NATIONAL TRANSPORTATION SAFETY BOARD
Office of Aviation Safety
Washington, D.C. 20594

PROPULSION GROUP CHAIRMAN'S FACTUAL REPORT

NTSB No: DCA15MA019

A. ACCIDENT

Location: Koehn Dry Lake, California

Date: October 31, 2014

Time: 1007 pacific daylight time (PDT)

Vehicle: Scaled Composites, LLC Model 339 SpaceShipTwo

B. PROPULSION GROUP

Group Chairman: Robert Hunsberger
National Transportation Safety Board
Washington, D.C.

Member: Ken Baker
Scaled Composites
Mojave, California

Member: Donald Sargent
Federal Aviation Administration
Washington, DC

Member: Jarret Morton
The Spaceship Company
Mojave, California

C. SUMMARY

On October 31, 2014, about 1007 Pacific daylight time,[1] a Scaled Composites SpaceShipTwo (SS2) reusable suborbital rocket, N339SS, experienced an in-flight anomaly during a rocket-powered flight test, resulting in loss of control of the vehicle. SS2 broke up into multiple pieces and impacted terrain over a 5-mile area near Koehn Dry Lake, California. One test pilot (the copilot) was fatally injured, and the other test pilot was seriously injured. SS2 had launched from the WhiteKnightTwo (WK2) carrier aircraft, N348MS, about 12 seconds before the loss of control. SS2 was destroyed, and WK2 made an uneventful landing. Scaled Composites was operating SS2 under an experimental permit issued by the Federal Aviation Administration's (FAA) Office of Commercial Space Transportation under the provisions of 14 *Code of Federal Regulations* (CFR) Part 437.

An on scene examination of the propulsion system was conducted in Koehn Dry Lake and further examination was conducted at the Scaled Composites Propulsion facility in Mojave, CA after the propulsion component wreckage was removed from the accident site. Members from Scaled Composites and the National Transportation Safety Board (NTSB) examined the propulsion system from November 1-5, 2014.

Additional members were added to propulsion group from the Federal Aviation Administration (FAA) and The Spaceship Company prior to an investigation update meeting in Mojave, California from January 27-28, 2015.

An examination of the propulsion hardware did not identify any pre-impact system anomalies. The case/throat/nozzle (CTN) assembly was sectioned and the fuel grain exhibited even burn without indications of pre-impact fuel cracking or localized hot spots. Propulsion system pressure parameters were reviewed from the telemetry feed and the rocket motor controller (RMC) internal memory and both data sources confirmed that rocket ignition was normal and pressure values climbed and stabilized at nominal levels prior to vehicle breakup.

D. DETAILS OF THE INVESTIGATION

1.0 ROCKET INFORMATION

1.1 PROPULSION SYSTEM DESCRIPTION

SS2 featured a hybrid rocket motor which utilized nylon fuel grain and nitrous oxide (N_2O) to generate thrust. The main components of the propulsion system were the forward pressure tank (FPT), main oxidizer tank (MOT), CTN, and two (b) (4) bottles (**Figure 1**).

All directional references to front and rear, right and left, top and bottom, and clockwise and counterclockwise are made aft looking forward (ALF).

[1] Unless otherwise indicated, all times in this report are Pacific daylight time based on a 24-hour clock.

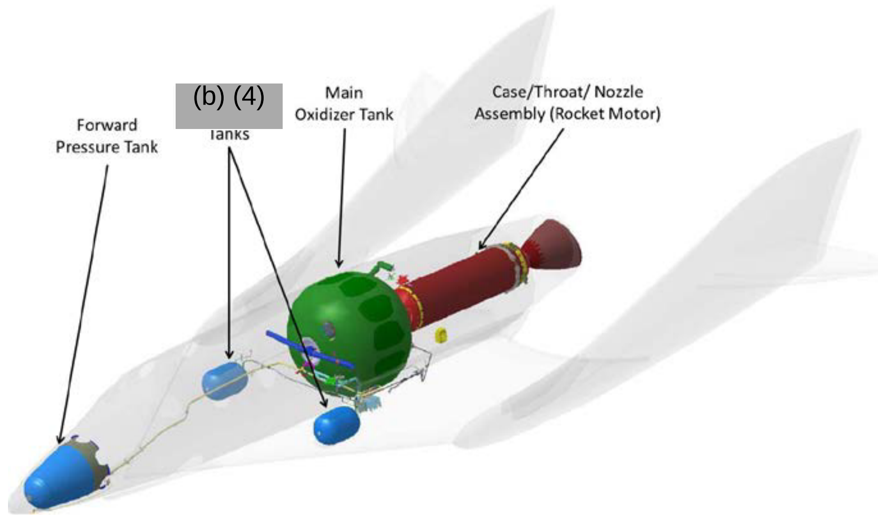

Figure 1- SS2 Propulsion System

1.1.1 Forward Pressure Tank

The FPT was a composite overwrapped pressure vessel (COPV) located in the nose of the vehicle that held (b) (4) (cu-ft) of (b) (4) at a nominal operating pressure of (b) (4) (psi). The FPT fed (b) (4) to the MOT to pressurize the N_2O.

1.1.2 Main Oxidizer Tank

The MOT was a COPV located in the fuselage with a volume of (b) (4) that holds N_2O stored at (b) (4) °F. The MOT had a nominal operating pressure (b) (4) psi and a maximum expected operating pressure (b) (4) psi. The aft bulkhead of the MOT housed the main oxidizer valve (MOV) assembly and (b) (4). The MOV assembly contained the MOV and backup oxidizer valve (BOV). Both valves within the MOV assembly were pneumatically actuated. The MOT also contained a burst disk assembly and redundant pressure relief valves.

1.1.3 Case/Throat/Nozzle Assembly

The CTN consisted of a (b) (4) COPV fuel cartridge integrated with a nozzle throat and nozzle expansion bell. The accident fuel cartridge held (b) (4) (**Photo 1**). The case and the forward and aft domes were lined with ethylene propylene diene monomer (EPDM) rubber. The forward dome mating flange included ports for instrumentation, (b) (4), and gaseous nitrogen (GN_2) purge[2].

[2] (b) (4)

[redacted] 

Photo 1- Representative Nylon Fuel Grain Puck, (L) Overhead View (R) Side View

1.1.4 [redacted] Tanks

The vehicle featured two [redacted] cu-ft COPV [redacted] bottles which were plumbed into the rocket combustion chamber [redacted].

1.1.5 Rocket Motor Controller

The RMC was a computer located in the aft fuselage that monitors and sequences propulsion system functions.

1.1.6 Pressurization System Controller

The PSC was a computer located in the forward cabin that regulated [redacted] flow into the MOT. The PSC received MOT pressure readings from [redacted]. The PSC also received valve command discrete indications from [redacted]. The PSC data logger was located in the aft fuselage on the main data acquisition system chassis and logged pressure readings and [redacted] control valve trunnion commands, positions, and voltages.

1.2 Rocket Ignition Sequence

The rocket motor ignition sequence was a four step process. Prior to vehicle release, the Inter-OV (Inter-Oxidizer Valve) switch was flipped to equalize pressure between the BOV and the MOV. Next the BOV open switch was selected to open the BOV, allowing N_2O to flow to the MOV. Following vehicle release, the arm and fire switches were selected. The fire switch sent a command to the RMC to assess the health of the system and to initiate the startup sequence. [redacted]

3 [redacted]

1.3 PROPULSION SYSTEM HISTORY/MAINTENANCE

The accident flight was powered flight #4 (PF-04) of SS2 and was the first powered flight following the addition of the (b) (4) [redacted] system. PF-04 was also the first powered flight to use a nylon fuel formulation. The change to a nylon fuel grain and increased propellant mass-flow rates resulted in a thrust (pound-force) increase from previous flights. PF-03 with a hydroxyl-terminated polybutadiene (HTPB) fuel grain (b) (4) [redacted] of thrust. According to telemetry data from the accident flight, the nylon fuel grain produced (b) (4) [redacted] of thrust.

The CTN assembly is replaced each flight but the FPT, MOT, and most of the associated plumbing was designed to be reusable between flights. The FPT, MOT and pressurization system plumbing used on PF-04 were common to the previous three powered flights. Significant maintenance performed on the propulsion system before PF-04 included:

-installation of (b) (4) [redacted] motor purge, and supporting safety systems (b) (4) [redacted]

[4] Thrust values are an approximation derived from rocket chamber pressure during operation.

2.0 ON SCENE EXAMINATION

The wreckage field was spread over about five miles with components concentrated at seven sites[5]. The location of the major propulsion components are shown in the image below and are labeled according to survey points gathered by the Federal Bureau of Investigation (**Figure 2 and Table 1**). A detailed description of all wreckage is available in the vehicle recovery factual report.

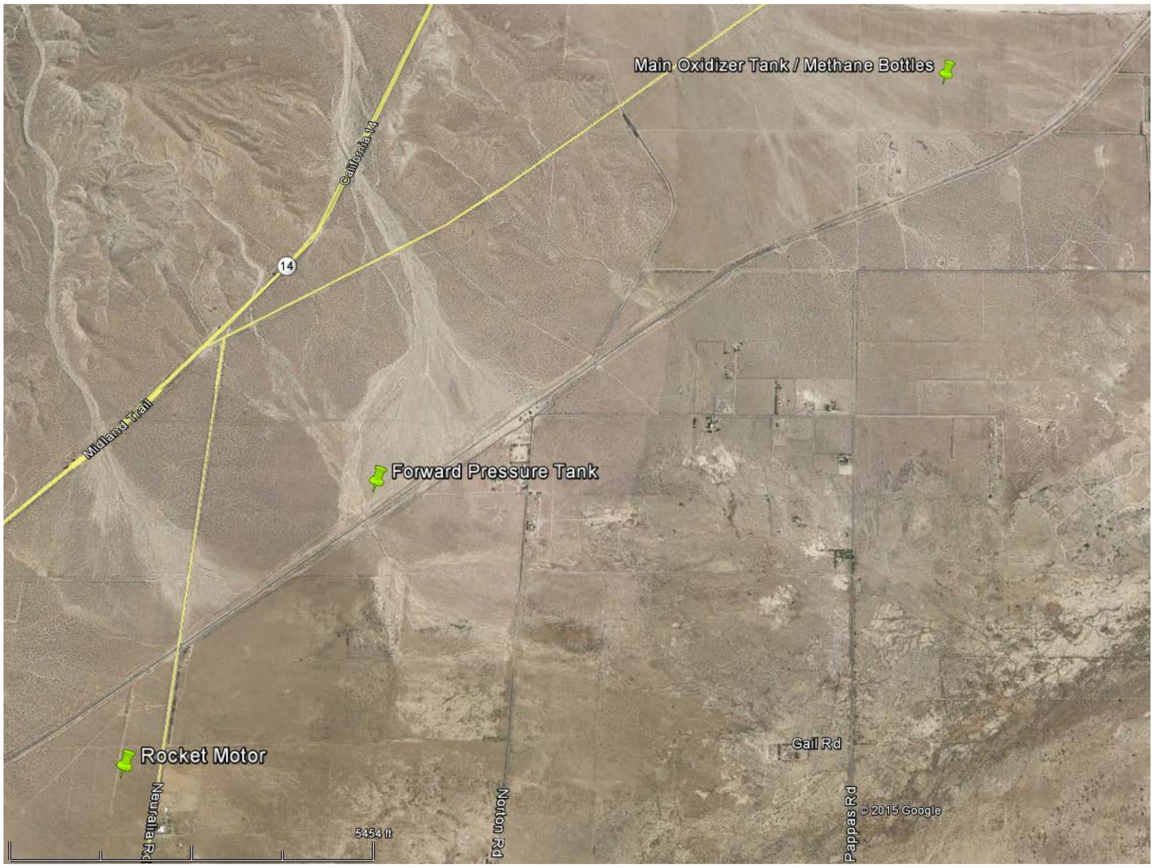

Figure 2- Map of Propulsion Wreckage Sites

Site Number	Coordinates (degree/minute/second)	Description
2	35°19'34.34"N 117°56'42.85"W	Main oxidizer tank (MOT) and wings, RMC, PSC data logger
4a	35°18'18.76"N 117°58'35.82"W	Forward pressure tank (FPT)
5	35°17'33.59"N 117°59'16.01"W	Rocket motor CTN

Table 1- Propulsion System Component Wreckage Locations

[5] Wreckage site numbering was established by the Kern County Sheriff's Department prior to NTSB arrival on scene.

2.1 MAIN OXIDIZER TANK AND (b) (4) BOTTLES (SITE 2)

A section of the fuselage with the integral MOT was located at site 2 and impacted the ground in an inverted attitude (**Photo 2**). The forward end of the tank exhibited fractures and bulging along the lower half consistent with impact. The forward MOT bulkhead was intact but all external plumbing connections were severed. The internal plumbing within the MOT was deformed. Pressurization system plumbing and valves were sheared away from the MOT and exhibited bending and deformation consistent with impact. The MOT burst disk was recovered intact/unburst on the ground under the wreckage (**Photo 3**). The MOT burst disk thrust cancelling tee connection was found sheared off, laying on the ground.

Photo 2- Fuselage Wreckage with Integral MOT, Inverted, Aft Side

Photo 3- MOT Burst Disk, Intact

The aft MOT bulkhead was intact but all oxidizer valve attachment bolts were sheared allowing the MOV and BOV to partially pull out of the MOT (**Photo 4**). The MOV connection was fractured at the aft bulkhead. The Inter-OV valve was intact but separated and found on the ground against the wreckage.

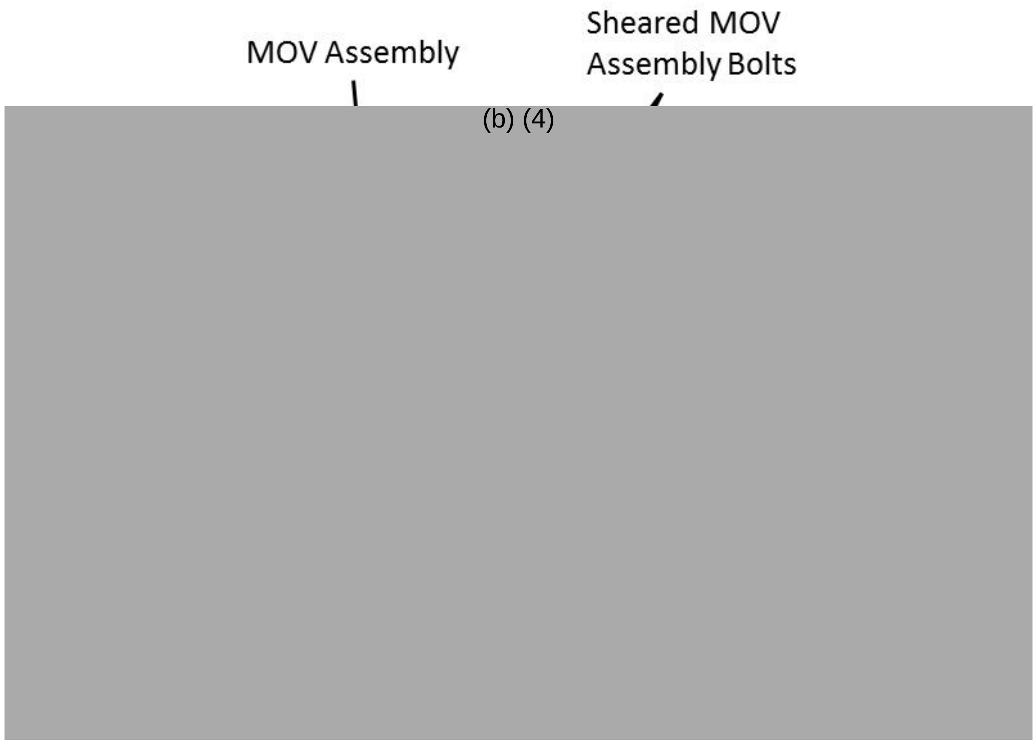

Photo 4- MOT Aft Flange, MOV/BOV Protruding

The MOT was lifted away from the wreckage with a crane. The 12 o'clock position of the tank was flat where it contacted the ground (**Photo 5**). A small amount of liquid ran from the tank when it was lifted.

Photo 5- MOT, Lifted By Crane

Both (b) (4) bottles were found intact and in good condition (**Photo 6**). The connecting lines were severed from the bottles but were recovered in the wreckage. All lines exhibited deformation consistent with impact.

(b) (4)

Photo 6- (b) (4) Bottle, Under Fuselage Wreckage

The PSC data logger was recovered within the wreckage attached to the main data acquisition system chassis. The data logger external case was deformed at multiple locations. The RMC was also recovered intact within the fuselage wreckage. The PSC data logger and RMC were both sent to NTSB headquarters for data recovery.

2.2 FORWARD PRESSURE TANK AND PRESSURIZATION SYSTEM CONTROLLER (SITE 4A)

The FPT was recovered at site 4a, several hundred yards away from the impact crater where the cockpit wreckage was located (**Photo 7**). The main body of the FPT was lying on its side and the nose of the tank was separated. The carbon fiber around the fracture surface was frayed and the metal liner exhibited curling. The nose of the tank was recovered closer to the cockpit wreckage. The metal liner was curled, the carbon fiber was fractured, and the forward tank line ports were bent consistent with impact (**Photo 8**). Both FPT sections and associated debris were in a line with the cockpit impact location. Inconel fragments from the FPT were identified in the impact crater. The PSC was recovered from the scattered wreckage near the cockpit.

(b) (4)

Photo 7- (L) Left Side of FPT, (R) Forward Side of FPT

Photo 8- FPT Nose

2.3 CASE/THROAT/NOZZLE ASSEMBLY- ROCKET MOTOR (SITE 5)

The CTN was found at site 5 in a 20 degree nose down attitude in a crater created by the impact. The forward most section of CTN was covered in dirt (**Photo 9**). The forward dome exhibited buckling and the carbon fiber was fractured between the 3 and 9 o'clock positions. The (b) (4) that connects the CTN to the MOT remained affixed, and showed some signs of metal fracture (**Photo 10**). The bottom most link of the aft support[6] was broken but the support was still resting on the case. The carbon on the aft dome was fractured and severed motor wiring harnesses were hanging from the aft end. The rocket nozzle was fragmented and pieces were scattered over about a 50 foot area behind the aft end of the rocket. The recovered nozzle fragments exhibited charring similar to what was seen after previous powered flights and rocket ground fire tests according to Scaled Composites engineers (**Photo 11**).

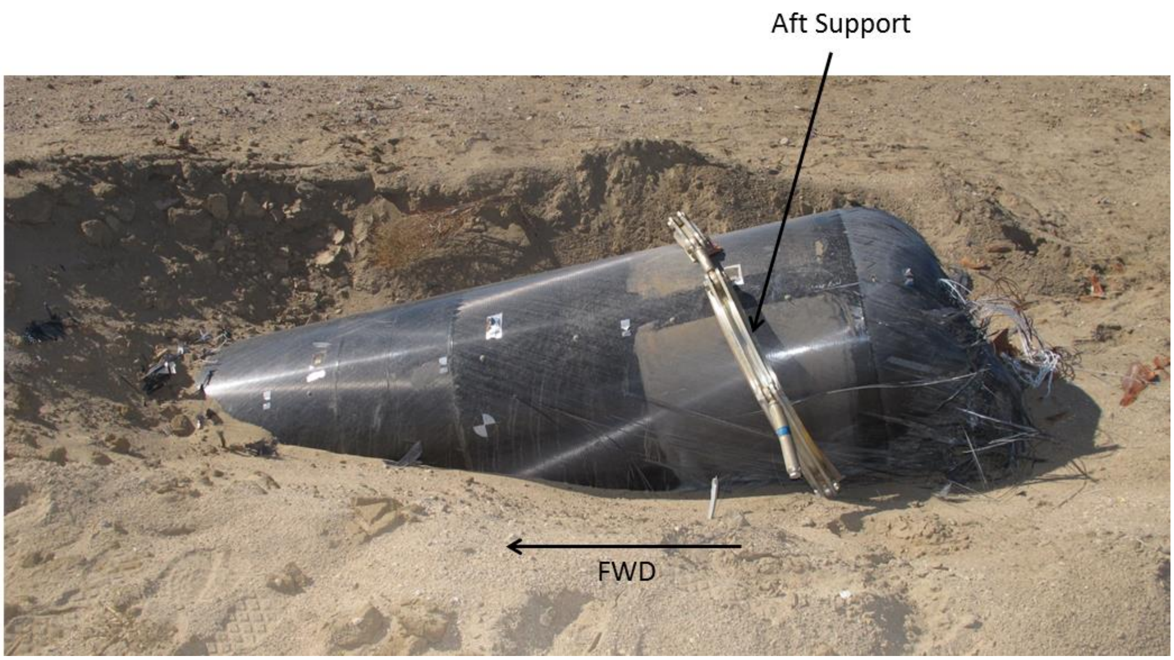

Photo 9- Case/Throat/Nozzle Assembly

[6] The aft support was a three link ring clamp that supported the aft end of the CTN in the fuselage structure.

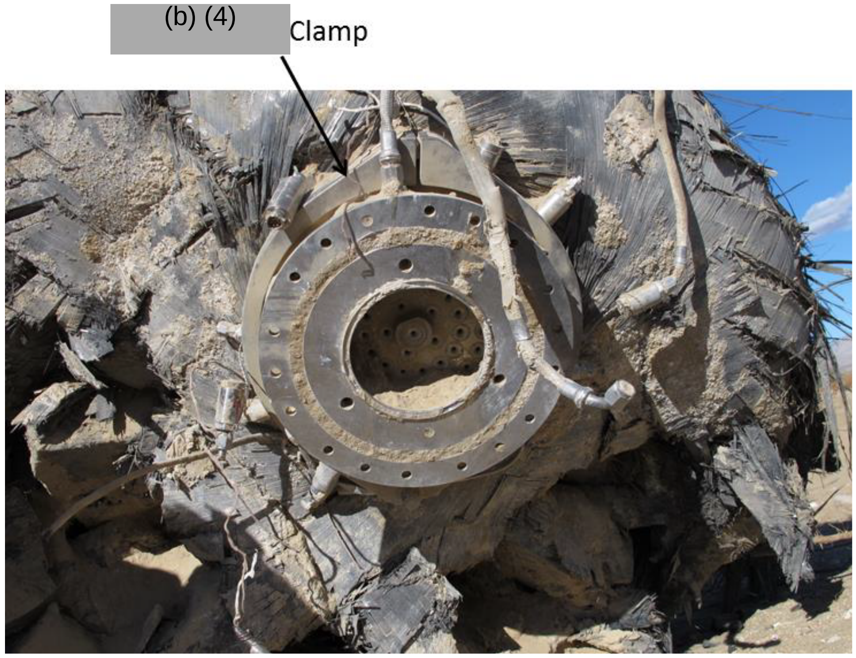

Photo 10- CTN Forward Dome (b) (4)

Photo 11- Rocket Nozzle Fragment Charring

Shovels and a front end loader were used to remove the dirt around the rocket and then a forklift and slings were used to lift the rocket out of the crater. No additional damage was noted during the excavation process.

3.0 CASE/THROAT/NOZZLE ASSEMBLY EXAMINATION

The CTN was transported to the Scaled Composites Propulsion facility for sectioning and internal examination. The forward and aft domes were cut off to expose the nylon fuel grain (**Photo 12**). The fuel grain surface exhibited even burn and there was no evidence of localized hot spots or burn through around the case. [redacted] (b) (4) had fuel fracture near the forward end but the fracture surfaces did not exhibit thermal exposure indicating the fracture happened as a result of impact (**Photo 13**). The forward end of the case and fuel grain exhibited substantial impact damage concentrated between the 3 and 9 o'clock positions. [redacted] (b) (4) from the forward dome was lodged into the [redacted] (b) (4) and the [redacted] (b) (4). Earthen debris was also found lodged along the lower half of the case.

[redacted] (b) (4)

[redacted] (b) (4)

Photo 12- (L) Forward Fuel Grain after Dome Sectioning, (R) Aft Fuel Grain after Dome Sectioning

Photo 13- [redacted] (b) (4) **Fuel Grain Fracture**

4.0 OXIDIZER FEED SYSTEM EXAMINATION

The CTN clamp was removed allowing for removal and inspection of the main oxidizer valve aft-housing, injector, and cavitating venturi assembly. Removal of the components was difficult due to material deformation from impact. The main and backup oxidizer valves were intact and in good condition. The injector and cavitating venturi connected to the CTN had a coating of dirt debris but there was no evidence of dark sooting or localized discoloration (**Photos 14 and 15**). The anti-swirl baffle material inside the MOT was deformed and torn.

(b) (4)

Photo 14- Cavitating Venturi

(b) (4)

Photo 15- Injector (L) Upstream Side, (R) Downstream Side

5.0 RECORDED DATA

5.1 TELEMETRY DATA

Select propulsion parameters were evaluated to determine if the rocket motor experienced any anomalies prior to or during operation. Pressure values in the oxidizer tank, the oxidizer injector plenum and the combustion chamber were plotted in **Figure (3)**. All pressures climbed normally after ignition and stabilized at expected values up to the point the data link was lost.

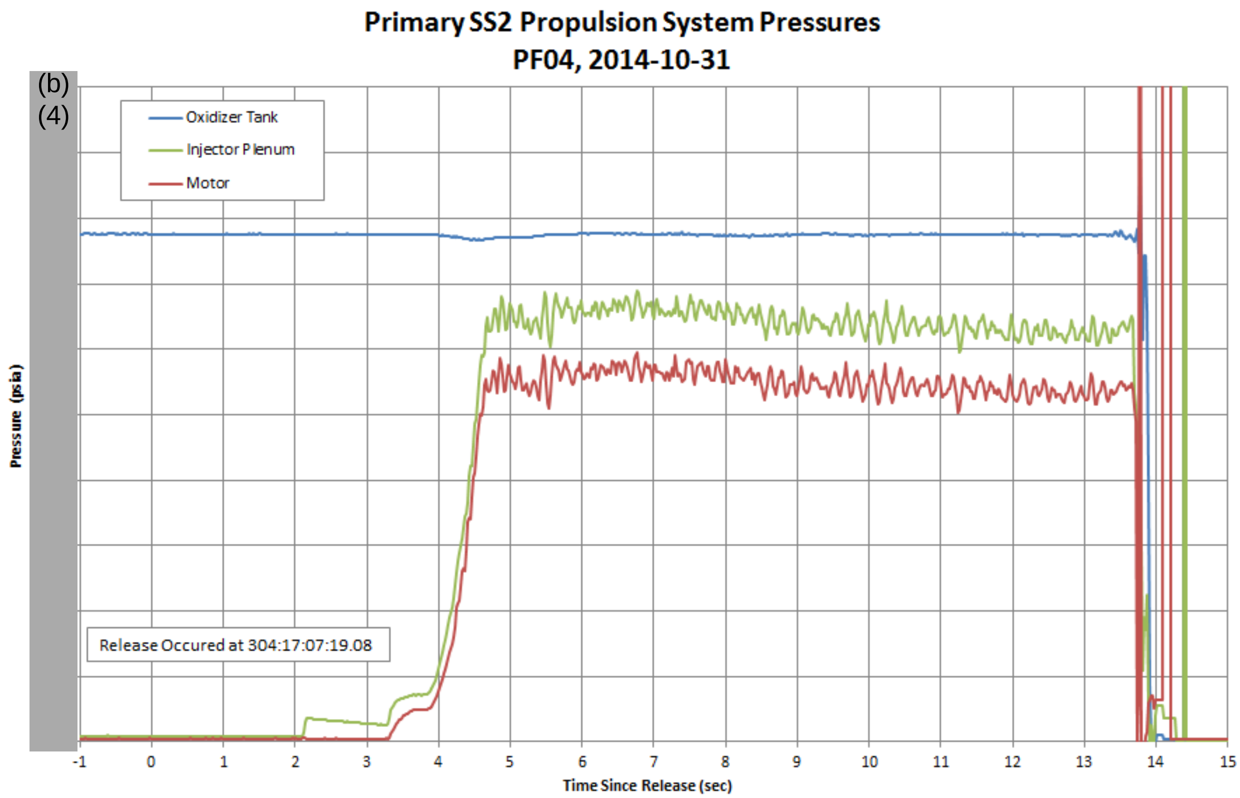

Figure 3- Propulsion Telemetry Parameters

5.2 ROCKET MOTOR CONTROLLER

The RMC was shipped to the manufacturer of the electrical boards, Aitech in Chatsworth, California for data download. The RMC was disassembled and the data chip was separated from the motherboard and installed on a test card. Through the test card all recorded data was successfully extracted and analyzed to ensure the rocket motor operated as designed. A more thorough documentation of the RMC condition and download is available in the Electronic Devices and Flight Data Factual Report

A review of RMC discrete parameters confirmed that the RMC commanded all launch steps in the proper order as programmed. The RMC commanded rocket abort between T+11.28 and T+11.30 seconds[7]. The abort was due to the PT-M3[8] pressure sensor reading of less than -200 PSIA for more than 25 milliseconds.

[7] T=0 is defined from the SS2_RMC_carrier_separated discrete.

An instability algorithm was programmed into the RMC to monitor frequencies between 3-20Hz due to human factors limitations. (b) (4) [redacted] The RMC instability limit is programmed at 0.8 g's , representing the human factors limit. (b) (4) [redacted] The instability threshold accounts for changes in g-loading as the vehicle weight decreases due to consumed propellant. During PF-04 the pressure fluctuations during the flight remained below the shutdown threshold limit (**Figure 4**). The black line "RMC Instability Threshold" indicates the value that "rocket motor chamber pressure (PT_M1) stability" must exceed for the RMC to command abort. The blue line indicates the RMC's computation of peak-to-peak chamber pressure oscillation which is derived from the red line, PT-M1.

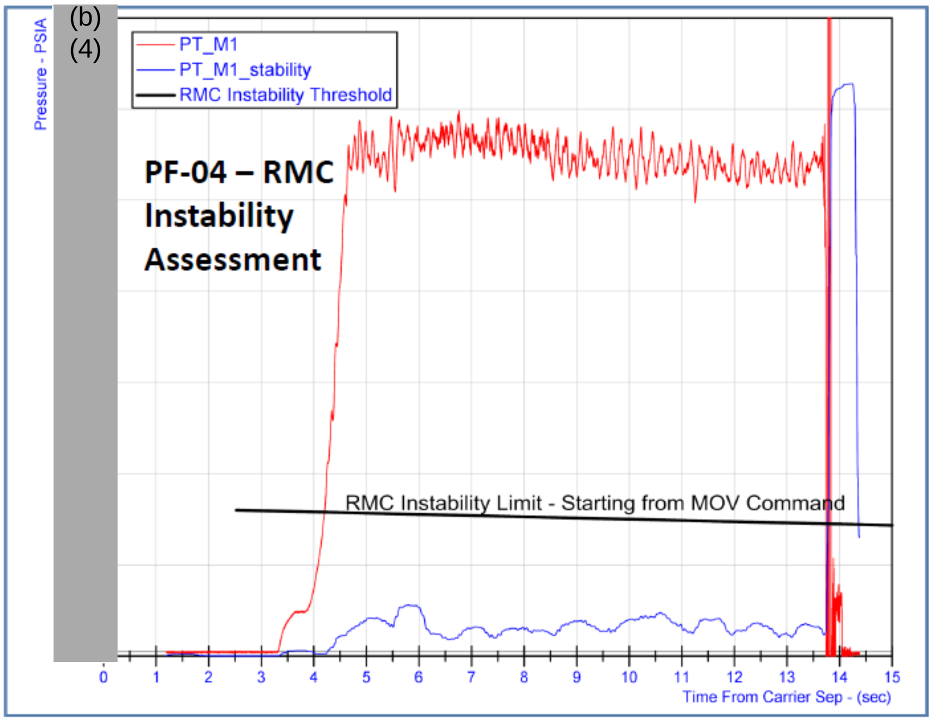

Figure 4- RMC Instability Plot

5.3 Pressurization System Controller

The PSC data logger external case exhibited deformation and after removal of the internal hard drive, four of the serial advanced technology attachment pins were found lifted from their respective solder pads. Under magnification the pins were manually resoldered and the hard drive data was successfully extracted. During a review of the data it was determined that the data recorded during the accident flight was unreadable. The PSC data logger recorded data on a circular buffer. The PSC

[8] PT_M3 is a measure of pressure in the seal cavity that separates the MOV from the CTN. The parameter is used to ensure the CTN was installed correctly and monitors rocket health during motor fire.
[9] The conversion from PSIA to g's is based on a rocket chamber pressure/g factor. The conversion factor was reached by comparing accelerometer data from the cockpit to the rocket chamber pressure readings.
[10] RMS is a statistical measure of the magnitude of sinusoids such as the rocket motor chamber pressure.

hard drive internal memory capacity was reached and began overwriting data recorded during past flights. The overwriting process began prior to vehicle release. No warnings or faults were noted during the accident flight that suggested pressurization system hardware anomalies.

6.0 ADDITIONAL INFORMATION

6.1 ROCKET FUEL GRAIN CHANGE

As noted earlier, SS2's first three powered flights featured a HTPB fuel grain rocket motor developed and manufactured by Sierra Nevada Corporation. Scaled Composites also developed a nylon fuel grain motor in parallel. The nylon motor was extensively ground tested and in the months leading up to PF-04 the nylon motor performance and long duration stability outpaced the HTPB motor development so the decision was made to switch.

Robert Hunsberger
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Propulsion