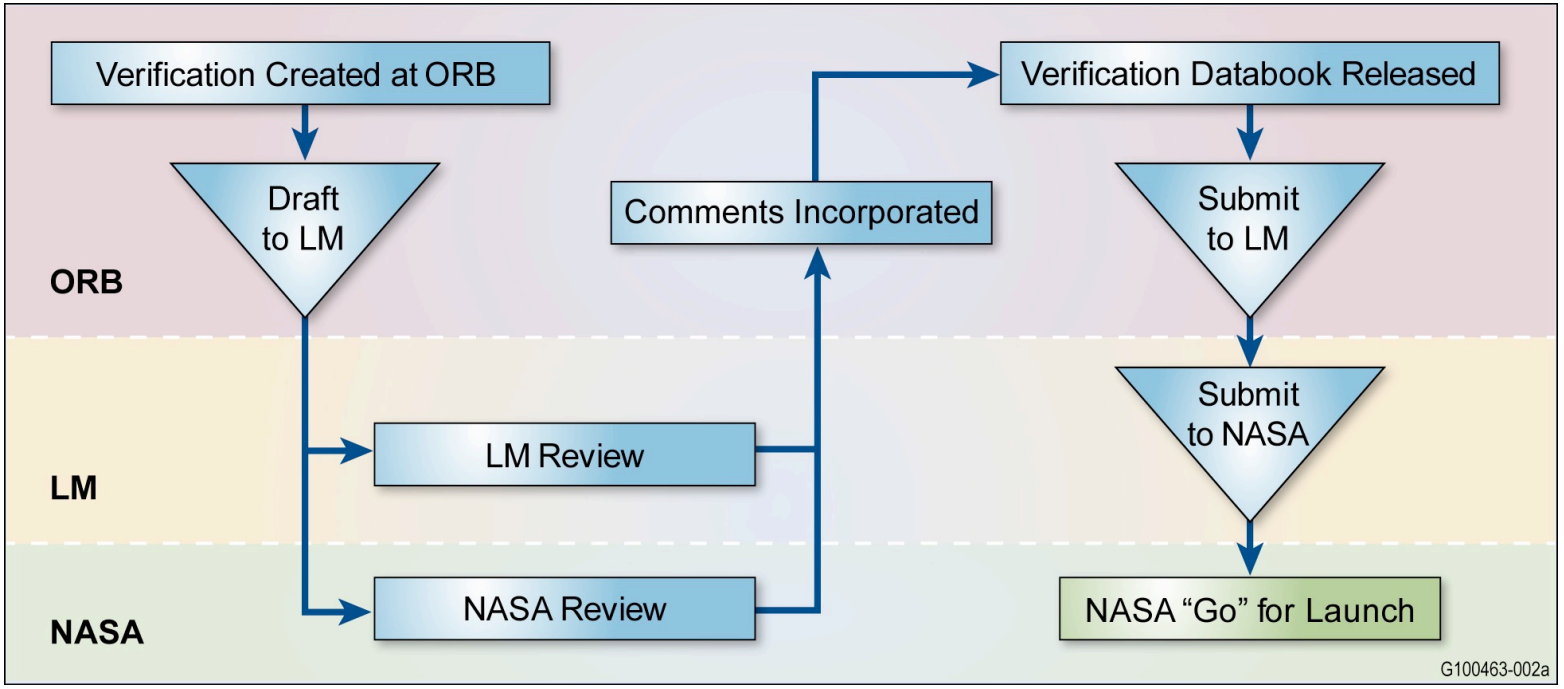
- Originally all verification data for the test flight would be delivered in a single data drop.



- This review process impacts the flight schedule if customers encounter any issues with the verification documentation provided.

The PA-1 Verification Approach

- Orbital, Lockheed Martin, and NASA came up with a new review process that allowed draft submissions and incorporation of review comments before the Verification Databook was delivered.



PA-1 Verification Glossary

- Verification Method:
  - An event or process that has a specific goal related to verification. Verification methods define whether verification is to be accomplished by a test, analysis, demonstration, or inspection.

- Verification Event:
  - The specific activity used to provide verification data. Verification events define **WHAT** test, analysis, demonstration, or inspection will verify a requirement. The verification event includes a description of the expected event.

The PA-1 Verification Approach

- Flight test articles had the same requirements as production (crewed) vehicles.
- Qualification campaigns weren't needed for most vehicle components and subsystems used on PA-1
- A event centric approach was used to verify requirements for the flight tests.
- Test and analysis reports directly address requirement verification.

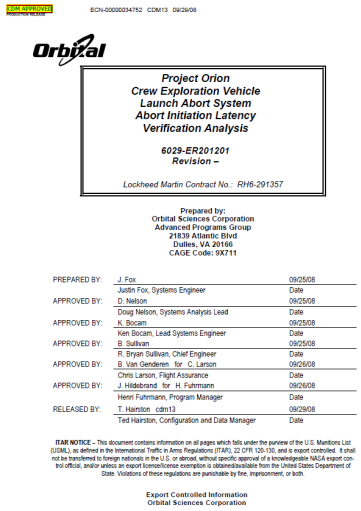
PA-1 Verification Execution

- Verification Methods and Events were coordinated in Working Groups with Lockheed Martin and NASA to decide what data were expected for requirement closure.
- A Verification Cross Reference Matrix (VCRM) was developed for each specification with the WG inputs.
- Completion of the Verification Events in the VCRM constitutes verification of the requirement.
- Documentation of the success of each event is submitted as verification evidence.

Verification Closure Example

- In this example a requirement is verified by two tests and an analysis.

Verification Status: Verified



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Orbital

Project Orion
Crew Exploration Vehicle
Launch Abort System
Abort Initiation Latency
Verification Analysis

6029-ER201201
Revision –

Lockheed Martin Contract No.: RH6-291357

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- Documentation references for these events is included in a compliance matrix and in the Verification Databook.

Mission Outcome: Success!

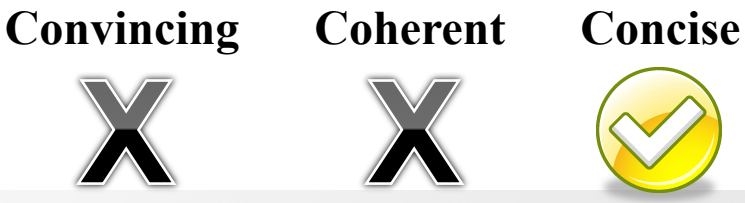
Problems With This Process

- Complicated reporting of status
- Usually, multiple verification reports and versions of the Databook are submitted to close a single requirement
- Reports separated from the Databook lost their context and are confusing or incomplete for reviewers.

Requirements									
				Associated Verification					
							Verification Documentation		
Number	Name	Text	Status	Number	Name	VMStatus	Document Number	Rev	Document Name
CP-7	Loads	The component shall meet all functional and performance requirements after exposed to the loads in the table below	Verified	CP-A5	Stress Analysis	Complete	6029-ER3093	-	Structural Analysis Report
							6029-ER30918	A	Structural Analysis Report
							6029-ER30926	A	Secondary Structural Analysis Report
							6029-TR3161	-	Bracket Assembly Static Loads Test
				CP-T6	Static Loads Test	Complete	6029-ER201153	-	Static Loads Test Verification Report
							6029-TR3161	-	Bracket Assembly Static Loads Test
							6029-TR3092	-	Structural Analysis Report

Problems With This Process

- The presentation of compliance data is fragmented.
  - This doesn't allow for **CONVINCING** verification to be easily reported to a reviewer.
- Multiple events that have related outcomes are not tied together for system considerations.
  - This doesn't allow for **COHERENT** verification to be easily reported to a reviewer.
- Systems Engineers and subject matter experts must explain results to tie fragments together.



Lessons Learned:

- Define verification expectations during requirements definition rather than vague verification tasks.
  - Stakeholders need to understand and communicate what they want early in the requirement development process.
- Relate verification data to requirements in the document where the data is generated.
  - When analysis or test reports didn't directly address requirement statements, additional reports had to be written to relate results to requirements.
- Prevent duplication of effort in verification definition and reporting.

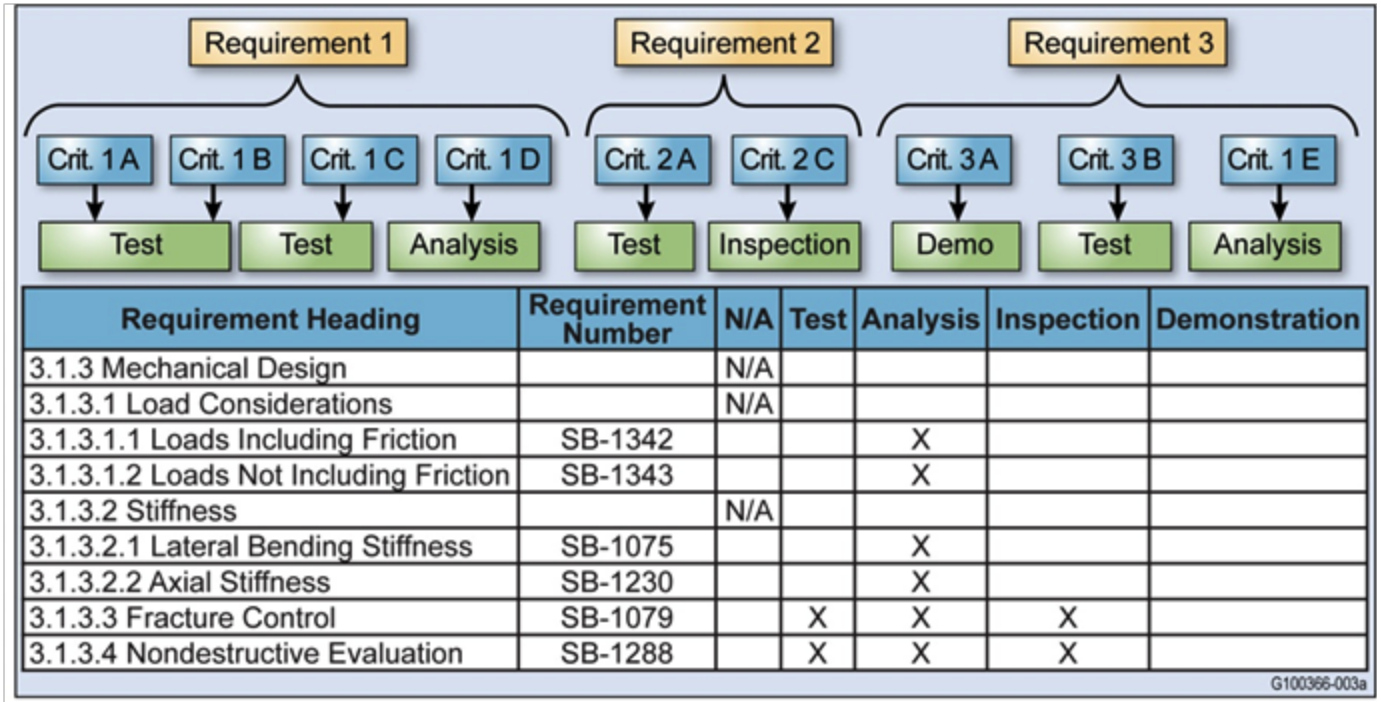
Recommended Approach: Overview

- Develop the verification plan concurrently with requirement development.
- Identify what inputs and results are needed for closure of a requirement.
- Document verification proof for each requirement in a single location.

Recommended Approach: Verification Planning

- Focus on what data (criteria) are necessary for verification of a requirement.

- Data requirements drive verification method selection.



Requirement Heading	Requirement Number	N/A	Test	Analysis	Inspection	Demonstration
3.1.3 Mechanical Design		N/A				
3.1.3.1 Load Considerations		N/A				
3.1.3.1.1 Loads Including Friction	SB-1342			X		
3.1.3.1.2 Loads Not Including Friction	SB-1343			X		
3.1.3.2 Stiffness		N/A				
3.1.3.2.1 Lateral Bending Stiffness	SB-1075			X		
3.1.3.2.2 Axial Stiffness	SB-1230			X		
3.1.3.3 Fracture Control	SB-1079		X	X	X	
3.1.3.4 Nondestructive Evaluation	SB-1288		X	X	X	

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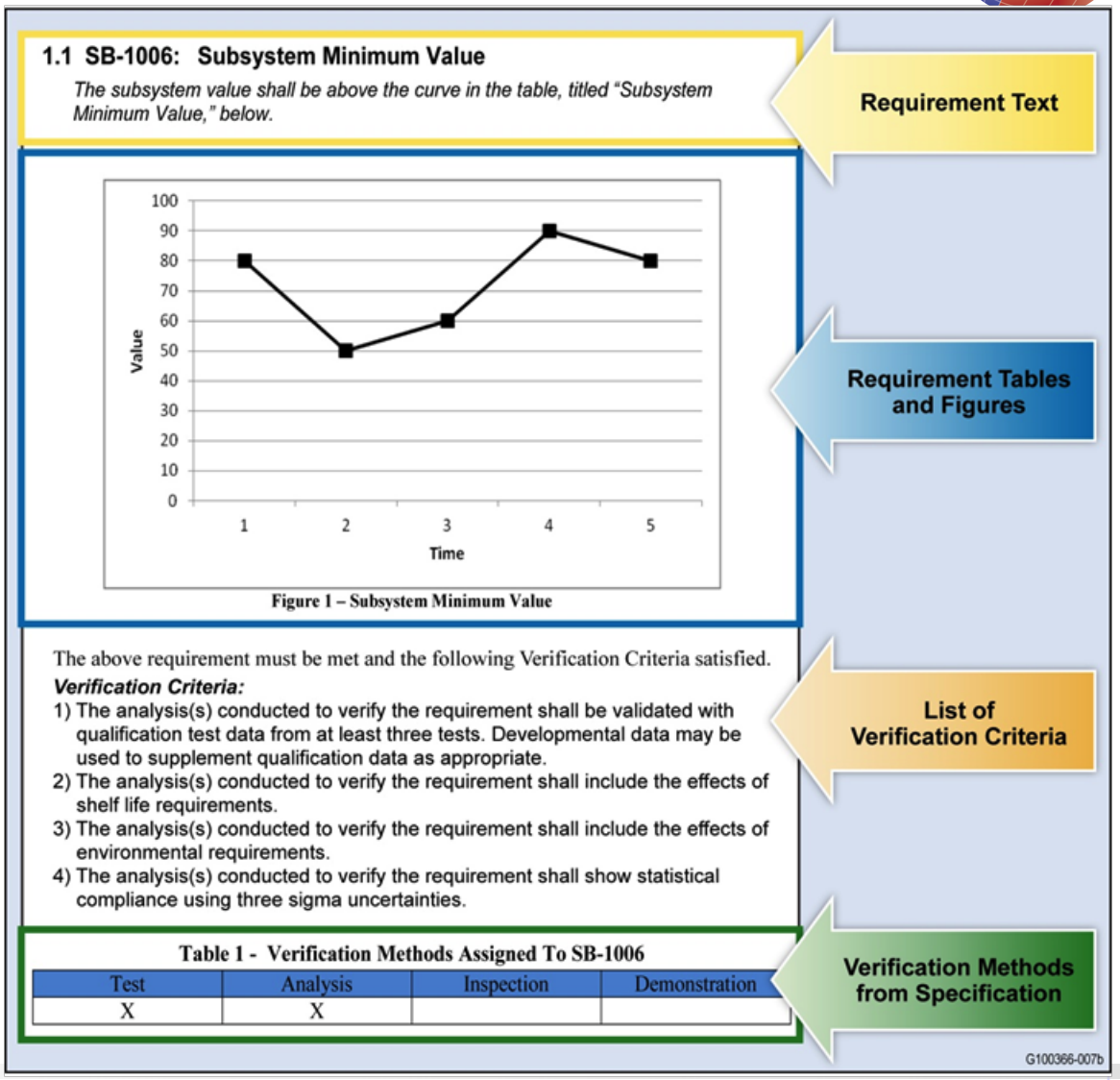
Recommended Approach: Verification Criteria

- Verification criteria specify the minimum standard for showing the requirement is met.
- Verification criteria provide the plan and success criteria to verify a requirement.
- The criteria should be documented and approved internally, possibly in the Master Verification Plan.
- Verification criteria should be defined in a way that allows an engineer to know when the requirement is met in the context of the other requirements.

Implementation Examples: Verification Criteria

- All information about this requirement is available for easy reference and review



Example Verification Criteria

3.2 SB-AM-1007: Delivered Impulse

The abort motor shall provide a minimum impulse of 996,600 lbf-sec during the action time burn at vacuum, a propellant mean bulk temperature of 30 degrees F, -3 sigma burn rate conditions and -3 sigma total impulse conditions (note that total impulse variability encompasses specific impulse and propellant mass variabilities).

The above requirement must be met and the following verification criteria satisfied.

Verification Criteria:

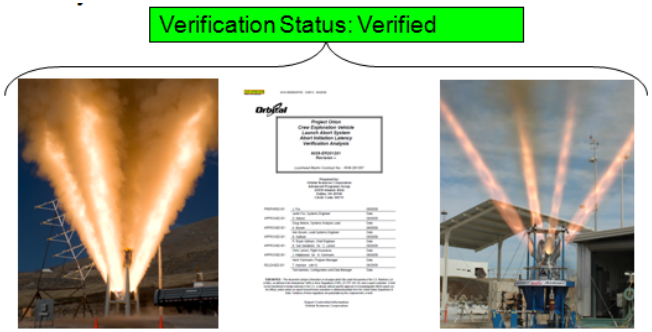
1) The analysis task(s) conducted to verify the requirement shall be validated with qualification test data from at least three static fires. Developmental data may be used to supplement qualification data as appropriate.
2) The analysis task(s) conducted to verify the requirement shall include the effects life requirements (e.g. propellant aging).
3) The analysis task(s) conducted to verify the requirement shall include the effects of environmental requirements (e.g. temperature, pressure).
4) The analysis task(s) conducted to verify the requirement shall show statistical compliance using three sigma uncertainties.
5) Test data from at least three qualification static fires shall show compliance to the requirement in the cold condition with one TBI and in the hot condition with two TBIs, at a minimum. Developmental data may be used to supplement qualification data as appropriate.

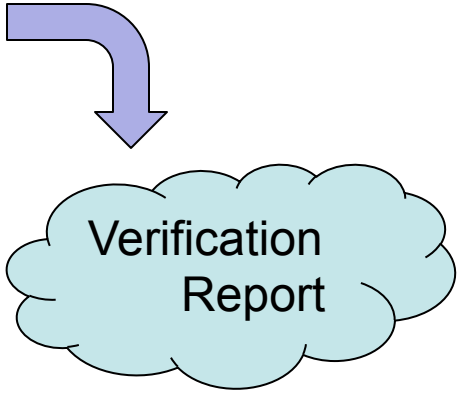
The following are the verification methods assigned to SB-AM-1007

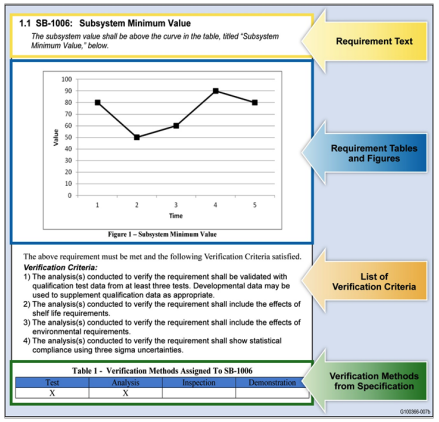
Test	Analysis	Inspection	Demonstration
X	X		

Recommended Approach: Verification Reporting

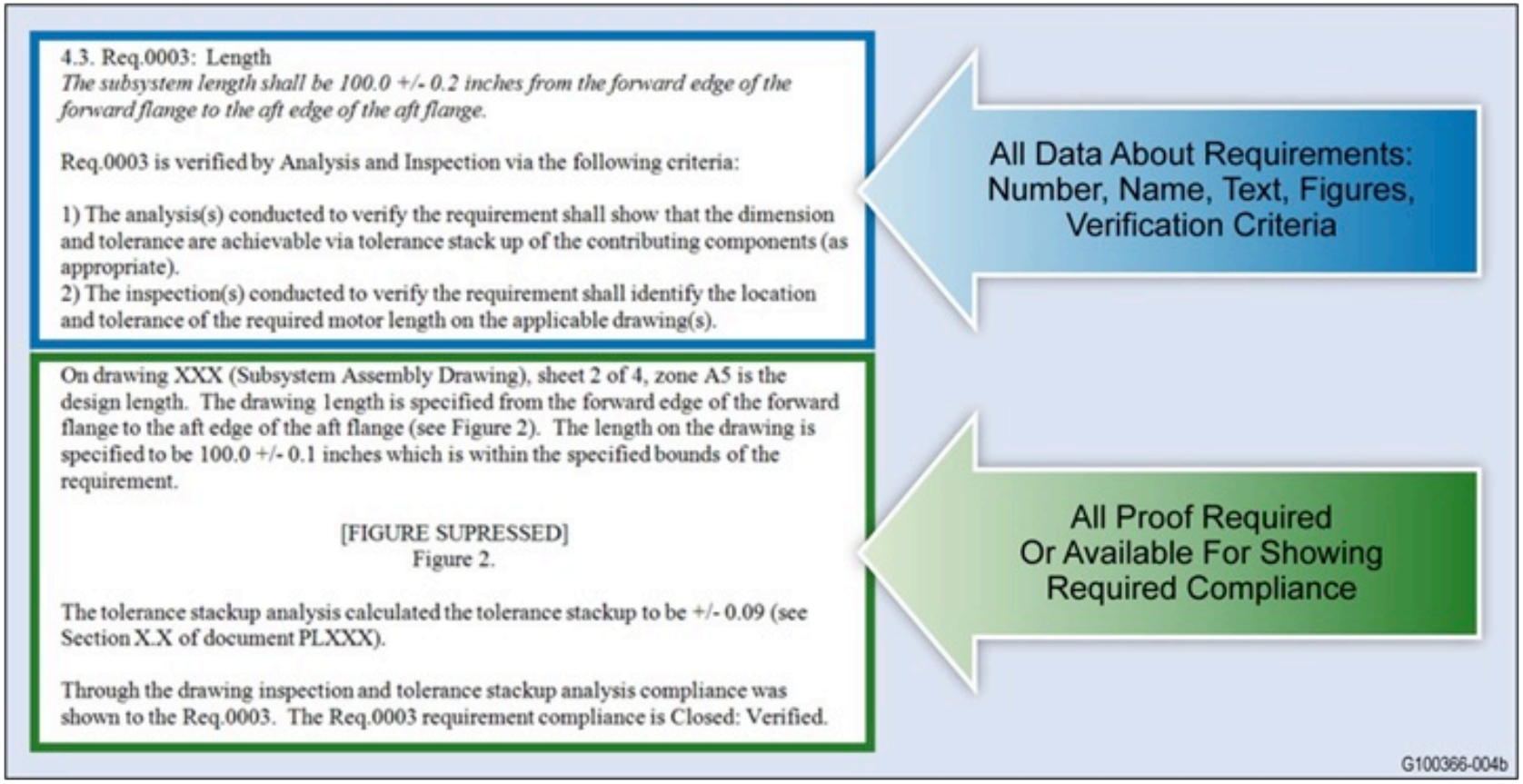
- Address requirements one at a time and completely in a dedicated report
- Present verification data with verification criteria and the requirement for context
- Include the actual data – do not just reference it
- Address all verification criteria







Implementation Examples: Verification Closure Notice



Implementation Proof

- These documents and techniques have been employed with considerably more success.

Conclusion

- Verification is reported in a summary document that has a focused scope.
  - This enables **CONCISE** verification statements to be written by referencing instead of including the background of a verification event.

VCN ID	Mission	Rev

Verification Closure Notice (VCN)

Status

Owner - NASA	Owner - Orbital

Estimated Closure Date

REQ Document	Paragraph #	SS # (Orbital)	REQ Title
SSP 50808	3.3.11.1.3.4	SS_8IRD_0727, [Safety]	VERIFIABLE SEAL LEAKAGE PATHS

REQ Description
Paths through which the atmosphere of any habitable pressurized section might leak to its external environment shall have the redundancy and verifiability requirements contained in Table 3.3.11.1.3.4-1, Seal Redundancy and Verified Requirements.

VER Description

Verification Event Description

Doc #	Revision	Document Title	Para #

Requirement Owner — Signature — Date

NASA T&V — Signature — Date

Concise

Coherent

Convincing

Conclusion

- The presentation of compliance data is in one place with all facets of the requirement addressed.
  - This enables **COHERENT** verification to be easily reported.

VCN ID	Mission	Rev

Verification Closure Notice (VCN)

Status

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Verification Event Description

Doc #	Revision	Document Title	Para #

Requirement Owner

Signature _____ Date _____

NASA T&V

Signature _____ Date _____

Concise

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Conclusion

- Verification events with related outcomes can be tied together by interspersing details from all applicable sources into a single narrative.
  - This enables **CONVINCING** verification by documenting system considerations that may extend beyond the scope of a single test

VCN ID	Mission	Rev

Verification Closure Notice (VCN)

Status

Owner - NASA	Owner - Orbital

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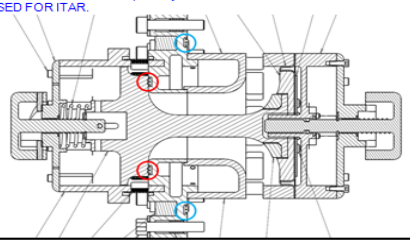
Verification Event Description

PPRV Seals – The PPRV seals in two places. It has 2 seals with the PCM primary structure that are located inside the PCM near the threaded ends of the 6 fasteners that hold the PPRV in place. REMAINING TEXT SUPPRESSED FOR ITAR.



Doc #	Revision	Document Title	Para #

Requirement Owner — Signature _____ Date _____

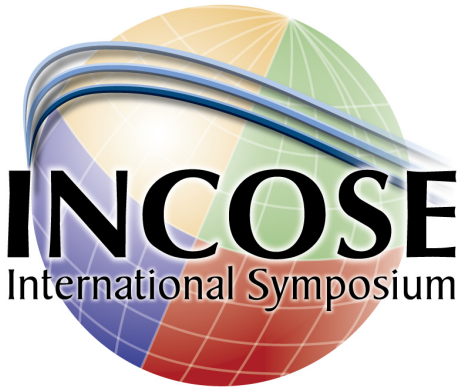
NASA T&V — Signature _____ Date _____

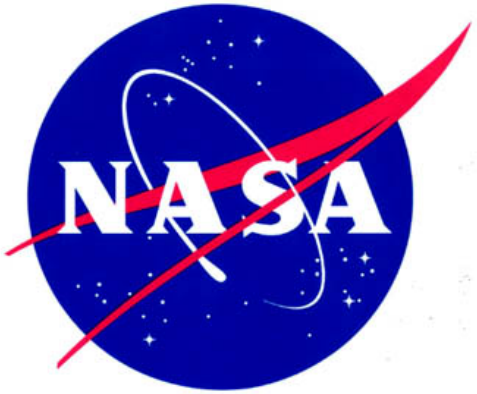
Concise

Convincing

Coherent

Thank Yous





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Questions