National Aeronautics and Space Administration

NASA Independent Review Team

SpaceX CRS-7 Accident Investigation Report

Public Summary

Date of Event: June 28th, 2015

Date of Report: March 12th, 2018

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Commercial Services and the International Space Station

In the past few years, as NASA has focused on developing capabilities to further human and robotic exploration beyond low Earth orbit, the Agency has incubated new commercial capabilities to provide access to and support the International Space Station (ISS). NASA's Commercial Crew and Cargo Program Office and the ISS Program Office have successfully developed and implemented two novel models for using commercial rather than government sources to deliver cargo to ISS. Implementation of the Commercial Orbital Transportation Services (COTS) and Commercial Resupply Services (CRS) approach required a significant change in culture throughout the Agency and in how NASA interacts with the aerospace industry. COTS and CRS established a new approach for sharing financial and technical risks with industry to develop and operate new space transportation systems in support of human exploration endeavors. Within a few short years at a reasonable financial investment from NASA, this new approach resulted in the development of the following:

- Two commercial companies (i.e., Orbital ATK and Space Exploration Technologies (SpaceX)) capable of providing cargo delivery services to and from the ISS

- Two new and different launch vehicles (i.e., Antares and Falcon 9) capable of not only supporting ISS missions, but also other commercial and government missions

- Two new and different spacecraft vehicles (i.e., Cygnus and Dragon) capable of not only transporting cargo to and from the ISS, but also providing a baseline capability that can support other commercial and government missions; these spacecraft also have the capability of being launched on different launch vehicles, increasing availability to space should launch vehicle issues arise

- Two new and different spacecraft vehicles (i.e., Cygnus and Dragon) capable of complex rendezvous and proximity operations with a human occupied spacecraft that must safely maneuver to a precise capture box for capture by the ISS crew and must fully meet the human requirements associated with the ISS

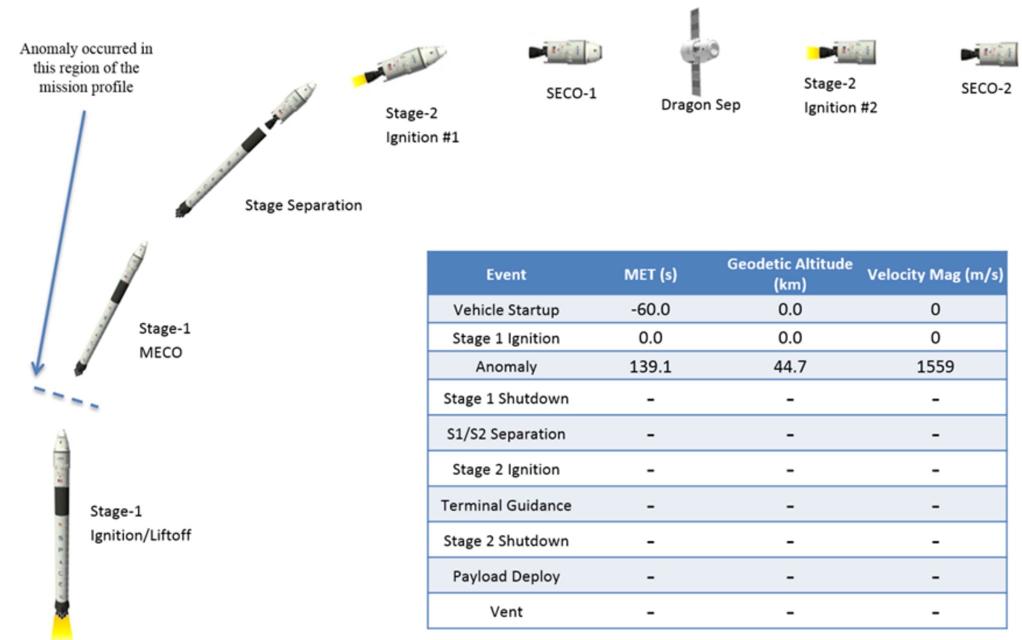
- Three new launch pads and supporting facilities (Pad 0A at Wallops Flight Facility, Launch Complex 40 at Cape Canaveral and launch Complex 39A at Kennedy Space Center) capable of launching medium-class Liquid Oxygen /Liquid Kerosene launch vehicles in support of the ISS Program and other commercial customers

- Four successful launches and missions to demonstrate the design and operational capability of the new launch vehicles, spacecraft, and support facilities; specifically single test missions for Antares and Falcon 9, and separate cargo demonstration missions to the ISS demonstrating the complete cargo delivery systems

This effort established the framework to allow commercial companies to execute a total of eight successful cargo transportation missions to the ISS using these new systems under the CRS contract. The first launch failure occurred using the Antares model 130 launch vehicle for the Orb-3 ISS mission on 24 October 2014, after two consecutive successful ISS missions using the Antares model 120 launch vehicle; the second launch failure occurred using the Falcon 9 version 1.1 launch vehicle for the CRS-7 ISS mission on 28 June 2015, after six consecutive successful ISS missions (two using the Falcon 9 version 1.0 and four using the Falcon 9 version 1.1) and a total of 13 successful flights using the Falcon 9 version 1.1. The NASA Independent Review Team (IRT) recognizes the incredible achievement of these efforts, and believes these are accomplishments for which NASA and its COTS and CRS contractors should be extremely proud.

SpaceX CRS-7 Accident

On 28 June 2015, at approximately 10:21 a.m. Eastern Daylight Time, SpaceX launched its CRS-7, or SpX CRS-7, cargo resupply mission bound for the ISS from launch complex 40 at the Cape Canaveral Air Force Station (CCAFS) in Florida.



Event	MET (s)	Geodetic Altitude (km)	Velocity Mag (m/s)
Vehicle Startup	-60.0	0.0	0
Stage 1 Ignition	0.0	0.0	0
Anomaly	139.1	44.7	1559
Stage 1 Shutdown	-	-	-
S1/S2 Separation	-	-	-
Stage 2 Ignition	-	-	-
Terminal Guidance	-	-	-
Stage 2 Shutdown	-	-	-
Payload Deploy	-	-	-
Vent	-	-	-

Figure 1. SpX CRS-7 Planned Ascent Sequence

The SpX CRS-7 mission consisted of a SpaceX Falcon 9 version 1.1 launch vehicle and a Dragon spacecraft loaded with 4303 lbs (1952 kgs) of cargo. At approximately 139 seconds into flight, the launch vehicle experienced an anomalous event in the upper stage liquid oxygen (LOx) tank, resulting in the loss of the mission. The first stage of the vehicle, including all nine Merlin 1D engines, operated nominally. The Dragon spacecraft also indicated no anomalous behavior prior to the mishap, and survived the second stage event, continuing to communicate with ground controllers until it dropped below the horizon. Figure 2 shows a gaseous cloud emanating from the launch vehicle. Figure 3 shows the disintegration of the launch vehicle. Table 1 identifies the events seen on the video.

Time (UTC)	Event
14:23:31.062	Gas first seen to exit the second stage
14:23:32.083	Combustion event seen in area of the second stage
14:23:33.759	First view of Dragon separated from Falcon
14:23:38:288	Large combustion event and gas cloud
14:23:39.256	Thrust termination on first stage
14:23:39:339	Beginning of complete vehicle breakup

Table 1. Summary of events seen in video

Figure 2. Gaseous Cloud from the Falcon 9
Universal Camera Site (UCS)-27 Tracking Camera

Figure 3. Falcon 9 Disintegration During Ascent
UCS-7 Tracking Camera

Immediately following the accident, SpaceX established an Accident Investigation Team (AIT) in accordance with its own, FAA approved contingency response plan, and consistent and compliant with the NASA Contingency Action Plan[1]. Representatives from NASA, FAA and the US Air Force were invited to be a part of the AIT. On 2 July 2015, the NASA Associate Administrator for Human Exploration and Operations designated[2] the Launch Services Program (LSP) to be the coordinating Program within NASA to interface with the SpX CRS-7 accident investigation. The LSP would provide the required insight for the three directorate programs that interface with SpaceX for its launch services: the LSP, the Commercial Crew Program and the ISS Program. The LSP representative was made a non-voting member of the SpaceX AIT.

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[1] SSP 50190-CRS, Contingency Action Plan, Annex A: Commercial Resupply Service, International Space Station Program, Baseline, October 2012.
[2] NASA Representation to the CRS-7 Accident Investigation, NASA Letter from Associate Administrator for Human Exploration and Operations to Ms. Gwynne Shotwell, dated July 2, 2015.

NASA Independent Review Team

On 3 August 2015, the NASA Associate Administrator for Human Exploration and Operations determined[3] that LSP should serve the function of an independent review team (IRT) for NASA for this investigation. It was stated that LSP would independently evaluate the events that occurred on SpX CRS-7 that led to its failure and ensure that the resulting corrective actions are implemented appropriately. The following are the elements of the IRT's charter:

- Independently evaluate the events that occurred on CRS-7 that led to the failure (i.e., develop independent event timeline; independently review fault tree; provide independent assessment of telemetry data);
- Ensure resulting corrective actions are implemented correctly
- Validate the SpaceX AIT efforts
- Inform the Agency's risk posture in order to support SpaceX's return-to-flight activities
- Determine and make recommendations on how to develop, operate, and acquire more reliable systems

Additionally, since the same launch vehicle configuration was on the NASA Launch Services II (NLS-II) contract with SpaceX for the launch of the Jason-3 mission, NASA would have the right to accept/reject any finding, root cause, and corrective action resulting from SpaceX's board.

The IRT's Independent Effort

Discerning the sequence of events that led to the occurrence of the anomaly proved to be a challenge since telemetry indications just prior to the event showed no obviously degrading or trending conditions. In fact, the anomalous event occurred over an 800-900 millisecond timespan. In other words, the vehicle went from flying fine to conflagration in less than a second, or "within a blink of an eye." In order to support the sequence of event determination, the IRT independently performed analysis of the Falcon 9 CRS-7 telemetry and independently developed a detailed timeline of events at the millisecond level consistent with the sampling capability of the instrumentation. The IRT independently analyzed the various Falcon 9 systems, and reviewed the SpaceX developed fault tree. The IRT's independent analyses, assessments, and review of SpaceX testing enabled closure of all fault tree blocks (i.e. First Stage, Propulsion, Avionics, Electrical, Dragon, etc.), with the exception of the Falcon 9's Stage 2. The IRT performed the Falcon 9 systems review completely independently from SpaceX, making its own judgments on the telemetry readings coming from the various systems throughout the flight. Multiple Engineering Review Boards were held to review the Falcon 9 systems and the data. In the end, the IRT independently came to the conclusion that all but the Stage 2 Fault Tree block could be closed. Based on a detailed review and analysis of the Falcon 9 telemetry collected prior to and during the launch, as well as review of the photographic and video media capturing the launch and failure, the IRT determined that the *direct (or proximate) cause* of the Falcon 9 launch vehicle failure was the rupture of the Stage 2 LOx tank. The IRT also performed a separate detailed review of what became the "primary failure scenario" as developed and investigated by the SpaceX AIT– that a helium filled composite overwrapped pressure vessel (COPV) within the Stage 2 LOx tank had become liberated, and had hit the LOx tank dome causing it to rupture.

[3] Memorandum for the Record from William H. Gerstenmaier, Associate Administrator for Human Exploration and Operations, dated August 3, 2015.

Alternative Scenarios Investigated

In addition to the independent review of the flight data, the independent review of the Falcon 9 systems and the independent review of the SpaceX AIT developed primary failure scenario, the NASA LSP IRT also developed and investigated multiple additional potential scenarios that could also explain some of the telemetry indications. This resulted in identifying two main alternative scenarios, each of which could have been the precipitating event in place of, or in addition to the "liberated COPV" scenario. A brief description of the two main alternative scenarios is that a leak could have occurred into the annulus of the LOx Transfer Tube that runs from the Stage 2 LOx tank down through the Stage 2 Rocket Propellant-1 (RP-1) tank and into the Stage 2 engine. Alternative Scenario #1 assumed "warm" RP-1 would leak into the annulus of the LOx Transfer Tube, and would warm the LOx, causing it to spew or "geyser". However, thermal analysis quickly determined that insufficient thermal energy would be transferred from the RP-1 (that could have leaked into the annulus) to the LOx in the LOx transfer tube. While that alternative was proven non-credible analytically, a second similar alternative required detailed testing to prove or disprove the potential for occurrence. Initial modeling and analysis indicated that, if instead of RP-1 leaking into the annulus of the LOx Transfer Tube, LOx had leaked into the annulus, there might be sufficient thermal energy transferred from the RP-1 surrounding the LOx Transfer Tube to initiate LOx gasification, and eventual geysering. This became Alternative Scenario #2. Rapid actions were initiated using resources at Marshall Space Flight Center to construct a test chamber and conduct testing to validate thermal energy transfer assumptions that were being used in the models for this scenario development. (See Figure 4.) After a two-week run of tests, the IRT was able to determine that there was greater thermal energy transfer in Alternative Scenario #2, but still insufficient thermal energy to initiate a geysering occurrence within the total 800-900 millisecond time span of the failure event.

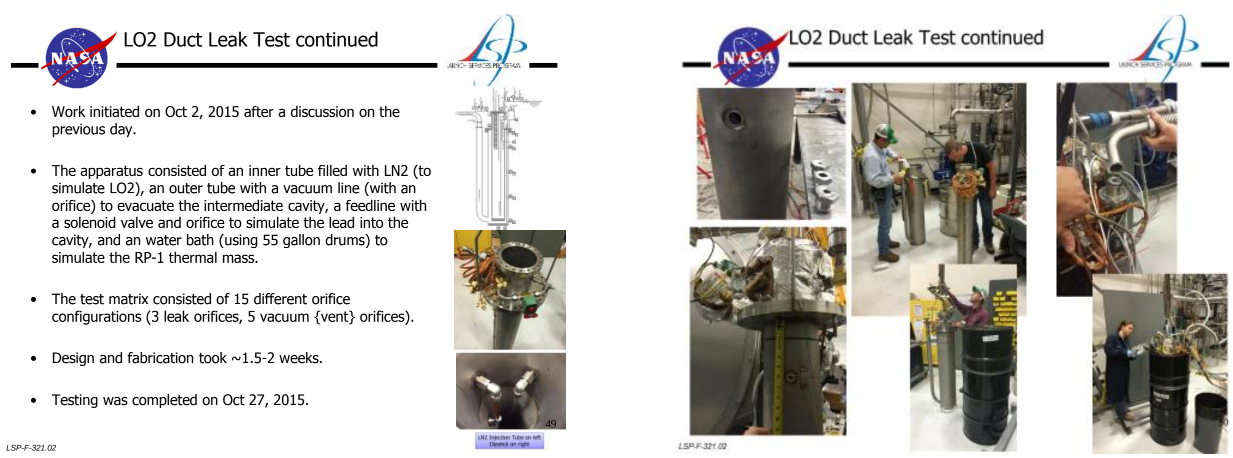

Figure 4. Alternate Scenario #2 Testing

IRT Investigation Summary

In the end, the effort by the IRT was able to account for the large majority of the 115 telemetry indications that occurred during the 800-900 millisecond failure time period, leaving 9 indications not fully explained. These independent efforts enabled the IRT to conclude the following:

- It is credible the *intermediate* cause of the Stage 2 LOx tank rupture was the liberation of a Stage 2 COPV within the Stage 2 LOx tank.

- It is credible the *initiating* cause was the failure of the axial strut supporting a COPV, which in turn liberated the aforementioned COPV, and which in turn ruptured the gaseous helium (GHe) plumbing system within the Stage 2 LOx tank.

- It is credible, that the COPV became liberated when a threaded cast stainless steel eye bolt (AKA: "rod end", see Figure 5) of the COPV's axial support strut broke under ascent loads, allowing the COPV to break free from its mounts, allowing it to accelerate, due to its buoyancy, to impact the LOx dome at the top of the LOx tank with great force.

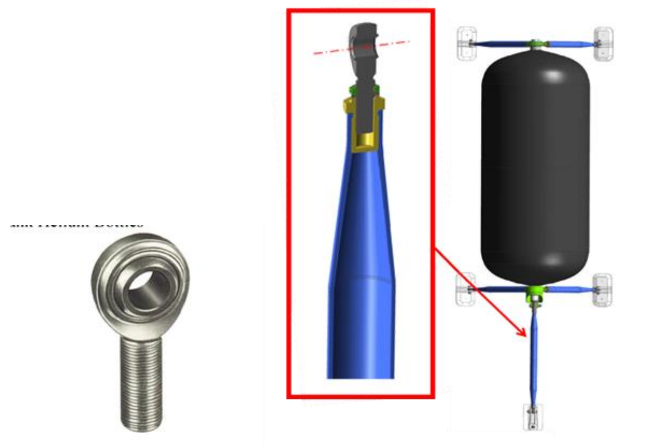

Figure 5. Liquid Oxygen Tank Helium Bottle, Srutt & Rod End

- It is important to note that the IRT's conclusions regarding the *direct*, and *immediate* causes are consistent with the determination made by the SpaceX AIT investigation findings. Where the IRT differs with SpaceX is in regards to the *initiating* cause. SpaceX in their AIT report identifies "material defect" as the "most probable" cause for the rod end breaking. However, the IRT's view is that while "rod end breakage due to material defect" is credible, the IRT does not denote it a "most probable" since the IRT also views "rod end manufacturing damage", "rod end strut mis-installation", "rod end collateral damage" or some other part of the axial strut breaking as equally credible causes to have liberated the COPV. Lastly, the key technical finding by the IRT with regard to this failure was that it was due to a design error: SpaceX chose to use an industrial grade (as opposed to aerospace grade) 17-4 PH SS (precipitation-hardening stainless steel) cast part (the "Rod End") in a critical load path under cryogenic conditions and strenuous flight environments. The implementation was done without adequate screening or testing of the industrial grade part, without regard to the manufacturer's recommendations for a 4:1 factor of safety when using their industrial grade part in an application, and without proper modeling or adequate load testing of the part under predicted flight conditions. This design error is directly related to the Falcon 9 CRS-7 launch failure as a "credible" cause.

- NASA LSP did not perform a programmatic assessment of the SpaceX CRS program but would note that due to LSP having awarded launch service contracts to SpaceX for the launch of "high value" NASA payloads, NASA LSP has developed deep insight to the SpaceX Falcon 9 version 1.1 launch vehicle due to the recent "Category 2" certification effort by SpaceX.

- Additional issues identified in the course of the investigation by SpaceX and NASA LSP were also addressed by corrective actions.

- The differences in launch vehicle configuration between the "Full Thrust" using densified propellants and the Version 1.1 do not add any qualifiers to the IRT's anomaly resolution conclusions.

In summary, the IRT determined that subject to the normal technical review of SpaceX's corrective actions implementation, including correction of their design error, the F9-020 CRS-7 flight anomaly is resolved with "credible", *direct*, *intermediate*, and *initiating* causes. That the *initiating* causes include more than just rod end "material defect", and the initiating causes are rated by the IRT as "probable".

Technical Findings and Recommendations

Table 2 lists the four Technical Findings (TFs) identified by the IRT. Table 3 lists the three Technical Recommendations (TRs) identified by the IRT that, if fully implemented, should prevent recurrence of a similar failure in the future and improve the operability of the Falcon 9 launch vehicle system.*

Technical Findings	
TF-1	Design Error: The use of an industrial grade 17-4 PH SS (precipitation-hardening stainless steel) casting in a critical load path under cryogenic conditions and flight environments, without additional part screening, and without regard to manufacturer recommendations for a 4:1 factor of safety, represents a design error – directly related to the F9-020 CRS-7 launch failure as a "credible" cause.
TF-2	General Finding: The use of commercially procured wire ropes to provide structural support to the LOx Transfer Tube Assembly, without regard for manufacturer's caution to specify pre-stretched ropes in a length-critical application, is a general finding – not directly related to the F9-020 CRS-7 launch failure.
TF-3	General Finding: The use of a 0.01 standard cubic feet per minute (scfm) gaseous Nitrogen (GN2) flow rate to purge the LOx Transfer Tube Assembly annulus was a general finding – not directly related to the F9-020 CRS-7 launch failure.
TF-4	General Finding: SpaceX's new implementation (for Falcon 9 "Full Thrust" flights) of non-deterministic network packets in their flight telemetry increases latency, directly resulting in substantial portions of the anomaly data being lost due to network buffering in the Stage 2 flight computer.

Table 2. List of Technical Findings Identified By the IRT

Technical Recommendation		**Finding(s) Addressed by Recommendation**
TR-1	Additional attention warranted for evaluating design application using commercially sourced parts. SpaceX should apply particular emphasis to understanding manufacturer's recommendations for using commercially sourced parts in flight critical applications.	TF-1, & TF-2
TR-2	SpaceX needs to establish and maintain the proper purge rates for stage testing and launch base operations.	TF-3
TR-3	SpaceX needs to re-think new telemetry architecture and greatly improve their telemetry implementation documentation.	TF-4

Table 3. List of Technical Recommendations Identified By the IRT

**The IRT notes that all credible causes and technical findings identified by the IRT were corrected and/or mitigated by SpaceX and LSP for the Falcon 9 Jason-3 mission. That flight, known as "F9-19", was the last flight of the Falcon 9 version 1.1 launch vehicle, and flew successfully on 17 January 2016.*

Acknowledgements

The LSP-led IRT would like to acknowledge and thank the organizations listed below for the support they provided during the NASA LSP investigation efforts. The IRT also recognizes that there were many other personnel who supported efforts behind the scenes and who may not be recognized below by name. Those personnel also have the thanks of the IRT for their dedication and efforts to support the IRT investigation efforts.

-Space Exploration Technologies (SpaceX)
-NASA Headquarters
-NASA International Space Station (ISS) Program
-Kennedy Space Center (KSC)
-Marshall Space Flight Center (MSFC)
-United States Air Force 45th Space Wing