Submission to the

NATIONAL TRANSPORTATION SAFETY BOARD

for the

Investigation of Scaled Composites, LLC's SpaceShipTwo, N339SS

Rocket-Powered Flight Test
Koehn Dry Lake, California, October 31, 2014

May 29, 2015

By

Virgin Galactic, LLC

and

The Spaceship Company, LLC

Table of Contents

EXECUTIVE SUMMARY

Factual Background

On October 31, 2014, at approximately 10:07 PDT, Scaled Composites' SpaceShipTwo flight test vehicle, SS2-001 (N339SS) experienced a serious in-flight anomaly during a rocket-powered test flight approximately 13 seconds after release that resulted in the destruction of the vehicle and the death of the copilot. The pilot survived after successfully parachuting to the ground. No other persons were injured in the air or on the ground.

The accident occurred during the program's 55^{th} overall and fourth powered test flight (PF-04) of SpaceShipTwo. Scaled Composites, the vehicle's designer and builder, held an experimental launch permit from the Federal Aviation Administration's Office of Space Transportation (FAA-AST) to conduct the vehicle's rocket-powered test flights. Scaled Composites, a wholly-owned subsidiary of the Northrop Grumman Corporation, was under contract with Virgin Galactic (VG) and The Spaceship Company (TSC) to carry out SpaceShipTwo's developmental flight test program, maintaining both operational control and safety oversight. At the time of the accident, SpaceShipTwo was piloted by two Scaled Composites test pilots.

The mishap test flight, designated PF-04, had three primary objectives:

1) Expand SpaceShipTwo's powered flight envelope utilizing a 38-second rocket burn to attain approximately 135,000 feet above mean sea level (MSL) and Mach 2.00;

2) Conduct the first supersonic feathered re-entry of SpaceShipTwo;

3) Conduct the first flight using an alternative, polyamide-based hybrid rocket motor fuel that was essentially structurally identical to previously flown motors.

Following a delay to ensure nitrous oxide (N_2O) temperatures warmed into the acceptable launch range, WhiteKnightTwo departed Mojave Air and Spaceport at 09:19:30 PDT with SpaceShipTwo mated to its underside. WhiteKnightTwo uneventfully carried SpaceShipTwo to a release altitude of approximately 47,000 feet MSL. An abbreviated timeline of the accident events follows:

10:07:19.27 – SpaceShipTwo released from WhiteKnightTwo.
10:07:19.51 – The pilot commanded the copilot to fire the rocket motor. Rocket motor ignition and burn were nominal.
10:07:26.83 – The vehicle accelerated through 0.80 Mach.
10:07:26.91 – The copilot announced 0.80 Mach in accordance with checklist procedures.
10:07:28.39 – The copilot announced "*unlocking*" at approximately 0.92 Mach.
10:07:28.90 – The copilot moved feather lock handles to the full unlock position.
10:07:32.80 – Telemetric data ceased.

At the loss of data, multiple onboard and offboard video and data sources documented SpaceShipTwo entering an accelerated, high-g pitch up that telemetry confirmed exceeded the vehicle's structural design loads. SpaceShipTwo broke up into several large pieces that impacted terrain over a five-mile area near Koehn Dry Lake, California.

A comprehensive investigation by the NTSB using telemetered and recovered onboard data conclusively demonstrated that all vehicle systems were operating normally up until the point of breakup. The rocket motor met or exceeded expectations, running smoother and with less vibration than during any previous powered flight.

SpaceShipTwo used a patented feathering system designed to aerodynamically provide stable reentry into the Earth's atmosphere upon completion of a sub-orbital spaceflight. It functioned by rotating SpaceShipTwo's twin tail booms upward about the wing's trailing edge approximately 65 degrees to increase both stability and drag during the descent. In the feather down position a pair of feather lock hooks were engaged at the leading edge of the boom to provide the structural integrity required during the transonic (approximately 0.8 to 1.2 Mach) region where large up loads on the tail during powered flight would otherwise overpower the actuators and cause the feather system to extend without any additional pilot action.

Normal extension of the feather system required a two-step sequence of aircrew actions:

1) **Feather Lock Handles – UNLOCK**. This action disengaged the feather lock hooks from the tail booms and enabled rotation of the system. Unlocking of the feather system was accomplished through the copilot's single movement of the feather lock handles into the unlocked position. When accomplished at 1.4 Mach or greater (as required per the SpaceShipTwo checklist procedures and the PF-04 test card) the feather system remained retracted due to a sufficient closing pre-load from the feather actuators and favorable, tail-down aerodynamic loads.

2) **Feather Handle – EXTEND**. This action commanded the feather system into the extended position. Normal extension occurred subsequent to unlocking the feather locks when the copilot moved the feather handle (a lever independent from the feather lock handle) to the extended position. On normal rocket-powered flights, checklist procedures called for this step to occur after rocket motor burn out while in space just prior to apogee.

Probable Cause and Contributing Causes

The **Probable Cause** of this accident was the copilot's unlocking of SpaceShipTwo's feather locks at 0.92 Mach, approximately 14 seconds prior to the flight manual minimum speed of 1.4 Mach.

Although normal checklist procedures maintained the feather locks in the locked position until after obtaining a minimum speed of 1.4 Mach, the mishap copilot prematurely unlocked the system at approximately 0.92 Mach. This premature unlocking was indisputably confirmed by telemetric, in-cockpit video and audio data. At this speed, lift from the horizontal tails well exceeded the feather actuator's ability to prevent a rapid aerodynamic extension of the feather system. These forces caused the feather to rapidly extend without any further pilot action or mechanical malfunction.

A thorough review of the mishap flight data conclusively determined that there were no misleading indications on the pilot displays and that all flight data were accurately displayed to the aircrew.

Extension of the feather while in boosted flight under these conditions imparted over 9g's of pitch up acceleration forces on the spaceship. These forces exceeded SpaceShipTwo's designed structural load capability and resulted in its in-flight breakup.

The **Contributing Causes** of the accident were:

- **Feather Lock system design.** The Feather Lock system design did not have an automatic mechanical inhibit to prevent premature movement of the feather system.
- **Crew Resource Management.** Scaled Composites' aircrew procedures did not require a challenge/response protocol prior to moving the feather lock handle.

Recommendations

Scaled Composites was responsible for all aspects of the flight test program at the time of the accident. Subsequently, Virgin Galactic has assumed full responsibility for the completion of SpaceShipTwo flight test program and the commercial operations which will follow.

Well prior to the accident, Virgin Galactic and TSC began a vehicle improvement program in anticipation of the program's planned January 2015 transition from Scaled Composites. The improvement program was based on lessons learned from both SS2-001's construction and the flight test program. Commercial service enhancements were scheduled to be included in both SS2-001 and SS2-002 (currently under construction by TSC) prior to either vehicle entering commercial service.

Following the accident, Virgin Galactic and TSC undertook a comprehensive internal and external program review of the SpaceShipTwo design and operations. Virgin Galactic recommends these actions:

1) Modify the SpaceShipTwo feather lock system with an automatic mechanical inhibit to prevent unlocking or locking the feather locks during safety-critical phases of flight.

   Status: Completed

2) Add to the SpaceShipTwo Normal Procedures checklist and Pilot's Operating Handbook an explicit warning about the consequences of prematurely unlocking the feather lock.

   Status: Completed

3) Implement a comprehensive Crew Resource Management (CRM) approach to all future Virgin Galactic SpaceShipTwo operations in a manner consistent with the pre-existing CRM program VG has employed for WK2 operations. This includes, as a minimum:

- Standardized procedures and call outs
- Challenge/response protocol for all safety-critical aircrew actions, to include feather lock handle movement
- Formalized CRM training

Status: Completed

4) Conduct a comprehensive internal safety review of all SpaceShipTwo systems to identify and eliminate any single-point human performance actions that could result in a catastrophic event.

Status: An initial assessment was completed and modifications to SS2-002 are in progress. Virgin Galactic will continually evaluate and improve System Safety throughout SpaceShipTwo's lifecycle.

5) Conduct a comprehensive external safety review of Virgin Galactic and The Spaceship Company's engineering, flight test and operations as well as SpaceShipTwo itself.

Status: Initial Assessment Completed. The external review team will review the program both prior to commencement of flight test activities as well as prior to entering commercial service.

6) Ensure Virgin Galactic employs pilots who meet or exceed the highest standards and possess a depth and breadth of experience in high performance fighter-type aircraft and/or spacecraft. Minimum VG qualifications during the flight test program shall be:

- A long course graduate of a recognized test pilot school with a minimum of 2.5 years post-graduation experience in the flight test of high performance, military turbojet aircraft and/or spacecraft.
- A minimum of 1000 hours pilot in command of high performance, military turbojet aircraft.
- Experience in multiengine non-centerline thrust aircraft
- Experience in multi-place, crewed aircraft and/or spacecraft

These criteria are based on industry best practices for flight testing, using DCMA INST 8210.1C, paragraph 4.3 as guidance.

Status: Completed. All current Virgin Galactic pilots exceed the above minimum VG standards.

FACTUAL INFORMATION

1.1 Background

1.1.1 Relationship between Scaled Composites, Virgin Galactic (VG) and The Spaceship Company (TSC)

In October 2004, Mojave Aerospace Ventures' (MAV) SpaceShipOne claimed the $10 million Ansari X PRIZE as the world's first privately developed human spaceflight program. Following SpaceShipOne's retirement from active service that same year, Virgin Galactic secured a license for the MAV Intellectual Property (IP). In 2006, VG, TSC and Scaled Composites entered into a development agreement whereby Scaled began design and development of what became SpaceShipTwo and WhiteKnightTwo. The Spaceship Company began as a joint venture between Galactic Ventures, LLC (Virgin Galactic's immediate 100% parent) and Scaled Composites. In 2007 Northrop Grumman purchased Scaled Composites and in 2012 Galactic Ventures acquired full ownership of the TSC venture. Today, TSC is responsible for manufacturing the full fleet of Virgin Galactic's SpaceShipTwo and WhiteKnightTwo vehicles and has built extensive capabilities in all aspects of aerospace vehicle design, analysis, fabrication and test.

At the time of the accident, Scaled Composites was under contract with TSC and Virgin Galactic to both design, build and develop SpaceShipTwo as well as execute its experimental flight test program. The program was planned to culminate in the demonstration of both maximum altitude and maximum duration powered flight. Upon completion of the program, SpaceShipTwo was to be transferred to TSC. Operations were also scheduled to be simultaneously transferred to Virgin Galactic for both follow on operational testing and eventual commercial operations.

WhiteKnightTwo was formerly transferred from Scaled Composites to TSC in February 2014. The accident aircraft, SS2-001, was scheduled to transfer to TSC in January 2015. At the time of the accident, SS2-001 was under the care, custody, and control of Scaled Composites.

Virgin Galactic and TSC will be interchangeably referred to as "Virgin Galactic" throughout this report. The corporate structure is diagramed on the next page in Figure 1.

1.2 SpaceShipTwo and WhiteKnightTwo Vehicle Information

SpaceShipTwo (SS2-001), shown in Figure 2, was designed and built by Scaled Composites, LLC. It held an experimental category Special Airworthiness Certificate originally issued by FAA-AST on July 23, 2008, and most recently re-issued on October 1, 2014. SpaceShipTwo was a hybrid rocket-powered, multi-configuration vehicle made of composite materials and designed to have eight seats (six space flight participants and two pilots) although the flight test vehicle was configured with only pilot and copilot seats for the accident flight. It had a low-wing, twin-tail booms, outboard horizontal tails, and "extension-only" tricycle landing gear. Scaled Composites designed the vehicle to provide regular suborbital space access for the general public. SpaceShipTwo was scheduled to be delivered to Virgin Galactic following completion of Scaled's flight testing in early 2015. (Ops. Fact. Rpt., page 17.)

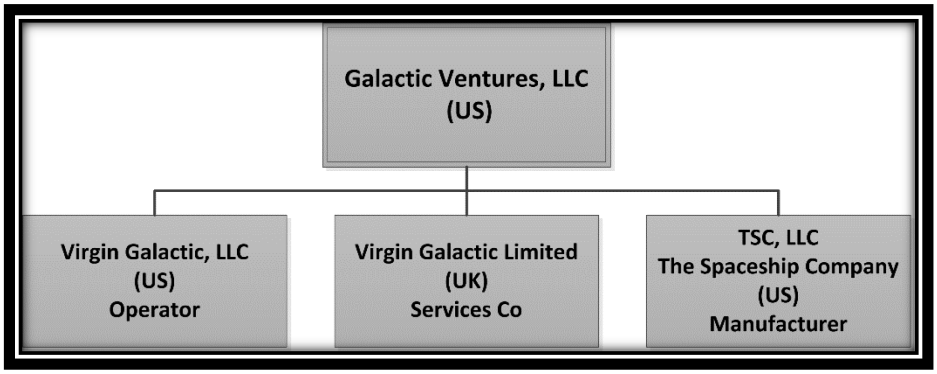

Figure 1 – Corporate Structure

Scaled Composites also designed and built WhiteKnightTwo (Figure 3) as a fixed-wing turbofan-powered airplane used as the first stage of the spaceflight system. It was intended to carry SpaceShipTwo to a release altitude of approximately 47,000. At the time of the accident WhiteKnightTwo was owned by TSC, but was operated by Scaled Composites as part of a Commercial Space Transportation Experimental Permitted launch system per Experimental Permit Number EP 12-007. (Ops. Fact. Rpt., page 18.).

Figure 2: SpaceShipTwo (Registration N339SS, S/N 001).

Figure 3: WhiteKnightTwo (N348MS, S/N 001) with SpaceShipTwo Mated.

1.3 Rocket Motor History

The accident occurred during Scaled Composites' fourth powered flight of SpaceShipTwo. The first three flights utilized a hybrid rocket motor with Hydroxyl-terminated Polybutadiene (HTBP) solid fuel. The accident flight was the first powered by a variant of the original motor using a polyamide based fuel. Structurally, there were no significant differences between the polyamide and HTPB rocket motors flown previously. Both of these motors share heritage back to the original hybrid motor successfully flown on SpaceShipOne.

Hybrid rocket motors are a unique blend of solid rocket motors and liquid rockets. A hybrid possesses many advantages over traditional liquid rockets or solid motor designs in terms of safety and simplicity. The fuel inside the hybrid motor is inert until exposed to both oxidizer and an ignition source. This feature provides exceptional safety during handling and transportation operations.

Ignition of the hybrid motor occurs when liquid Nitrous Oxide (N_2O) is passed across the HTBP or polyamide fuel in the presence of an ignition source. Unlike a solid motor which can't be shut down once running, shutting down SS2's hybrid motor is accomplished by simply stopping the flow of N_2O across the fuel. This hybrid arrangement eliminates a significant deficiency of solid motors without the addition of complex turbopumps and other systems found in liquid rockets.

Additionally, these second generation hybrid motors flown on SpaceShipTwo included significant safety improvements over the first-generation rocket motors of the SpaceShipOne program. Utilization of both chilled N_2O and inclusion of a helium tank to both pressurize and inert the main oxidizer tank (N_2O) were included to mitigate N_2O hazards.

Significantly, this accident validated the effectiveness of these significant safety improvements. During the vehicle's breakup, ground-based video conclusively captured the separation of an actively-burning rocket motor from a nearly full N_2O tank and the rapid N_2O venting that followed. A detailed examination of the wreckage conclusively determined that the vehicle neither exploded in flight nor burned in any manner. Additionally, it was determined that the damage to all of the pressurant tanks were due to ground impact following the accident event.

1.4 Flight Test Program History

Scaled Composites held an experimental launch permit from the FAA to operate SpaceShipTwo and was under contract with Virgin Galactic to carry out the test program for SpaceShipTwo, referred to as Tier1b. This extensive test flight program was undertaken by Scaled Composites to validate the design of the aircraft, including the vehicle's unique "feathering" re-entry system, and to gradually expand SpaceShipTwo's flight envelope beyond Earth's atmosphere.

Scaled Composites' flight test program for SpaceShipTwo followed an incremental approach, with the goal of eventually sending SpaceShipTwo beyond the boundary of outer space. The test program was modeled from the SpaceShipOne program and is divided into 3 phases:

Phase I included captive-carry flights with SpaceShipTwo mated to WhiteKnightTwo (see Figure 4), unpowered glide flights and "Cold Flow" test flights where oxidizer was flowed through the craft's propulsion system to verify readiness for Phase II powered flights.

Phase II included powered flights that would gradually expand the flight envelope to a demonstration of maximum altitude and duration.

Phase III included demonstration test flights for repeatability. (Ops. Fact. Rpt., page 28.)

Figure 4: SpaceShipTwo Captive-Carry Flight.

1.4.1 Powered Test Flights

Prior to the accident flight, there had been three powered test flights of SpaceShipTwo. The first powered test flight (PF-01) expanded the flight envelope with a 16 second burn and reached a maximum speed of approximately Mach 1.2. (Interview of M. Stucky[1], Ops. Fact. Rpt., Attachment 1, page 32.)

For the second and third powered flight tests (PF-02 and PF-03), the feather was unlocked by the copilot at Mach 1.2 and Mach 1.3, respectively, as per the test card procedures for those flights. Neither of the flights was anticipated to reach a speed of 1.4 Mach due to the limited duration rocket burn of 20 seconds (Ops. Fact. Rpt., page 29.) The combination of aircraft configuration and specific fight test profile differences during PF-02 and PF-03 resulted in a different transonic tail load profile during these flights when compared to those experienced on PF-04. This allowed

[1] At the time of the accident, Mark Stucky was a Scaled Composites Test Pilot. On February 2, 2015, Mark Stucky was hired by Virgin Galactic's commercial flight team responsible for flying WhiteKnightTwo and SS2- 002.

the feather locks to be safely unlocked at a lower Mach number during PF-02 and PF-03 without danger of inadvertent feather extension.

Scaled Composites' fourth powered flight test (PF-04) planned to expand the flight envelope with a 38-second burn using a motor with significantly more thrust than the previous flights. The maximum speed for the boost portion of the launch was anticipated to be Mach 2.00. (Ops. Fact. Rpt., page 8.)

According to the Scaled Composites' SpaceShipTwo Program Manager, the fourth powered test flight was expected to reach an altitude of approximately 135,000-138,000 feet and one of the primary objectives for the flight was to conduct the first supersonic, feathered re-entry. (Interview of M. Stinemetze, Hum. Perf. Rpt., Attachment 1, page 35; *see also* Interview of F. Sturckow, Ops. Fact. Rpt., Attachment 1, page 8).

1.5 Simulator Training

Scaled Composites' test pilots prepared for PF-04 using a fixed-base simulator with a 180-degree curved screen replicating the cockpit of SpaceShipTwo. (Hum. Perf. Fact. Rpt., page 22). The simulator was the main training device for systems reviews, flight readiness reviews, and discussions among the pilots. (Interview of D. Mackay, Ops. Fact. Rpt., Attachment 1, page 43.)

Before each mission, Scaled Composites' test pilots and flight test engineers used the SpaceShipTwo simulator for initial mission planning and test point specification. After the objectives and test points were refined, the entire mission team (including the control room personnel) conducted full mission rehearsals (integrated simulations). During those mission rehearsals, the team worked through both normal and emergency procedures and abort scenarios.

The simulator allowed flight crews to conduct multiple scenarios of the PF-04 profile, including scenarios from release to feather. (Interview of M. Stucky, Hum. Perf. Rpt., Attachment 1, page 12.) The simulator generated information that could be used to track flight crew proficiency. Each time the simulator was started, the pilot and copilot names were selected, and these data were appended to a log file that included the date, time, simulated wind information, simulator state information and initial condition information. (Ops. Fact. Rpt., page 34.)

The feather locks for PF-04 were scheduled to be unlocked at 1.4 Mach. If the feathers were not unlocked by 1.5 Mach, the crew would receive an aural/visual alert "FEATHER LOCKS" on the display screen. (Ops. Fact. Rpt., page 49.) Both accident pilots conducted training in the SpaceShipTwo simulator multiple times leading up to PF-04. (Ops. Fact. Rpt., page 35.) Backup pilots also observed and participated in simulator training with the accident crew. (Interview of D. Mackay, Ops. Fact. Rpt., Attachment 1, page 47.)

Scaled Composites' test pilots stated that on the day before the accident, the accident crew conducted more practice scenarios than usual involving the release, rocket motor burn and feather portion of the flight profile (boost profiles). (Interview of M. Stucky, Hum. Perf. Rpt., Attachment 1, page 12.)

Scaled Composites' Simulator Log records show that the copilot logged fourteen simulator sessions the day before the accident. (Ops. Fact. Rpt., Attachment 14, page 175.) In the two days prior to the accident flight, the accident aircrew's simulator preparation consisted of 17 total boost profiles, only one of which didn't involve a simulated emergency or abnormal occurrence. Simulated emergencies or abnormal conditions both add additional workload to the piloting task and disrupt the normal cadence of a routine flight.

1.6 Flight Crew

1.6.1 Accident Pilot Experience

The accident pilot was 43 years old and resided in Tehachapi, CA. His date of hire with Scaled Composites was December 16, 1996. Previous to his employment with Scaled Composites, he was employed an aircraft dispatcher and ground instructor in Santa Barbara, CA from October 1991 to December 1994 at Above All Aviation. He was an information services intern at Lockheed Martin Skunk Works in Palmdale, CA from July 1995 to September 1995, and was a flight instructor at the Cal Coast Flying Club in San Luis Obispo, CA from January 1994 to 1996.

He has been the Director of Flight Operations for Scaled Composites since 2008. According to interviews, he had overall responsibility for flight test and normal flight operations, managing flight crews and selecting flight crews, scheduling flight crews, providing training and currency opportunities for flight crews. Prior to assuming the role of Director of Flight Operations he was a test pilot for the SpaceShipOne test program, and was responsible for the development of the simulator, avionics/navigation system, and ground control system for the SpaceShipOne program. (Ops. Fact. Rpt., page 11).

The accident pilot accumulated the following flight times:

Total pilot flying time (hours)	2,980
Total Pilot-In-Command (PIC) time	2,550
Total flying time SS2	48.8
Total flying time WK2	188.0
Total flying time last 24 hours*	0.7
Total flying time last 30 days*	2
Total flying time last 90 days	42
Total flying time last 12 months	125

*Includes accident flight while mated to WK2 (Ops. Fact. Rpt., page 13.)

1.6.2 Accident Copilot Experience

The accident copilot was 39 years old and resided in Tehachapi, CA. At the time of the accident, he was a project engineer and test pilot for Scaled Composites. His date of hire with Scaled Composites was January 17, 2000. Prior to his employment with Scaled Composites, he was a wing and empennage engineer on the Vantage airplane at VisionAire Jets from January 1998 to January 2000. Prior to that, he worked part time for The Boeing Company during the summers of 1996 and 1997 as a systems engineer and propulsion engineer. (Ops. Fact. Rpt., page 14).

Based on records provided by Scaled Composites to the NTSB, including written logbooks, electronic logbooks and aircraft records, including the SpaceShipTwo, the copilot accumulated the following flight times:

Total pilot flying time (hours)	2,154
Total Pilot-In-Command (PIC) time	1,961
Total flying time SS2	31.8
Total flying time WK2	42.8
Total flying time last 24 hours*	0.7
Total flying time last 30 days*	20.7
Total flying time last 90 days	43.4
Total flying time last 12 months	163.9

*Includes accident flight while mated to WK2 (Ops. Fact. Rpt., page 16.)

1.6.3 Pre-accident Programmatic History

In the month preceding the accident, the copilot worked on two other projects in addition to SpaceShipTwo and had only two days of pilot training. During the month of October 2014, he worked an average of about 51 hours per week, ranging from 16-26 hours on the SpaceShipTwo project per week, or about 32-55% of his time. (Hum. Perf. Rpt., page 5.) According to Scaled Composites' VP of Engineering, some staff, including test pilots, worked on multiple projects at the same time. Regarding the copilot, he stated that at the time of the accident, he was a project engineer on one project and a test pilot on the SpaceShipTwo program. He was also a part of the senior leadership at Scaled Composites and would informally mentor people. The copilot would also assist on other projects as a subject matter expert, although it was not an official assignment. (Interview of B. Diachun, Ops. Fact. Rpt., Attachment 1, page 87.)

According to Scaled Composites' VP of Operations, it was rare to find a program where everyone was dedicated to that program 100% of the time. He stated that this was in line with the business model of the company that supported multiple functions within the company. (Interview with J. Kelley, Ops. Fact. Rpt., Attachment 1, page 67.)

During post-accident interviews, several Scaled Composites test pilots and engineers discussed the copilot's involvement with other projects outside of the SpaceShipTwo program. According to the accident pilot, all pilots involved in the SpaceShipTwo project also worked on other projects. He estimated that 90% of the copilot's time was taken by other responsibilities not related to SpaceShipTwo. (Interview of P. Siebold, Ops. Fact. Rpt., Attachment 1, pages 70-71.) A Scaled Composites engineering manager working on the SpaceShipTwo program stated that the copilot's training was not continuous or on-going, and that there was a period when he did not fly for an extended period of time. (Interview of D. Armstrong, Ops. Fact. Rpt., Attachment 1, page 83.)

Two days prior to the accident, the copilot was sent home earlier than planned from another project on which he was working, due to concerns that he have enough time to prepare for PF-04. (Interview of M. Stucky, Hum. Perf. Rpt., Attachment 1, page 17.)

1.7 History of Accident Flight

1.7.1 Pre-Flight Brief

On October 30, 2014, the day before the accident flight, Scaled Composites conducted a pre-flight brief for everyone involved in the test flight, including personnel from Scaled Composites, Virgin Galactic and TSC. This review started with the Maintenance and Engineering Request Brief, and the longer Flight Brief. (Interview of D. Mackay, Ops. Fact., Attachment 1, page 43.) The review followed the Scaled Composites Mission Briefing Guide which called for an in-depth review of the vehicle status, requirements of participants, and the specific conduct of the tests to be performed. (Hum. Fact. Rpt., page 10.) The commander of WhiteKnightTwo led the briefs. Everyone involved in the mission participated. (Interview of Todd Ericson, Ops. Fact., Attachment 1, pages 49-50.) There were no anomalies or concerns expressed at this briefing. (Interview of Michael Masucci, Ops. Fact. Rpt., Attachment 1, page 11.)

The flight crews for WhiteKnightTwo and SpaceShipTwo participated in a “delta” briefing at 4:00 a.m. PDT the morning of the flight, which involved the launch team and pilots, and covered items such as weather, NOTAMs, N_2O loading and a review of the flight test data card. The launch was originally planned for approximately 8:00 a.m. PDT, but was delayed due to N_2O temperatures which were a few degrees colder than deemed allowable for takeoff. (Ops. Fact. Rpt., page 8.)

According to interviews, pilots and engineers were also concerned about landing crosswinds and the forecasted window of acceptable launch conditions due to an approaching cold front. (Interview of Todd Ericson, Ops. Fact. Rpt., Attachment 1, page 50.)

1.7.2 Takeoff to Launch Phase

WhiteKnightTwo successfully departed Mojave Airport (KMHV) carrying SpaceShipTwo at 09:19:30 PDT. (Ops. Facts. Rpt., page 9.) Prior to takeoff, the accident crew performed a check of the feather locks during preflight of the vehicle on the ground and again airborne during the L-10 (ten minutes prior to release) checklist per the Normal Procedures Manual. The crew tested the feather lock system by cycling the feather locks while still mated to WhiteKnightTwo and verifying the indications on the pilot’s MFD (multi-function display). Control room personnel also confirmed successful testing of the feather lock system during the L-10 checklist. (Interview of Todd Ericson, Ops. Fact. Rpt., Attachment 1, page 51.) There were no anomalies detected during testing of the feather lock. (Ops. Fact. Rpt., page 48.)

Wind levels remained within limits through take-off. (Interview of Peter Kalogiannis, Ops. Fact. Rpt., Attachment 1, page 20.) During the climb and shortly after takeoff, a minor discrepancy occurred with SpaceShipTwo’s center MFD, which was rebooted. According to interviews with the surviving pilot and mission control room personnel, the MFD reboot did not cause any issues and all systems were normal during take-off, climb and release of SpaceShipTwo from WhiteKnightTwo. (Interview of P. Siebold, Ops. Fact. Rpt., Attachment 1, page 54.)

1.7.3 Planned Timeline of Events

The brief timeline below depicts an average times between significant events during a normal flight using 0.80 Mach as the zero time. The data in black are the average times from simulator runs 3, 4 and 5 contained in the Human Performance Factual Report, Attachment 10, while the data listed in blue are derived from other sources.

-0:08.80 — SS2 Release from WK2

-0:07.00 — SS2 Rocket Motor Ignition

0:00.00 — 0.80 Mach – Copilot makes "Point 8 Mach" call
Pilot makes "trimming" call
Copilot reads stabilizer position until reaching 14 degrees nose up

0:07.00 — 1.2 Mach – Tail uploads reduce sufficiently to the point where the feather locks can be safely unlocked

0:16.10 — 1.4 Mach – Copilot makes "Unlocking" call and unlocks feather locks.

0:38.00 — Rocket Motor Burnout – Planned duration for PF-04 test flight

1.7.4 Cockpit Image Recorder and Telemetry Data- Timeline of Events

After climbing to an altitude of 47,000 feet MSL, WhiteKnightTwo successfully released SpaceShipTwo. Cockpit audio and video data shows the following timeline of events from release until vehicle breakup approximately 12 seconds later. Times and events from the Cockpit Image Recorder transcript are listed in **black**. Data derived from Telemetry are in **blue**. Elapsed times in seconds are in parenthesis beginning with 0.8 Mach as the zero time.

10:07:19.27 PDT — Release

10:07:19.51 — Pilot commands copilot to fire the rocket motor

10:07:26.83 — Vehicle accelerates through 0.80 Mach

10:07:26.91— (0+00 sec) Copilot makes a 0.80 Mach callout

10:07:28.39— (1.48 sec) Copilot stated "unlocking" in reference to the feather lock system. The recorder shows the copilot subsequently move the feather lock handle using his left hand from the locked to the unlocked position. This occurred approximately 14 seconds early.

10:07:28.80— (1.89 sec) Both the left and right unlock pressure switches indicated pressure in the unlock circuit. The vehicle's speed was just above 0.92 Mach.

10:07:28.90— (1.99 sec) Feather lock handle reaches full unlock position. The copilot then releases the feather lock handle and places his left hand upon his left thigh.

10:07:29.50 — (2.59sec) Both the left and right lock position switches began to show a transition occurring from a locked to an unlocked state.

10:07:30.60 — (3.69 sec) Feather position parameter indicated the start of movement of the feathers. At this time, the feather retract (down) pressure was approximately 432 psig in the left actuator and 460 psig in the right actuator. The pressure readings from the extend side (up) pressure for both actuators were slightly less than 0 psig. This conclusively indicates that aerodynamic forces, not the actuators, were driving the system towards the feather extended (up) position.

As the feather began to extend over the next 1.8 seconds, the pressure in the retract side (down) of the feather actuators continued to increase. During the extension sequence, the maximum pressure in the retract side (down) of the feather actuators was approximately 710 psig in the left actuator and 759 psig in the right actuator. The pressure readings for the extend side (up) pressure for both actuators was slightly less than 0 psig during the feather extension. This conclusively indicates that aerodynamic forces, not the actuators, continued to drive the system towards the feather extended (up) position for the remainder of the accident sequence.

10:07:31.10 —(4.19 sec) Both the left and right feather locks reached an unlock state. The total time to unlock was approximately 1.6 seconds.

10:07:31.42 — (4.51 sec) Pilot stated "pitch up."

10:07:32.44 — (5.53 sec) Data for the feather position was considered unreliable at this point.

10:07:32.80 — (5.89 sec) End of cockpit recording

10:07:33.02 — (6.11 sec) Loss of signal for recorded data occurs.

(Cockpit Image Record Fact. Rpt., pages 59-64.)

(Systems Fact. Rpt.[2], pages 14-15; *see also* Elec. Rec. Dev. and Flt. Data Rpt., pages 19-20.)

1.8 Feather System

SpaceShipTwo used a feather system to configure the vehicle for aerodynamic re-entry. Extension and retraction of the feathers on SpaceShipTwo was a two-step process. To extend the feather for re-entry, the pilots would first unlock the system by moving the connected feather lock handles on the center console down to the unlock position and then extend the feather by pulling an independent actuation handle. The status of the feather and lock system was monitored through indicator lights in the cockpit, a full-time display field on the center MFD, and, in detail, on a crew-selectable feather systems page on the MFD. (Ops. Fact. Rpt., page 39.)

When the feather was not extended, it was locked in the retracted position to provide requisite structural integrity to counter up loads on the tails that were encountered during the vehicle's initial acceleration and turn to the vertical after launch. The feather locks were a mechanical system that locked and unlocked the feather on SpaceShipTwo. When the two feather locks were unlocked, the feather actuators in the aft fuselage, when commanded, could rotate the feather assembly upward 65° to place the vehicle in the feathered configuration for re-entry, as show in Figure 5. (Ops. Fact. Rpt., page 40.)

[2] For comparative purposes, data taken from the Systems Factual Report has been converted from PDT to UTC.

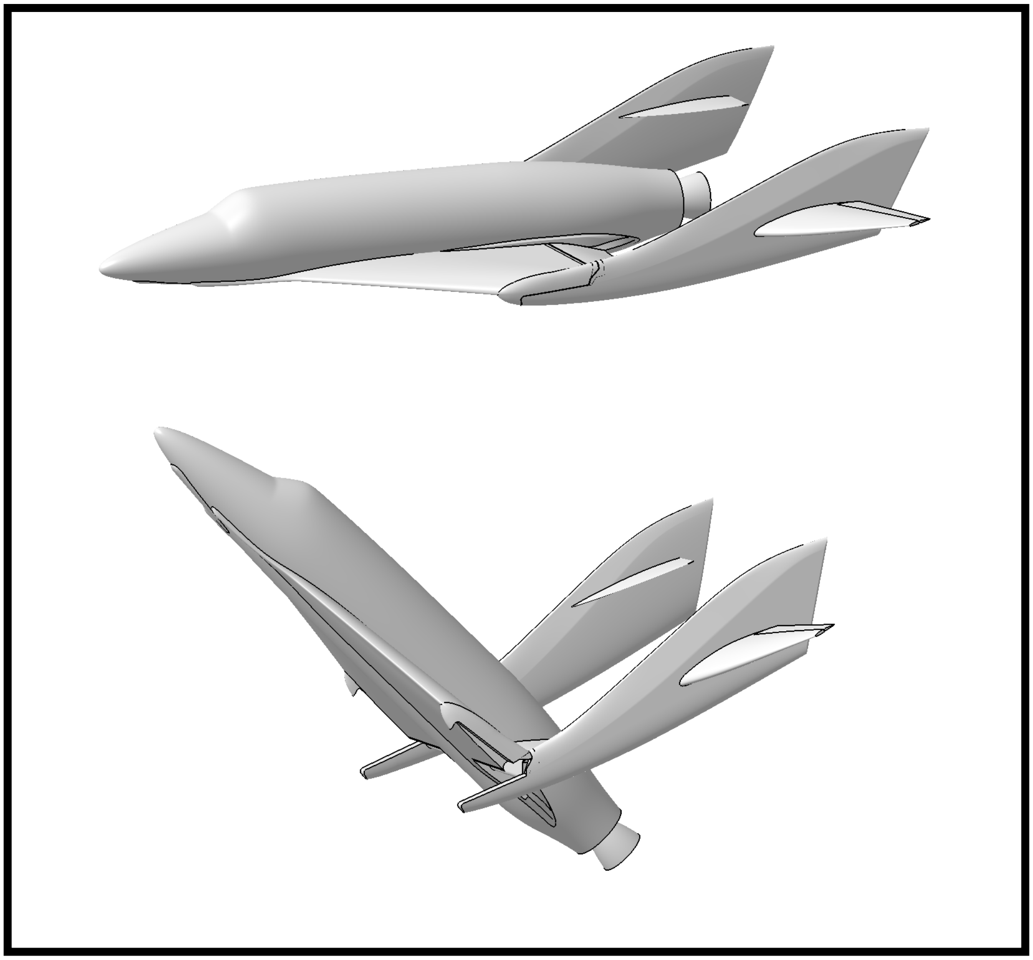

Figure 5: SpaceShipTwo Unfeathered and Feather Up Configuration.

The feather locks must first be unlocked by the copilot before the feather actuation handles can easily be pulled, deploying the feathers. To unlock the feather locks, the pilot moves the lock handles located on the center console downward to their mechanical stop. To lock the feathers, the pilot returns the handles to the up stop. The feather lock handles did not incorporate an automatic mechanical inhibit and it was therefore possible for the aircrew to lock or unlock the system during any phase of flight.

The feather locks actuate within one to two seconds of the feather lock handles reaching full travel. The feather lock handles were held in the locked or unlocked positions by small gates. The gates prevented the handles from moving under normal vibration. To move the handles, a slight side force to the right side would allow the handles to move past the gates. (Ops. Fact. Rpt., page 41.)

According to Scaled Composites' former Chief Aerodynamicist, the only means employed to prevent inadvertent unlocking of the feather locks was that moving the handle downward required "*quite a bit of force*" so that the pilot knew he was moving the handle. (Interview of J. Tighe, Hum. Perf. Rpt., Attachment 1, page 3.) During post-accident interviews, Scaled Composites' Program Manager for the SpaceShipTwo project stated that the design of the feather system was predicated on the requirement that the feather is not to be deployed at the wrong time or at the wrong speed. (Interview of M. Stinemetze, Hum. Perf. Rpt., Attachment 1, pages 31-32.)

According to Scaled Composites' engineers, the feather locks were designed to ensure the feathers remained in a retracted position when it was not intended to be feathered:

> "The design parameters for the feather actuators were selected such that the feather retracting forces provided by the actuators were adequate to retract the feathers during the recovery phase of flight (after re-entry) and less than the feather extending forces caused by aerodynamic loads during the transonic flight regime and gamma-turn maneuver. The design parameters of the locks were selected so that they would maintain the feather in a retracted position during the portions of the trajectory when the feather was not intended to be extended, including the transonic flight regime and the gamma-turn maneuver."

(Systems Fact. Rpt., page 3.)

According to Scaled Composites' former Chief Aerodynamicist, who developed SpaceShipTwo's feather system, 1.4 Mach was established for PF-04 as the speed to unlock because it gave a significant safety margin beyond the transonic region where the upward forces on the tail exceeded the opposing forces of the actuators. He stated that the highest upload forces on the tail would occur between 0.8 and 1.0 Mach, which is when the tail would want to feather if unlocked. (Interview of J. Tighe, Hum. Perf. Fact. Rpt., Attachment 1, pages 6-7; *see also* Hum. Perf. Rpt., page 21.) The feather locks were designed to ensure the tail remained retracted and did not feather during transonic flight.

1.9 Pilot Operating Procedures

1.9.1 Normal Procedures Manual

Normal pilot operating procedures and checklists for preflight, flight and post-flight were set forth in the SpaceShipTwo Normal Procedures Manual prepared by Scaled Composites. According to test pilot interviews, the Normal Procedures Manual was one of the source documents for SpaceShipTwo pilots. (Interview of D. Mackay, Ops. Fact. Rpt., Attachment 1, page 46.) Generally, checklists from the Normal Procedures Manual were referenced by pilots to accomplish required tasks based on the phase of the flight. (Ops. Fact. Rpt., page 43.)

After release and rocket motor ignition, the vehicle would accelerate toward the transonic phase of flight (approximately 0.80-1.20 Mach). Upon reaching 1.40 Mach during the rocket-powered boost portion of the flight the Normal Procedures Manual required the copilot (referred to as the Pilot Not Flying or PNF) to unlock SpaceShipTwo's feather as shown in Figure 6 below.

M339 SPACESHIPTWO
NORMAL PROCEDURES
SS2-90P002 REV J

BOOST PHASE

1. Stick – maintain < 15° AOA

When >0.95 Mach (after pitch bobble)

2. Pitch Trim – Set –15.0 NU (or per flight card)

@ >1.4 Mach

3. PNF FEATHER -- UNLOCK
4. Pitch Trim – as required to capture zenith

Figure 6 – Boost Phase Normal Procedures

(SS2-90P002, Rev. J, Change 5, 14 October 2014, page 37; *see also*, Ops. Fact. Rpt., page 48.)

1.9.2 Flight Test Data Card Procedures

In addition to the Normal Procedures Manual, mission specific information is included on a flight test data card. This card included vehicle restrictions and limitations, weight and balance information, performance information, mission timeline information and expected pilot actions during the various phases of flight. (Ops. Fact. Rpt., page 43.) Scaled Composites' test pilots stated that the PF-04 Flight Data Test Card was developed by the accident crew to address specific procedures for PF-04 and was designed to serve as a primary reference containing the important steps for the mission.

According to Scaled Composites' engineers and test pilots working on the SpaceShipTwo project, the important steps were put on the card and were written in a way that helped ensure the cadence of the steps taken by the crew continued properly (Interview of M. Stucky, Hum. Perf. Rpt., Attachment 1, page 13.)

The PF-04 Flight Test Data Card shown in Figure 8 defined pilot tasks during the boost portion of the flight after the rocket motor is fired. (Ops. Fact. Rpt., page 44.) According to interviewed pilots and engineers, the boost procedures for the copilot would have been memorized. These procedures are highlighted in Figure 7 below.

COPILOT

CALL – 0.80M

CALL – Stabs (degrees)

1.4 Mach – FTHR UNLOCK

Figure 7 – Copilot's Boost Phase Responsibilities

(Ops. Fact. Rpt., page 49.)

According to post-accident interviews with the accident pilot, the 0.80 Mach callout was designed to give the pilot flying information that the transonic pitch bobble was about to occur. He further stated that the boost phase was a very dynamic environment where the pilot workload was extremely high. (Ops. Fact. Rpt., pages 46-47.)

According to the accident pilot, after the transonic pitch up was complete the pilot's task was to actively trim the stabilizers (*i.e.*, "stabs") to optimize the pitch up ("Gamma Turn") maneuver into the vertical. The primary trim indication was on the center MFD, and the test procedures required the copilot to call out trim settings so that the pilot did not need to look over during such a busy time of the flight. (Interview of P. Siebold, Ops. Fact. Rpt., Attachment 1, page 70.)

1.9.1 Feather Unlock Procedures

The flight data card for the accident flight required the feather locks to be unlocked by the copilot once SpaceShipTwo reached 1.4 Mach during the boost phase of the flight. According to post-accident interviews with Scaled Composites' engineers and test pilots, the boost phase was a high workload phase of flight and duties were divided between the pilot and copilot. The copilot would unlock the feather at 1.4 Mach, with or without a callout, as indicated on the PF-04 Flight Data Test Card. (Hum. Perf. Rpt., page 21.)

According to the Scaled Composites Program Manager for the SpaceShipTwo project, there was a small window in which they counted on the pilot "*to do the right thing*" so they did not build any safeguards into the system. (Hum. Perf. Rpt., page 21; *see also* Interview of M. Stinemetze, Attachment 1, page 32.)

Test pilots were made aware of the speed at which to unlock the feathers by referencing the SpaceShipTwo Pilot Operating Handbook (POH), Normal Procedures Manual, and flight test cards. It was also discussed formally in meetings and informally among test pilots and engineers involved in the test program. There was no documentation in the POH that discussed the risk of unlocking the feather before 1.4 Mach, but, according to interviews, pilots were aware of the risk of unlocking the feather during the transonic phase of flight.

SCALED COMPOSITES	FLIGHT TEST DATA CARD M348 / M339 M339 PF04_Rev U	CARD 7

13.SS2 Powered Flight 04

Release Altitude	[redacted]	Drop Weight	[redacted]
Release Airspeed		Drop C.G.	
Pitch/Roll Trim		Full Burn Ldg Wt	
Burn Timer		Full Burn Ldg CG	

#	Maneuver	kft	PILOT	COPILOT
A	RM2 Burn	46	• After transonic bobble – TRIM to -14.0° NU	• CALL – 0.80M • CALL – Stabs (degrees) • 1.4M – FTHR: UNLOCK
B	Coast	80	• Pitch: Capture Red Circle • Goal = vertical	• RM2 Sw's (L←R) – OFF (2") [redacted]
C	Feather	135	• ROLL BOOST - OFF • PRI RCS – ENABLE • Pitch–Belly down • RCS – 3 axis eval **When ϒ ~ +20°**	• FTHR: EXTEND • Trim to -10° NU/+0.5Roll
D	Reentry	60	**When > 40 KEAS** • RCS – DISABLE • DAMPERS – Verify ON • ROLL BOOST – A/R **When <60K' or <1.3Nz** • ROLL BOOST – A/R • 10° α dive recovery	• Trim to -10° NU/+0.5Roll **When <60K' or <1.3Nz** • FTHR: RETRACT
E	N20 Dump	40	**0.5g < Nz < 2.7g & <10°α** • DAMPERS – OFF (<0.8M) • S/B – ENABLE • Left Window Heat - Auto • ≥ 160 KEAS	• N2O AUTO DUMP – ON • PSC – Verify **ACTIVE** *When MOT @ 160 PSI* • N2O AUTO DUMP– OFF [redacted]
F	Landing		• **HK360 WIF L / R RWY 30 / 12 / 26 / 08**	

Figure 8: PF-04 Flight Data Test Card (Card 7) flown Oct. 31, 2014

Scaled Composites' former Chief Aerodynamicist stated he was not sure whether the pilots were given an official document that showed the tail load during the transonic region, but the issue was discussed in an email on July 8, 2010 and in a presentation at the Flight Readiness Review (FRR) in April 2011. The risk of a catastrophic event, however, was not documented. According to a Scaled Composites' Vice President, they never imagined that the feather system would be unlocked too soon. He believed pilots were aware when to unlock the feather system, because that was how they did it in the simulator. (Hum. Perf. Fact. Rpt., pages 21-22; *see also* interview of C. Bird, Attachment 1, page 22.)

SECTION 2. ANALYSIS

2.1 Accident Sequence

2.1.1 Flight Test Procedures Required the Feather Locks to be Unlocked Only Once the Vehicle Reached a Speed of 1.4 Mach

Evidence reviewed by investigators demonstrates that the feather locks were not to be unlocked until the vehicle reached a speed of 1.4 Mach. Test pilots were made aware of the speed at which to unlock the feathers by referencing the Pilot Operating Handbook, the Normal Procedures Manual and flight test cards. It was also discussed formally in meetings and informally among test pilots and engineers involved in the test program. (Hum. Perf. Rpt., page 21.)

After release and rocket motor ignition, the vehicle would accelerate toward the transonic phase of flight (approximately 0.80-1.20 Mach). Upon reaching 1.40 Mach during the boost portion of the flight, the Normal Procedures Manual required the copilot to unlock the feather locks. (SS2-90P002, Rev. J, Change 5, 14 October 2014, page 37; *see also*, Ops. Fact. Rpt., page 48.) In addition to the Normal Procedures manual, flight test data cards included mission specific data that required the copilot to "Unlock the feather once the vehicle reaches 1.4 Mach." (Ops. Fact. Rpt., page 49.)

Consistent with the Normal Procedures Manual, the flight test data card for the accident flight required the copilot to unlock the feather once the vehicle reached a speed of 1.4 Mach.

2.1.2 The Copilot Unlocked the Feather Locks Before the Vehicle Reached a Speed of 1.4 Mach

Evidence reviewed by investigators demonstrates that the copilot unlocked the feather before the vehicle reached a speed of 1.4 Mach. According to the cockpit audio and video data, the copilot made a 0.80 Mach callout at 10:07:26.91 PDT. At 10:07:28.39, the copilot stated "unlocking" and, at 10:07:28.90, video documented the copilot moving the feather lock handles to the fully unlocked position. The final frame in the video recording occurred at 10:07:32.80, followed by the vehicle experiencing an in-flight breakup. (Cockpit Image Record Fact. Rpt., pages 59-64.)

This sequence of events is consistent with telemetric data, which shows a correlation between the time the video depicts the copilot moving the feather lock handle to unlock and the time at which the left and right unlock pressure switches reflect pressure in the unlock circuit. Telemetric data also shows that, at 10:07:28.80 PDT, both the left and right unlock pressure switches indicated pressure in the unlock circuit and, at 10:07:29.50, the lock position switches transitioned from locked to not locked. (Systems Fact. Rpt., page 14.)[3]

The vehicle's recorded speed at 10:07:28.80 PDT, when both the left and right unlock pressure switches indicated pressure in the unlock circuit, was just above 0.92 Mach. (Systems Fact. Rpt., page 14.) The cockpit audio and video data shows the copilot unlocking the feather within 0.10 seconds of when the telemetric data recorded the vehicle speed to be just above 0.92 Mach.

[3] For comparative purposes, cockpit audio and video data times have been converted to PDT standard.

A thorough review of the mishap flight data and playback of those data through flight hardware conclusively determined that there were both no misleading indications on the pilot displays and that all flight data were accurately displayed to the aircrew. (Systems Fact. Rpt., page 18.) Additionally, post-accident analysis and interviews also demonstrated that cockpit vibration levels were lower during the accident flight than on any of the previous powered sorties. The accident pilot reported that the rocket motor burn was "smooth, with no vibration". (Interview of Pete Siebold, Ops. Fact. Rpt., Attachment 1, page 78). Succinctly, there is no evidence that either the vehicle displays or cockpit vibration levels were a factor in the accident.

Taken together, the above evidence conclusively supports a finding that the copilot unlocked the feather when the vehicle was traveling at approximately 0.92 Mach.

2.1.3 Unlocking the Feather Locks at 0.92 Mach Caused the Tails to Extend into the Feather Position

Telemetric data reviewed by investigators demonstrates that, once unlocked, upward aerodynamic forces on the tail of the aircraft overcame the actuator pre-load and caused the tails of SpaceShipTwo to extend into the feather position.

Data show that the feather position begin to change at 10:07:30.6 PDT. At this time, the feather retract side (down) pressure was approximately 432 psig in the left actuator and 460 psig in the right actuator. Over the next 1.8 seconds, the feathers began to extend (up) and the pressure in the retract side (down) of the feather actuators continued to increase. This is consistent with upward aerodynamic forces on the feathers opposing and ultimately overcoming the actuator pre-load pressures.

During the feather extension sequence, a maximum pressure in the retract side (down) of the feather actuators of approximately 710 psig in the left actuator and 759 psig in the right actuator was recorded. The pressure readings for the extend side (up) pressure for both actuators was slightly less than 0 psig during the feather extension. These data confirm that aerodynamic forces on the tail were acting to extend the feather. Starting at 10:07:32.44, data for the feather position was considered unreliable by investigators. (Systems Fact. Rpt., page 14.)

These telemetric data are consistent with high upward load forces on the tail. Scaled Composites' former Chief Aerodynamicist stated that this was the flight regime where aerodynamic upload forces would cause the tails to feather, if unlocked. Referring to Figure 9, above approximately 0.80 Mach (if the feather locks are not engaged) aerodynamic forces overcome the actuator pre-load and the feather loses approximately 90% of its structural stiffness in countering an upward load on the tail. Above approximately 0.84 Mach with the feather locks unlocked, aerodynamic forces are of sufficient magnitude to extend the feather without any other action.

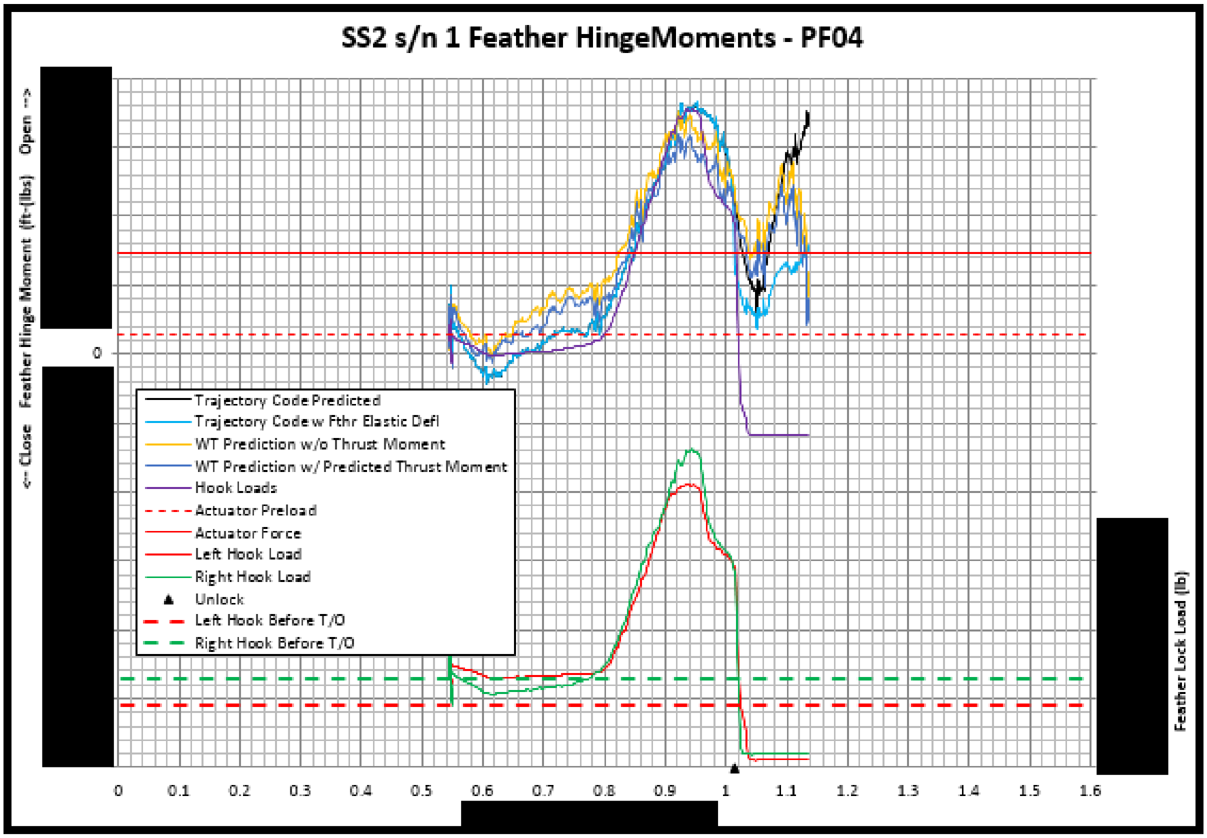

Figure 9 – Feather Forces versus Mach Number

2.1.4 Feathering the tails at 0.92 Mach Caused the Vehicle to Lose Control and Break Up

The evidence reviewed by investigators demonstrates that extending the feathers at 0.92 Mach caused the vehicle to become uncontrollable and break apart. Post-accident analysis and testing confirmed that all vehicle systems were normal up until the point at which the feather lock was unlocked. According to the accident pilot, the last thing he could recall in SpaceShipTwo was "a very violent, large pitch-up with high Gs." This vehicle behavior is consistent with a rapid deployment of the feather system.

According to Scaled Composites' engineers, if the feather was unlocked below 1.2 Mach, the tails would feather uncommanded and the vehicle would pitch up. (Interview of M. Bassette, Ops. Fact. Rpt., Attachment 1, page 17.) According to Scaled Composites' Program Manager, the design of the feather was predicated on the requirement that the feather not be deployed at the wrong time or at the wrong speed. (Interview of M. Stinemetze, Hum. Perf. Rpt., Attachment 1, pages 31-32.)

Unlocking the feather lock while the vehicle was traveling at 0.92 Mach allowed aerodynamic forces to overcome the actuator pre-load and caused the tails to feather. This, in turn, caused the aircraft to pitch up violently, after which SpaceShipTwo was broken apart by positive G-loads, well in excess of the vehicle's design load limitations.

2.2 Other Factors

2.2.1 The Feather Lock System Design Included the Potential for a Single Pilot Action to Result in a Catastrophic Outcome.

SpaceShipTwo's Feather Lock system design incorporated a single point human performance failure risk that allowed a single pilot action to result in a catastrophic outcome. Specifically, the vehicle design allowed a single pilot error (*i.e.,* unlocking the feather locks in the transonic region) to result in a catastrophic structural failure during the boost phase at transonic speeds.

Since the feather system is critical to a safe re-entry, it was designed to be both simple and mechanically redundant. It was essential that the feather locks remain locked during the transonic boost phase of flight while equally critical that they are able to be unlocked prior to extending the feather for re-entry. As a result of this design requirement, all aspects of SpaceShipTwo's feather system (locks and booms) are capable of being both extended and retracted using only one of two independent activation systems.

Human performance failure modes were not considered in Scaled's System Safety analysis. The failure modes the engineers were concerned with were not pilot-centric and most of the discussion centered on getting the feather up, not keeping it down. There was a small window in which they counted on the pilot "*to do the right thing*", so they did not build any safeguards into the system. (Interview of M. Stinemetze, Hum. Perf. Rpt., Attachment 1, pages 31-32.)

The requirement to unlock the feather locks during the boost phase was implemented as a safety mitigation against a high-altitude re-entry with the feather stuck in the down position. Aerodynamic analysis determined that the vehicle could safely return from space in the feather down configuration if the rocket motor was shut down not later than Mach 1.8. Mach 1.4 was selected as a speed which allowed sufficient margin above the critical Mach 1.2 speed where the feather locks were required to remain engaged while still providing sufficient time for the aircrew to shut down the rocket motor in the event the feather locks failed to unlock. TSC is currently conducting a comprehensive review of SS2-002's feather down re-entry capability. According to Scaled Composites' engineers, the design of SpaceShipTwo's feather system was predicated on a requirement that the pilot would not make a human performance error resulting in feather extension during the first 20-25 seconds of flight. An automatic interlock that prevents the pilot from unlocking the feather locks during critical phases of flight may have prevented this accident. For this reason, Virgin Galactic has already implemented design changes for SpaceShipTwo that will prevent a pilot from inappropriately unlocking or locking the feather locks during critical phases of flight.

As part of Virgin Galactic and TSC's comprehensive Systems Safety Review (SSR) process, it was recommended, and the VG/TSC Change Control Board (CCB) authorized development of an electro-mechanical inhibit device to prevent inadvertent pilot actuation of the feather locks in either scenario. The device utilizes an electronic solenoid to inhibit movement of the feather locks during critical phases of flight. The concept is similar to landing gear switch inhibits which are commonplace throughout the aerospace world. It is also very similar to the inhibit on all cars with an automatic transmission that prevents moving the transmission out of Park without the driver's foot on the brake pedal.

TSC's new SpaceShipTwo feather lock inhibit design fulfills all of the design and system safety team's requirements:

1) Inhibits both inadvertent feather lock opening and inadvertent closure during critical phases of flight.
2) The Inhibit fails to the uninhibited position (Fail Safe).
3) Override of the Inhibit requires an action(s) by the aircrew that are distinct and separate from normal activation of the control.
4) The Inhibit incorporates both an electrical and an independent mechanical override.

2.2.2 The Copilot Did Not Follow Manual and Flight Test Card Procedures

The copilot did not follow manual and flight test card procedures when he skipped a sequence of required callouts on the flight test card. The Normal Operations manual and flight data test card for the accident flight required the following crew tasks during the boost portion of the flight after the rocket is fired:

PILOT	***COPILOT***
	Make 0.8 Mach callout to alert the pilot that they would be transitioning 1.00 Mach (transonic) and to anticipate a transonic "bobble."
Starts manually trimming SpaceShipTwo's stabilizers to -14.0 degrees.	
	Callout each degree stabilizer movement one-by-one in sequential order to help the pilot optimize pitch up to 14 degrees (*e.g.,* 10, 11, 12, 13, 14).
	Unlock the feather lock once the vehicle reaches 1.4 Mach.

(*See* Ops. Fact. Rpt., pages 44-49.)

According to interviewed pilots and engineers, the boost portion of the test flight is a very dynamic environment and the pilot workload is extremely high. The important pilot tasks were included on the flight data card and were written in a way that helped ensure that the cadence of the steps taken by the crew continued properly. (Interview of M. Stucky, Hum. Perf. Fact. Rpt., Attachment 1, page 13.) This segment of the flight profile is practiced repeatedly in the simulator.

Analysis of cockpit audio and video data shows that the copilot did not follow the steps on the flight data card. While the copilot did make the required 0.80 Mach callout, he did not make any stabilizer trim position callouts as required by the flight data card and the Normal Operations Manual. (Cockpit Image Record Fact. Rpt., pages 59-64.)

In addition to helping the pilot fly the vehicle into the vertical, the stabilizer trim callouts act as a cadence for required steps during a critical and very dynamic portion of the flight. The failure to make stabilizer callouts likely disrupted the flow and timing of required pilot tasks during the boost portion of the flight.

2.2.3 Crew Resource Management (CRM)

Crew resource management encapsulates the concept of a pilot using all of the resources at his or her disposal to safely accomplish the vehicle's mission. The implementation of CRM concepts across the aerospace industry is directly responsible for a significant decrease in global air carrier accident rates over the last several decades. In a flight test environment, CRM involves not only the pilots but also the discipline engineers monitoring various systems during the flight from the control room.

A cornerstone of CRM involves using challenge and response protocols prior to the movement of a safety critical switch or lever. Such a procedure would, for example, require the copilot to receive confirmation from the pilot prior to the copilot taking an action. Such a protocol provides an effective and proven procedural mitigation against the aircrew committing a human performance error of omission or commission. The potential for these errors is increased during high workload, highly dynamic and/or unfamiliar environments.

During the SS2 program, simulator sessions provided the primary means to practice CRM between both the SS2 pilots and the mission control room. During these simulator sessions, the team worked to not only accomplish the planned mission, but also to safely recover the vehicle during various emergency and off-nominal scenarios.

The CRM approach utilized by the accident crew was described by the surviving pilot during a post-accident interview. The summary of that interview states:

> When asked if the procedures were written in such a way that there was time to respond to a verbal call, he said in his opinion and perception, there were certain phases of flight where it was just not practical to have a command-response type CRM setup. There was not enough time. He approached this flight that they were two highly trained individuals working together, and they would execute their responsibilities at the appropriate time and place. Other times it would be different at times when the workload was reduced. He briefed Mike that once they were clear of the hooks, he would arm the motor and Mike did not need his approval to do it, but not to throw the fire switch until he [Pete] commanded it, giving him a last chance to decide not to fire the rocket motor. It never crossed his mind that Mike would unlock the feather early. Mike did not need his concurrence to unlock the feather. (Ops. Fact. Rpt., Re-interview of Pete Siebold, page 8.)

If a challenge and response protocol had been implemented between the pilots for movement of the feather lock handle, it may have prevented the copilot's premature movement of the feather lock handle during the accident flight.

2.2.1 Non-Contributing Factors

Evidence reviewed by the investigators reveals many factors that did not have an impact on the accident sequence.

The weather conditions at the time of the accident flight were deemed to not be a factor in the accident. The weather was discussed at the "delta" briefing at 4:30 am PDT on the morning of the flight and was monitored throughout the mission. (Ops. Fact. Rpt., page 8.) One item being watched was the forecast of an approaching cold front. (Interview of Todd Ericson, Ops. Fact. Rpt., Attachment 1, page 50.) The forecast remained "go" and wind levels remained within limits through take-off. (Interview of Peter Kalogiannis, Ops. Fact. Rpt., Attachment 1, page 20.)

No evidence indicated any pre-existing medical or physical condition that might have adversely affected the flight crew's performance during the accident flight. (Human Perf. Fact. Rpt, page 7)

The vehicle systems were performing nominally throughout the flight and examination of recovered components revealed no evidence of any preexisting system or structural failures. (Systems Fact. Rpt, and Structures Fact. Rpt.)

The evidence indicates that the hybrid propulsion system performance was normal, including rocket ignition, and that system pressures were at normal levels prior to vehicle breakup. (Propulsion Fact. Rpt., page 2). Rocket motor vibration levels were continually monitored by the Rocket Motor Controller (RMC) and remained well below the limit thresholds established for automatic shutdown, structural limits and human factors. (Propulsion Fact. Rpt., page 16). The accident pilot reported that the rocket motor burn was "smooth, with no vibration". (Interview of Pete Siebold, Ops. Fact. Rpt., Attachment 1, page 78).

Information that was being presented to the flight crew via the on-board instruments and displays did not show any anomalous behavior during playback of the telemetric data. (Systems Fact. Rpt., page 18)

SECTION 3. CONCLUSIONS

3.1 Findings

1. SpaceShipTwo was designed, built and operated by Scaled Composites as a Commercial Space Transportation Experimental Permitted launch system per FAA Experimental Permit Number EP 12-007.

2. **(CONTRIBUTING CAUSE)** The feather lock system did not incorporate a mechanical inhibit to prevent inadvertent activation by the aircrew during critical phases of flight.

3. **(CONTRIBUTING CAUSE)** Normal and test card procedures did not require a challenge/response protocol between the pilot and copilot prior to manipulation of the feather lock handle.

4. The flight and accident crew were properly certificated and qualified under federal regulations.

5. The Normal Procedures Manual and the Flight Data Test Card specified that the feather locks should not be unlocked until 1.4 Mach.

6. During the boost phase of the accident flight, checklist and procedures on the Flight Data Test Card for the test flight required the copilot to:

   - Make a 0.80 Mach callout;
   - Callout the stabilizer trim setting to aid the pilot in achieving the proper setting for the turn to the vertical;
   - Unlock the feather locks once the vehicle reached a minimum speed of 1.4 Mach.

7. The accident crew confirmed that SpaceShipTwo's feather locks were functioning properly during ground checks prior to launch as per Normal Procedures.

8. WhiteKnightTwo successfully carried SpaceShipTwo up to an altitude of approximately 47,000 feet AGL.

9. The accident crew confirmed that SpaceShipTwo's feather locks were functioning properly during the L-10 (ten minutes prior to release) checklist per the Normal Procedures.

10. All systems operated normally during takeoff, climb and release of SpaceShipTwo from WhiteKnightTwo.

11. SpaceShipTwo was successfully released from WhiteKnightTwo at 10:07:19.27 PDT and at 10:07:19.51, the pilot commanded the copilot to fire the rocket motor.

12. At 10:07:26.83, the vehicle accelerated through 0.80 Mach and at 10:07:26.91, the copilot made a 0.80 Mach callout per checklist procedures.

13. The copilot did not make any stabilizer trim setting callouts to the pilot during the boost phase of the flight.

14. At 10:07:28.39, the copilot announced "unlocking."

15. **(CAUSAL)** At 10:07:28.90 and approximately 0.92 Mach, the copilot moved the feather lock handles to the full unlock position.

16. Cockpit displays were correct and cockpit vibration levels were low.

17. Once the feather locks were unlocked at 0.92 Mach, lift from the horizontal tails exceeded the feather actuator's ability to prevent aerodynamic extension of the feather system. These forces caused the feather to extend without any further pilot action.

18. Extension of the feather while in boosted flight under these conditions imparted over 9g's of pitch up acceleration forces on the spaceship. These forces exceeded SpaceShipTwo's designed structural load capability and resulted in its in-flight breakup.

19. The final frame in the video recording occurred at 10:07:32.80, followed by the vehicle experiencing an in-flight breakup.

20. The accident pilot was thrown from the vehicle during the breakup sequence. During his descent, the pilot separated himself from the seat and his parachute automatically deployed.

21. The accident copilot was fatally injured during the inflight breakup.

22. Weather was not a factor in the accident.

23. SpaceShipTwo's rocket motor operated normally throughout the entire flight to the point of vehicle breakup.

24. No evidence indicated any preexisting medical or physical condition that might have adversely affected the flight crew's performance during the accident flight.

25. Examination of recovered components revealed no evidence of any preexisting engine, system or structural failures.

26. No uninvolved persons were injured in the accident.

3.2 Probable Cause and Contributing Cause

The **Probable Cause** of this accident was the copilot's unlocking of SpaceShipTwo's feather locks at 0.92 Mach, approximately 14 seconds prior to the flight manual minimum speed of 1.4 Mach.

The **Contributing Causes** of the accident were:

- **Feather Lock system design.** The Feather Lock system design did not have an automatic mechanical inhibit to prevent premature movement of the feather system.
- **Crew Resource Management.** Scaled Composites' aircrew procedures did not require a challenge/response protocol prior to moving the feather lock handle.

SECTION 4. RECOMMENDATIONS

4.1 General

Scaled Composites was responsible for all aspects of the flight test program at the time of the accident. Subsequently, Virgin Galactic has assumed full responsibility for the completion of SpaceShipTwo flight test program and the commercial operations which will follow.

Well prior to the accident, Virgin Galactic and TSC began a vehicle improvement program in anticipation of the program's planned January 2015 transition from Scaled Composites. The improvement program was based on lessons learned from both SS2-001's construction and the flight test program. Commercial service enhancements were scheduled to be included in both SS2-001 and SS2-002 (currently under construction by TSC) prior to either vehicle entering commercial service.

Following the accident, Virgin Galactic and TSC undertook a comprehensive internal and external program review of the SpaceShipTwo design and operations. Virgin Galactic recommends these actions:

1) Modify the SpaceShipTwo feather lock system with an automatic mechanical inhibit to prevent unlocking or locking the feather locks during safety-critical phases of flight.

   Status: Completed

2) Add to the SpaceShipTwo Normal Procedures checklist and Pilot's Operating Handbook an explicit warning about the consequences of prematurely unlocking the feather lock.

   Status: Completed

3) Implement a comprehensive Crew Resource Management (CRM) approach to all future Virgin Galactic SpaceShipTwo operations in a manner consistent with the pre-existing CRM program VG has employed for WK2 operations. This includes, as a minimum:

   - Standardized procedures and call outs
   - Challenge/response protocol for all safety-critical aircrew actions, to include feather lock handle movement
   - Formalized CRM training

   Status: Completed

4) Conduct a comprehensive internal safety review of all SpaceShipTwo systems to identify and eliminate any single-point human performance actions that could result in a catastrophic event.

Status: An initial assessment was completed and modifications to SS2-002 are in progress. Virgin Galactic will continually evaluate and improve System Safety throughout SpaceShipTwo's lifecycle.

5) Conduct a comprehensive external safety review of Virgin Galactic and The Spaceship Company's engineering, flight test and operations as well as SpaceShipTwo itself.

Status: Initial Assessment Completed. The external review team will review the program both prior to commencement of flight test activities as well as prior to entering commercial service.

6) Ensure Virgin Galactic employs pilots who meet or exceed the highest standards and possess a depth and breadth of experience in high performance fighter-type aircraft and/or spacecraft. Minimum VG qualifications during the flight test program shall be:

- A long course graduate of a recognized test pilot school with a minimum of 2.5 years post-graduation experience in the flight test of high performance, military turbojet aircraft and/or spacecraft.
- A minimum of 1000 hours pilot in command of high performance, military turbojet aircraft.
- Experience in multiengine non-centerline thrust aircraft
- Experience in multi-place, crewed aircraft and/or spacecraft

These criteria are based on industry best practices for flight testing, using DCMA INST 8210.1C, paragraph 4.3 as guidance.

Status: Completed. All current Virgin Galactic pilots exceed the above minimum VG standards.