Launch Vehicle and Spacecraft Sensor Fabrication and Qualification Standards

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Sensor Definition

- What is a sensor?
  - A measurement device of the physical properties of a system?
  - A scientific instrument for the measurement of physical phenomena in a test object?
  - Both?

Sensor Reliability

- Sensor reliability is essential to launch reliability and mission success.
  - Sensor failures lead to loss of data, loss of spacecraft functions, and launch delays.
  - Sensor reliability is driven by 3 components: Confirmation, Data Qualification, and Manufacturing Reliability.
    - Confirmation and Data Qualification deal with ensuring sensor readings are valid in flight and disqualifying sensors whose reading are not valid.
    - Manufacturing Reliability provides a basis that improves both pre-launch Launch Commit Criteria (LCC) violation rates and in-flight sensor failures.
      - Sensors are complex systems of unique physical properties spanning mechanical, electrical, material, optical, and chemical domains.
      - The integration of these different physical domains is highly complex and not covered explicitly by the concatenation of existing standards.
      - Current sensor manufacturing processes are based on various NASA, Military, and Industry standards that address portions of the sensor construction but not the sensor as a whole element.
      - When these various standards are applied they generally leave holes in the manufacturing process standards, especially in the sensor element.
      - In addition, the application of the existing standards does not focus on the sensor application which involves components located in harsh thermal, pressure, and chemical environments.
      - Thus, the application of these standards does not always adequately address manufacturing of the sensors.
  - Sensors are often procured based on vendor specifications and manufacturing processes are often considered adequate once a qualification test is past.
    - Process variations, material changes, vehicle or spacecraft sustaining engineering changes can lead to subsequent failures traced back to inconsistent manufacturing processes.

Sensor Standard Scope

Sensor Classes

- A standard for the manufacturing of sensors is needed to address all classes of sensors
  - electrical,
  - optical,
  - Micro Electro Mechanical Systems (MEMS),
  - piezo,
  - thermocouple,
  - resistive thermal devices (RTD),
  - Transistor Devices,
  - encoders,
  - mechanical position,
  - chemical detection,
  - radiation detection,
  - etc.

Sensor Characteristics

- Covering general sensor characteristics
  - mechanical design and construction,
  - electrical design and construction,
  - Printed Circuit Board (PCB) design and construction,
  - Electro Magnetic Compatibility (EMC),
  - materials acceptable for use in differing environments (e.g., cryogenic, high temperature, vacuum),
  - process controls,
  - repeatability,
  - calibration,
  - tolerances, and
  - qualification.

Sensor Standard Scope

- The existing standards are sometimes based on components that operate in controlled environments (i.e., focused on avionics in conditioned compartments with cold plates, vibration damping).
- Sensors tend to see much more harsh environments which leads to the application of often conflicting standards driving sensor fabrication.
- Consider appropriate referencing of existing NASA Technical Standards, DoD standards, and external standards where applicable
- Provide guidance for areas not clearly covered by the existing standards or where conflicts exist among standards.

Sensor Manufacturing Improvements

- A Sensor Manufacturing Standard will provide substantial improvements in the Launch Commit Criteria (LCC) violation rates for launch vehicles and in flight sensor failures for satellites and spacecraft.
- This will provide consistency in the application of standards to sensor manufacturing
  - The concatenation of current NASA Technical Standards and external standards has been very project specific. This results in variations and inconsistencies between programs and projects in the quality of sensor implementations. None of these approaches fully address the complex issues involved in the manufacture of sensors.
  - This new manufacturing standard should avoid conflicting or confusing requirements placed on the manufacture of sensors.
- The provision of clear and concise standards for the manufacturing of sensors is essential to achieve the high levels of reliability in sensor applications necessary for an affordable U.S. Space Program.

Examples of Current Standards Applied to Sensor Manufacturing

- NASA-STD-8739.3, Soldered Electrical Connections;
- MIL-STD-2000, Military Standard Requirements for Soldered Electrical and Electronic Assemblies;
- MIL-PRF-55110, Performance Specification, General Specification for Printed Circuit Board, Rigid;
- MIL-P-50884, Performance Specification, General Specification for Printed Wiring Board, Flexible or Rigidflex;
- MIL-PRF-31032, Performance Specification, General Specification for Printed Circuit Board/Printed Wiring Board;
- NHB 5300.4, Inspection System Provisions for Aeronautical and Space System Material, Parts, Components, and Services;
- MIL-STD-810F, DOD Test Method Standard for Environmental Engineering Considerations and Laboratory Tests;
- NSTS-37330, Bonding, Electrical, and Lightning Specifications;
- DOD-D-100, Standard Practice for Engineering Drawings;
- DOD-D-1000, Military Specification for Drawing, Engineering, and Associated Lists;
- Various ASTM, ANSI, IEEE standards.

Shuttle Sensor Failure Survey

- A survey has been conducted of Shuttle sensor failures in the Shuttle Problem Reporting and Corrective Action (PRACA) database.
  - 450 sensor failures where identified over the life of the Shuttle program:
    - 349 Space Shuttle Main Engine (SSME),
      - 67% of the SSME High Pressure Fuel Turbo Pump (HPFTP) sensor failures were identified as related to manufacturing problems.
    - 64 External Tank (ET), and
    - 37 Solid Rocket Booster (SRB).
- Specific manufacturing areas identified to be addressed in this example included moisture sealing, wire coating, and material compatibility with environment.

SHUTTLE SURVEY NOMENCLATURE

Failure Mode refers to a specific symptom shown when a sensor fails.

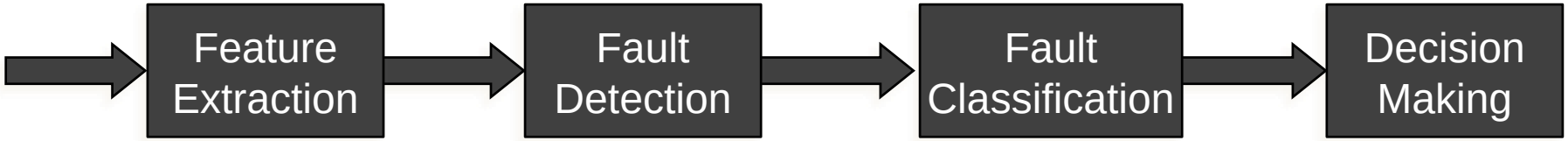
Failure Cause refers to a specific manufacturing-related factor that is attributed to the failure.

Failure Frequency refers to the number of times a specific sensor has failed in the same mode.

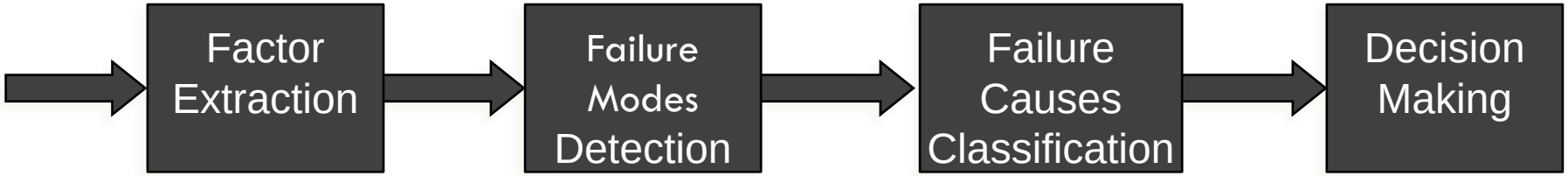
Failure Occurrence is the same as ***Failure Frequency***

DIFFERENT APPROACHES, SIMILAR PROCESSES

Diagnosis of Sensor Fault



Identification of Manufacturing Causes of Sensor Failure



SPACE TRANSPORTATION SYSTEM (STS)
CASE STUDY

PRACA database provides the shuttle-related Sensor Problem Records (PRs) for the following projects/systems:

- Space Shuttle Main Engine (SSME)
- Solid Rocket Motor (SRM)
- Solid Rocket Booster (SRB)
- External Tank (ET)
- System Engineering and Integration (SE&I)
- Common Shuttle Hardware (CSH)
- Advanced TurboPump Development (ATD)
- Inertial Upper Stage (IUS)

SPACE TRANSPORTATION SYSTEM (STS)
CASE STUDY

Each project/system consists a number of components/elements:

- Space Shuttle Main Engine (SSME)
  - High Pressure Fuel Turbopump (HPTF)
  - Low Pressure Fuel Turbopump (LPFT)
  - High Pressure Oxidizer Turbopump (HPOT)
  - Low Pressure Oxidizer Turbopump (LPOTP)
  - Fuel Preburner (FPB)
  - Oxygen Preburner Oxidizer Valve (OPOV)
  - Main Combustion Chamber (MCC)
  - Main Fuel Valve (MFV)
  - Main Injector (MI)
- Solid Rocket Booster (SRB)
  - Auxiliary Power Unit (APU)
  - (FWD IEA)
  - (AFT IEA)

SPACE TRANSPORTATION SYSTEM (STS)
CASE STUDY

High Pressure Fuel Turbopump (HPTF)

- 98 Temperature Sensor NCAs
- 10 Pressure Transducer NCAs
- 18 Speed Sensor NCAs
- 3 Motional Transducer NCAs
- 4 Speed Pickup NCAs

Total 133 NCAs

High Pressure Oxidizer Turbopump (HPOT)

- 35 Temperature Sensor NCAs
- 17 Pressure Transducer NCAs

Total 52 NCAs

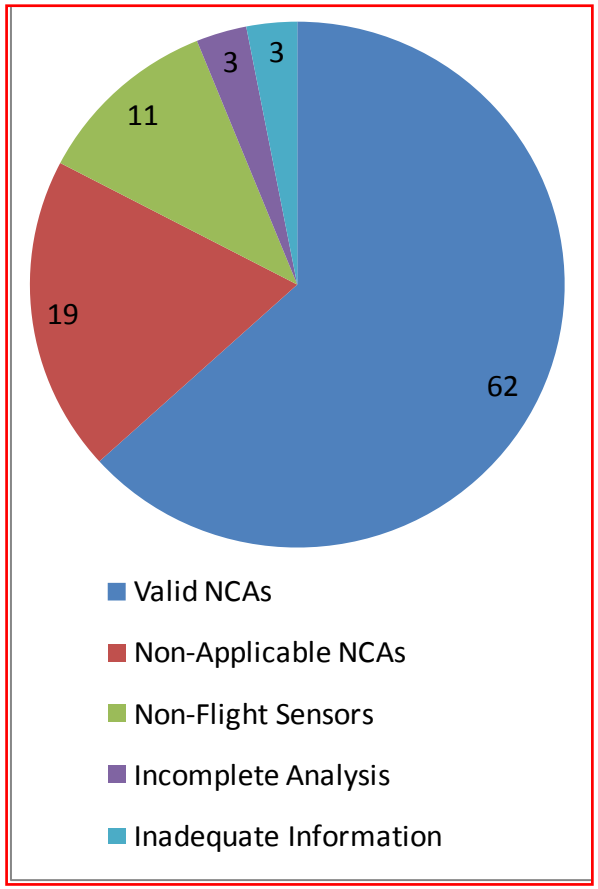
Auxiliary Power Unit (APU)

- 15 Magnetic Speed Sensor NCAs
- 14 Pressure Transducer NCAs
- 4 Temperature Sensor NCAs
- 4 Turbine Speed Sensor NCAs

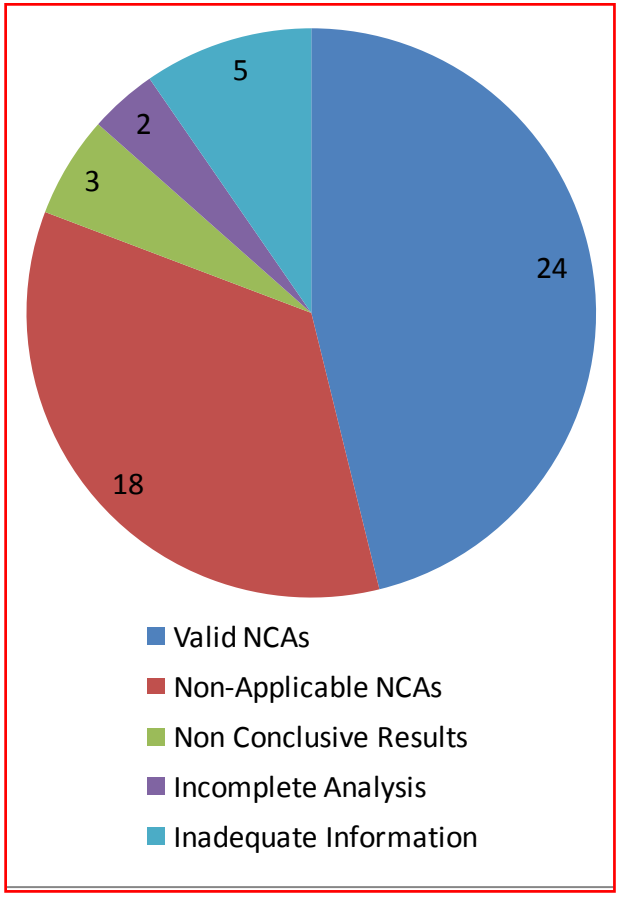
Total 27 NCAs

SPACE TRANSPORTATION SYSTEM (STS)
CASE STUDY ANALYSIS RESULTS

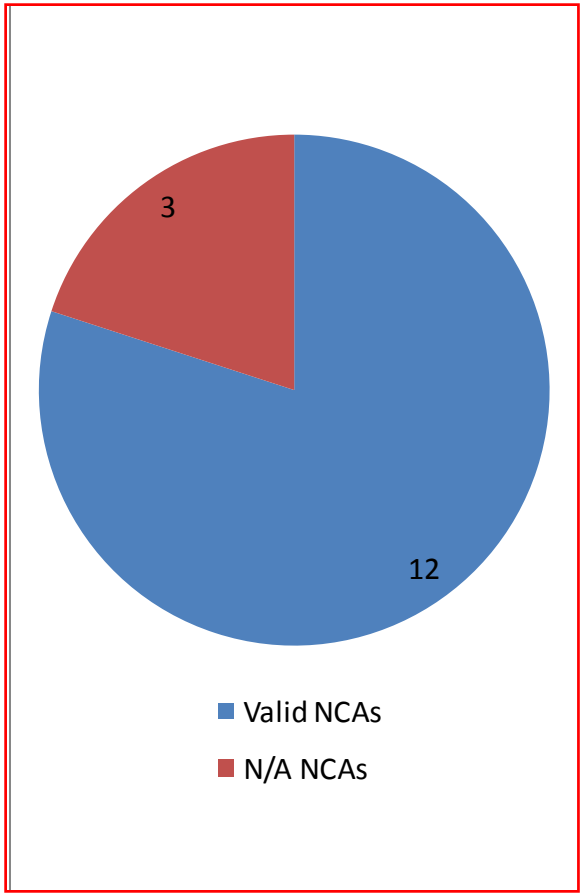
HPTF (98)



HPOT (52)



APU (15)



SPACE TRANSPORTATION SYSTEM (STS)
CASE STUDY ANALYSIS RESULTS

Temperature Sensor Types		Sensor Models	Note
RTD	RES7002 Series (Cryo Temp)	RES7002-231 RES7002-241	The higher the model number, the newer the design. E.g. sensor model RES7004-101 is the newer version than RES7004-91.
RTD	RES7004 Series (Hot Fire Temp)	RES7004-41 RES7004-51 RES7004-71 RES7004-81 RES7004-91 RES7004-101	
RTD	MRE7013 Series (Hot Fire Temp)	MRE7013-01	
Thermal Couple	RE1751 Series (Hot Fire Temp)	RE1751-01 RE1751-02 RE1751-03 RE1751-04	

SPACE TRANSPORTATION SYSTEM (STS)
CASE STUDY ANALYSIS RESULTS

Pressure Sensor Type		Sensor Models	Notes
Strain-gage pressure transducer	RES7001 Series	RES7001-34, RES7001-39, RES7001-54, RES7001-102, RES7001-114, RES7001-119, RES7001-202 RE2233-001*	The higher the model number, the newer the design. E.g. sensor model RES7004-91 is the newer version than RES7004-71. * RE2233 is a replacement of RES7001-202, according to Bob Burns.

Speed Sensor Type		Sensor Models	Notes
Magnetic Pickup Unit or Magnetic speed sensor	10201-0049	-809 -820	The bigger the model number, the newer the design.

SPACE TRANSPORTATION SYSTEM (STS)
CASE STUDY ANALYSIS RESULTS

Failure Mode	Description
Mode 1	Electrically Open on Sensor Output
Mode 2	Intermittent Open On Sensor Output
Mode 3	Sensor Output Drifting/noisy/ erratic
Mode 4	Low Insulation Resistance (I.R.)
Mode 5	Probe Tip Partially Broken
Mode 6	Crack occurred in probe nose
Mode 7	Spiking Sensor Output
Mode 8	discrepancy between ch. outputs of the same unit
Mode 9	High-potential (HIPOT) insulation reading irratic
Mode 10	Coil winding resistance infinity (open)

SPACE TRANSPORTATION SYSTEM (STS)
CASE STUDY ANALYSIS RESULTS

Failure Causes	Description
Cause 1	Break/fracture in sensor element wire to cause output open/off scale.
Cause 2	Heavy plasma coating induced wire distress to cause wires fatigue
Cause 3	Thermally induced wire stress, expansion or contraction cycles
Cause 4	Crack in coax tube at rear pressure seal braze to cause leak
Cause 5	Charred foam in sensor housing to produce moisture
Cause 6	Oxide build-up on chromel contacts causing noise
Cause 7	Inadequate back fill of Helium gas (insulation to block moisture)
Cause 8	Entrapped moisture produced by silicon foam curing process
Cause 9	Sensor probe tip partially damaged. Material can't sustain debris within the flow
Cause 10	Engine debris impact on the element glass tube to cause glass crack and ele. wire broken
Cause 11	Sharp geometry change induced high residual stress/fatigue to cause metal crack
Cause 12	Excessively-high-voltage generated heat to cause bridge resistor crack
Cause 13	Inadequate strain relief induced high stress/fatigue to cause thin gage wires broken
Cause 14	Residual metal burr/wire piece/solder to short circuit contacts, causing erratic output
Cause 15	Wrong materials used for the electrical connector pins to cause signal errors
Cause 16	Ceramic bobbin broken caused by assembly interference (due to inaccurate fabrication), resulting in sensor dielectric insulation failure.
Cause 17	Coil wire broken due to excessive tensile stress (caused by improper strain relief, excessive bending, thermal expansion, etc.)
Cause 18	Lack of electrical insulation between coil wire to lead wire terminal(s) and the MPU case.
Cause 19	Water/moisture leaked into MPU through o-ring seals, resulting in low I.R.

SPACE TRANSPORTATION SYSTEM (STS)
CASE STUDY ANALYSIS RESULTS

Sensor Type/Model		Failure Mode	Cause 1	Cause 2	Cause 3	Cause 4	Cause 5	Cause 6	Cause 7	Cause 8	Cause 9	Cause 10	Cause 11	Cause 12	Cause 13	Cause 14	Cause 15	Cause 16	Cause 17	Cause 18	Cause 19
RES7001	-34	Mode 3													1						
	-39	Mode 1												1							
	-54	Mode 2													1						
	-102	Mode 7														1					
	-114	Mode 3													1						
		Mode 4													1						
	-119	Mode 7													1						
	-202	Mode 7														1					
RE2233	-002	Mode 3													1						
RES7002	-231	Mode 3										2									
	-241	Mode 3										2									
RES7004	-41	Mode 4				1															
		Mode 5									4										
	-51	Mode 4				1															
	-71	Mode 1	10	2	3																
		Mode 2	3	2	1																
		Mode 3				1															
		Mode 4				13															
	-81	Mode 1	3																		
		Mode 4							2	7											
	-91	Mode 1	1																		
		Mode 2		1																	
		Mode 4				1			2												
		Mode 6											1								
	-101	Mode 1	1																		
		Mode 4								1											

SPACE TRANSPORTATION SYSTEM (STS)
CASE STUDY ANALYSIS RESULTS

Sensor Type/Model		Failure Mode	Cause 1	Cause 2	Cause 3	Cause 4	Cause 5	Cause 6	Cause 7	Cause 8	Cause 9	Cause 10	Cause 11	Cause 12	Cause 13	Cause 14	Cause 15	Cause 16	Cause 17	Cause 18	Cause 19
MRE7013	-101	Mode 1	3																		
RE1751	-01	Mode 3						3													
		Mode 4							2												
	-02	Mode 4							1												
	-03	Mode 6											3								
	-04	Mode 8															1				
10201-0049	-809	Mode 4																		1	2
		Mode 9																8			
	-820	Mode 10																	1		

SPACE TRANSPORTATION SYSTEM (STS)
CASE STUDY ANALYSIS RESULTS

Sensor Models	Failure Modes	Number of Failures (Occurrences) 0 5 10 15
RES7004-41	Mode 5: Probe Tip Partially Damaged	Failure Cause 9
	Mode 4: Low Insulation Resistance (I.R.)	Failure Cause 4
RES7004-51	Mode 4: Low Insulation Resistance (I.R.)	Failure Cause 4
RES7004-71	Mode 1: Electrically Open on Sensor Output	Failure Cause 1 Failure Cause 2 Failure Cause 3
	Mode 2: Intermittent Open On Sensor Output	Failure Cause 1 Failure Cause 2 Failure Cause 3
	Mode 3: Sensor Output Drifting or Fluctuation	Failure Cause 4
	Mode 4: Low Insulation Resistance (I.R.)	Failure Cause 4
RES7004-81	Mode 1: Electrically Open on Sensor Output	Failure Cause 1
	Mode 4: Low Insulation Resistance (I.R.)	Failure Cause 7 Failure Cause 8
RES7004-91	Mode 1: Electrically Open on Sensor Output	Failure Cause 1
	Mode 2: Intermittent Open On Sensor Output	Failure Cause 2
	Model 4:Low Insulation Resistance (I.R.)	Failure Cause 7 Failure Cause 4
RES7004-101	Mode 1: Electrically Open on Sensor Output	Failure Cause 1
	Mode 4: Low Insulation Resistance (I.R.)	Failure Cause 8
MRE7013-01	Mode 1: Electrically Open on Sensor Output	Failure Cause 1
RE1751-01	Mode 3: Sensor Output Drifting or Fluctuation	Failure Cause 6
	Mode 4: Low Insulation Resistance (I.R.)	Failure Cause 2
RE1751-02	Mode 4: Low Insulation Resistance (I.R.)	Failure Cause 7
RE1751-03	Mode 6: Crack occurred in probe nose	Failure Cause 11
RE1751-04	Mode 8: discrepancy between ch. outputs of the same unit	Failure Cause 15
RES7002-231	Mode 3: Sensor Output Drifting/noisy/ erratic	Failure Cause 10
RES7002-241	Mode 3: Sensor Output Drifting/noisy/ erratic	Failure Cause 10

SPACE TRANSPORTATION SYSTEM (STS)
CASE STUDY ANALYSIS RESULTS

Sensor Models	Failure Modes	Number of Failures (Occurrences) 0 1 2 3 4 5
RES7001-34	**Mode 3:** Sensor Output Drifting/noisy/ erratic	Failure Cause: #13
RES7001-39	**Mode 1:** Electrically Open on Sensor Output	Failure Cause: #12
RES7001-54	**Mode 2:** Intermittent Open On Sensor Output	Failure Cause: #13
RES7001-102	**Mode 7:** Spiking Sensor Output	Failure Cause: #14
RES7001-114	**Mode 3:** Sensor Output Drifting/noisy/ erratic **Mode 4:** Low Insulation Resistance (I.R.)	Failure Cause: #13
RES7001-119	**Mode 7:** Spiking Sensor Output	Failure Cause: #13
RES7001-202	**Mode 7:** Spiking Sensor Output	Failure Cause: #14
RE2233-001	**Mode 3:** Sensor Output Drifting/noisy/ erratic	Failure Cause: #13

Sensor Models	Failure Modes	Number of Failures (Occurrences) 0 1 2 3 4 5 6 7 8
10201-0049-809	**Mode 4:** Low Insulation Resistance (I.R.)	Failure Cause: #18 Failure Cause: #19
10201-0049-809	**Mode 9:** HIPOT insulation reading irratic	Failure Cause: #16
10201-0049-820	**Mode 10:** Coil winding resistance infinity (open)	Failure Cause: #17

Indicated Sensor Standards

- Manufacturing
  - Moisture Sealing
    - Foam curing
    - He fill
  - Seal Brazing
  - Plasma wire coating
- Environment Qualification (and/or material selection)
  - Oxide Formation environment
  - Thermal Stress
  - Foam Charring
- TBD
  - Debris Impact

Sensor Standard Summary

- The concatenation of the existing standards is program specific and not consistently done between projects. In addition, conflicts between standards have led to reliability issues and gaps exist in various processes necessary for manufacturing of reliable sensor for space application.
- The individual standards are not targeted for sensor applications and modifying these standards would be exhaustive and impractical considering the number of standards and various external agencies involved. In addition, this approach still does not address the gaps and integration issues when all of these standards are concatenated. The proposed approach is to develop a standard which appropriately references the existing standards, fills the gaps and provides concise instruction for sensor manufacturing.
- The existing standards are in place for applications other than sensors and these needs will not be changed by this activity. Potential consolidation or elimination of standards will be noted, if any, during the complete survey of existing standards and recommended as appropriate.
- In some cases standards exist in other areas that may be, and at times are, applied to some portion of sensor manufacturing.
- At times multiple standards exist and the choice of the appropriate standard is unclear and often based on vendor experience.
- The Sensor Manufacturing standard should clarify and reference applicable standards where these exist. Where more than one possible standard option exists for application to sensor manufacturing, this standard will clearly define which standard to invoke avoiding confusion in standards application.
- The Sensor Manufacturing Standard should provide a complete end to end manufacturing standard, integrating in standards where they exist, clarifying overlapping standards, and filling the gaps where vendor processes are used without regulation.
- The specific form of this standard needs to be defined