SUBMISSION TO NTSB BY SCALED COMPOSITES REGARDING THE OCTOBER 31, 2014 SPACESHIPTWO ACCIDENT (DCA15MA019)

MAY 29, 2015

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I. EXECUTIVE SUMMARY

Scaled Composites (Scaled) is an aerospace and specialty composites development company located in Mojave, California. Since its founding by Burt Rutan thirty-three years ago, Scaled has successfully designed, built, and flight tested over 30 unique manned aircraft and spacecraft for the United States Government, national defense contractors, and other commercial customers. Scaled specializes in unique aircraft design, rapid prototyping, and flight testing. Scaled focuses on developing proof-of-concept aircraft using novel and creative approaches to solve difficult technical challenges presented by its customers.

Scaled has been recognized for its ability to safely and efficiently develop breakthrough air and spacecraft. For example, in 2000, Scaled's Proteus airplane set an altitude record for its class, reaching over 63,000 feet, and in 2005, Scaled's GlobalFlyer airplane set the record for the fastest time around the world unrefueled. Scaled's SpaceShipOne, which debuted in 2004, pioneered a number of design firsts and captured the Ansari X Prize, awarded to the first non-governmental organization to launch a reusable manned vehicle into space, and the National Aeronautic Association's Collier Trophy, awarded annually for the greatest achievement in aeronautics or astronautics in America, with respect to improving the performance, efficiency, and safety of air or space vehicles, the value of which has been thoroughly demonstrated by actual use during the preceding year.

Scaled tailors its customized designs to meet government and commercial customer specifications. The company brings creative solutions to unique design challenges, and builds and tests prototypes efficiently and safely based on those designs. Scaled's engineers and test pilots, along with its other employees, are carefully selected. They bring to the company great talent and a wide-ranging mix of cross-disciplinary expertise that enables them to participate in various aspects of Scaled's flight programs. This multidisciplinary approach allows members of Scaled project teams to develop a comprehensive understanding of different aircraft systems and to participate in what Scaled believes to be a safer, more efficient manner than may be possible under the "siloed" approach of more traditional companies in which each employee is assigned a narrower set of roles and responsibilities.

Safety and quality have always been paramount values at Scaled, and Scaled's transparent, non-hierarchical culture enhances both. Scaled's approach is best expressed by one of Burt Rutan's oft-repeated mottos: "Question, don't defend." This means that it is every employee's responsibility to enhance quality and safety by openly and continually probing all aspects of their projects.

SpaceShipTwo was the second manned, privately-funded spacecraft prototype designed and built by Scaled. The SpaceShipTwo program originated in 2006 to create a prototype for Virgin Galactic. The prototype would be used as an initial model for Virgin Galactic to develop a vehicle to carry private passengers into space and back to earth as part of a Virgin Galactic commercial space program. The SpaceShipTwo prototype evolved from SpaceShipOne, after years of additional design, development, manufacture, and testing by Scaled.

On the morning of October 31, 2014, the SpaceShipTwo prototype was on a rocket-powered test flight mission over the Mojave Desert with an experienced flight crew. It had previously completed over 50 successful test flights. Shortly after the aircraft released from its carrier plane, known as WhiteKnightTwo, and was accelerating, a catastrophic accident occurred. The evidence indicates that the accident happened when the feather reentry system deployed early because it was unlocked by the copilot prematurely, outside the sequence set forth in the flight test card and Normal Procedures.[1] When the feather system was unlocked, it was subjected to aerodynamic loads that caused the feather to open early, during a phase of flight when it was supposed to remain retracted. The early opening of the feather caused the SpaceShipTwo prototype to break apart, resulting in the loss of the aircraft. The accident resulted in serious injury to the pilot and the tragic death of the copilot. The reason for the copilot's premature unlocking of the feather locks is unknown.

Since the October 31, 2014 accident, Scaled has been extensively supporting the accident investigation conducted by the National Transportation Safety Board (NTSB). As a party to the investigation, in accordance with NTSB procedures, and consistent with its active cooperation, Scaled is making this submission to provide its analysis of the facts and probable cause of the accident, its proposed findings and recommendations, and a summary of safety actions that Scaled has already taken since the accident.

As explained more fully below, Scaled believes the facts demonstrate that:

- *SpaceShipTwo's crew were well-qualified and well-trained.* The SpaceShipTwo test pilots were fully qualified and properly licensed and trained for the flight. The test pilots had each logged thousands of hours of flight time, including in experimental test aircraft, and each had successfully piloted or copiloted SpaceShipTwo on a number of prior occasions. They were both highly credentialed aerospace engineers who were familiar and involved with the design of the vehicle and aware of its operating limitations. Both had an active role in developing test flight and safety procedures. They both had participated in numerous formal and informal SpaceShipTwo flight simulations during which they repeatedly practiced flight procedures, including the proper and timely unlocking of the feather system.

- *The SpaceShipTwo prototype was carefully designed in accordance with industry-recognized procedures and Scaled's design processes.* The SpaceShipTwo prototype's design, including its unique feather reentry system, was carefully considered and designed based on years of research, development, and analysis. The design evolved from that of the successful SpaceShipOne program and used simple, proven technologies as a means to limit failure modes. SpaceShipTwo's systems, including the feather system, were tested and regularly inspected and maintained; functioned successfully on dozens of flights; and were reviewed and improved upon over time by Scaled engineers. Detailed data review and analysis show that, during the October 31 test flight, until the premature unlocking of the feather, SS2's systems and structures functioned as designed.

[1] Test flight documentation of flight crew procedures, including the flight test card and Normal Procedures, is discussed in more detail in Part III.C, *infra.*

- *Procedures for the feather system were tested and analyzed for safety, and disseminated and discussed among SpaceShipTwo program team members.* Scaled's procedures include assessing and mitigating identified risks, and it followed these procedures with respect to SpaceShipTwo. The design of and procedure for unlocking the feather system were fundamental aspects of the aircraft design and of the flight test plan. The flight test procedures provided for the feather to be unlocked at a specific speed (measured by a Mach number) that Scaled had selected to permit a safety margin both before and after the unlocking procedure. Scaled documented this feather unlocking procedure in numerous sources, including as a part of the flight test card, which test pilots follow during practice in simulated flight sessions, carry with them, and use as their guide to test flight procedures, including on the October 31 test flight. Throughout the design process, program engineers and test pilots discussed that unlocking the feather system at the wrong time could have catastrophic effects.

- *Scaled has a robust safety process and culture.* Scaled's culture of "question, don't defend" calls for all employees to understand design choices on the aircraft and to question, analyze, and respond to safety concerns rather than simply defend current designs or procedures. Scaled subjected SpaceShipTwo to a seven-year systems safety assessment – using industry-recognized methods – that encompassed identifying potential hazards, analyzing the likelihood of those hazards, and employing design or procedural mitigations as needed. Scaled routinely revised and updated this systems safety assessment as systems were modified. Through Scaled's flight test procedures, test pilots and engineers regularly reviewed and analyzed the design of the vehicle, flight procedures, and potential hazards, including the risk of human error. This review took many forms and took place in many forums, including program-wide "Flight Readiness Reviews." In these reviews, program team members and independent subject matter experts discussed potential hazards and were required by Scaled's procedures to determine those hazards were adequately mitigated before flights could occur. One such Flight Readiness Review was held only days before the October 31 test flight.

- *SpaceShipTwo complied with regulatory requirements and at the time of the October 31 test flight was appropriately permitted with an Experimental Permit duly issued by the FAA.* Throughout its systems safety assessment and testing process, Scaled worked closely with the FAA. Both before and at the time of the accident, the SpaceShipTwo program was operating with the proper FAA permits and with the proper regulatory authority. The FAA had issued Scaled an Experimental Permit to operate SpaceShipTwo as a reusable suborbital rocket, and Scaled flew SpaceShipTwo in compliance with that permit.

- *Scaled is committed to learning from this accident and continuing to enhance even further the safety of its procedures for vehicle design, manufacture, and testing.* Scaled will incorporate learning from this accident into its flight procedure review and safety assessment in future projects. Scaled will expand the documentation of training and testing further to promote safety, including with emphasis on the challenges inherent in rocket flight. Scaled will regularly review and evaluate this data and documentation to ensure that lessons learned and procedural rationales are disseminated and reinforced. Scaled will enlist the services of human performance experts to provide further input on crew workload, in-flight conditions, and simulator training. In addition to implementing these recommendations, Scaled hopes the industry as a whole can learn from the accident in order to further improve the safety of experimental flight testing.

Space travel is a culmination of mankind's dream of conquering flight. Revolutionary advancements in aviation, from the Apollo program, to the Space Shuttle, to SpaceShipOne, are inspiring to so many in our country in part because of the unparalleled challenges and potential rewards they present. But the history of American aviation and space travel demonstrates that with those historic challenges come potential risks to and extraordinary sacrifices by some of the people most dedicated to and passionate about the endeavor. Recognizing those challenges, sacrifices, and the importance of the enterprise to the industry and to the nation, Scaled is committed to learning everything it can from this accident, doing all in its power to prevent similar tragedies, and continuing to build on its reputation for innovation, quality, and safety.

II. BACKGROUND

A. Scaled Composites

Scaled specializes in unique aircraft design, rapid prototyping, and flight testing. Scaled focuses on developing proof-of-concept aircraft using novel and creative approaches to solve difficult technical challenges presented by its customers. Scaled develops prototypes and demonstrators, rather than mass producing aircraft, and relies on efficient design and building techniques to find the simplest, safest design that meets the customer's requirements. After developing, modeling, and ground testing the aircraft, Scaled's test pilots flight test the prototype to refine and further develop the design and ensure that its parameters are proven.

Scaled's culture encourages employees to understand all aspects of the design, construction, and testing process and to question rather than instinctively to defend current designs and procedures. Scaled uses industry-recognized safety methodologies, including rigorous systems safety assessment, which incorporates functional hazard analysis, fault tree analysis, and numerous other safety assessment methods. These assessments are updated and reanalyzed as new data emerges and Scaled considers additional potential risks.

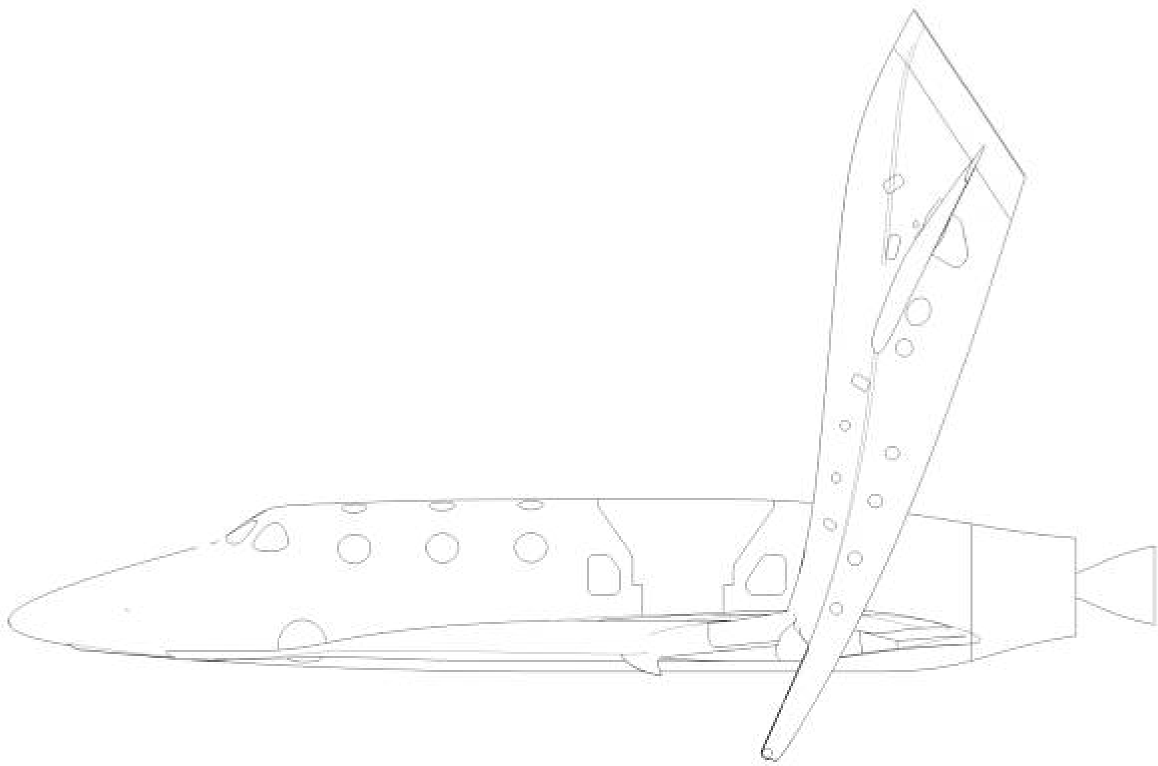
Scaled employees come from a diverse background of talents, experience, and interests. Approximately 50 percent of Scaled engineers are also pilots, which gives them a valuable perspective when designing the features, systems, and avionics of new aircraft. Because of their multidisciplinary backgrounds, Scaled employees are able to occupy a variety of different roles, allowing employees to develop broader skillsets and a greater depth of understanding of program needs. This staffing model, where employees are not siloed into more limited roles, enables project teams to engage with all aspects of different aircraft systems from multiple perspectives. Scaled's employees' breadth of understanding coupled with a small team size contributes to a culture of dedication to performance, quality, and safety.

B. SpaceShipTwo

SpaceShipTwo (SS2) refers to a hybrid-rocket-powered, reconfigurable prototype aircraft. Scaled designed and built SS2 based on Virgin Galactic's developmental program goals of creating and testing a prototype commercial vehicle that could transport 2 pilots and at least 6 passengers to an apogee of 110 kilometers, vertically. SS2 would be lifted to high altitude by a carrier aircraft, the WhiteKnightTwo (WK2), also commissioned by Virgin Galactic. SS2 would then be released from WK2 and would use rocket power to travel to its suborbital apogee, then reenter and glide back to Earth where it would land on a runway.

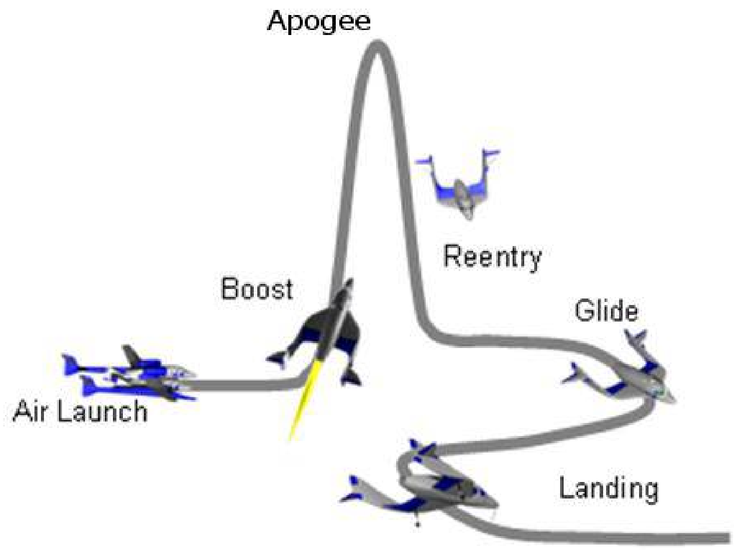
SS2 was based on the design of SpaceShipOne (SS1). SS2's basic design elements, carried forward from SS1, incorporated simple, proven technologies to limit potential failure modes so that crew and passengers could safely be transported to and from space. Scaled's design philosophy today continues to be based in part on Burt Rutan's personal philosophy that simple and robust is safe, while complexity is almost always more dangerous.

Like SS1, SS2 employed a feather reentry system. The SS2 prototype design uses a "feather," a long, interconnected, specially-designed assembly that can extend vertically from the aircraft and act as a kind of stabilizer and brake, to provide stability during reentry and to increase drag. This orients the aircraft and reduces reentry speeds as well as the associated loads and heat on the vehicle. The feather of SS2 functions similarly to the feather of a badminton shuttlecock, which likewise stabilizes the shuttlecock, ensures that it flies in an upright position, and creates drag to slow its velocity.



SS2 and WK2 compose the suborbital launch system. A space flight begins with SS2 attached to WK2. WK2 takes off and climbs to approximately 50,000 feet. SS2 is released from WK2 and ignites the rocket motor. SS2 then accelerates, and reaches 1.0 Mach. Around that speed, SS2 pitches nose up, then nose down (the pitch bobble) as it transitions to supersonic flight. Once supersonic, SS2 is trimmed nose up to capture a vertical flight path, and the feather is unlocked. For the contemplated Virgin Galactic flights to space, at approximately 150,000 feet, the rocket motor would be shut down. SS2 would coast to apogee, would be feathered, and would then begin to descend. During reentry the feather keeps SS2 in a high drag orientation to minimize G forces and aerodynamic heating. Once SS2 is subsonic, the feather is retracted, and SS2 glides to a conventional landing.

The feather locks resolve tail trim forces when the feather is down. In the transonic regime (during the pitch bobble) there are periods of high tail lift, beyond what the feather actuators can resist. The feather locks are required to keep this tail load from deploying the feather. Once SS2 is supersonic, the tail is generating down force, and the locks are not required to hold the feather down. Additionally, unlocking sufficiently before apogee provides the flight crew with adequate time safely to abort boost and conduct an unfeathered reentry in the event the lock actuators jam.



C. The October 31, 2014 Accident

On the morning of October 31, 2014, the SS2 prototype flew its fourth powered test flight (Powered Flight 4, or "PF04"). It carried two crew members: a pilot and a copilot. Both were experienced, well-trained test pilots and prepared for the test flight. After release from WK2, SS2's crew ignited the rocket motor, without incident, and the aircraft accelerated into the boost phase as planned. The PF04 pilot has noted that the thrust from the rocket motor was "smooth." From the time SS2 was released from WK2, all systems and structures on SS2 operated within known and predicted performance limits.

According to flight procedures, the co-pilot was supposed to call out when SS2 reached a speed of 0.8 Mach, primarily to alert the pilot that the craft was about to enter the transonic regime. This would allow the pilot to prepare for what is sometimes referred to as the transonic "bobble," a "pitch up/pitch down" movement as the craft passed the sound barrier. Once supersonic, the pilot is required to trim to a nose up flight path angle. During the transonic phase, the feather is supposed to remain locked, because aerodynamic loads would otherwise force the feather up into a deployed position. When the craft reached 1.4 Mach, the co-pilot was then supposed to unlock the feather system. At 1.4 Mach, unlocking the feather is safe because, by that speed, the feather would remain retracted without the locks. Unlocked, the feather remains retracted until commanded to open by the crew near apogee.

The recorded data indicates that during PF04, very soon after release from WK2, the copilot called out 0.8 Mach in accordance with procedures when the aircraft reached that speed. Shortly after, the copilot announced he was unlocking the feather and did so. That was well before SS2 would have reached 1.4 Mach, when the flight procedure provided for the feather to be unlocked. The recorded data shows that because of the loads acting on the feather at the point of the premature unlock, and without the locks to hold them in place, the feather was forced open. This premature opening of the feather locks and the resulting deployment of the feather while SS2 was in the boost phase and at the beginning of the transonic region created overpowering forces on the craft that caused it to break up. The pilot and his seat were separated from the craft and began to fall to earth. The pilot was able to separate himself from his seat. His parachute deployed automatically during his fall and although he was severely injured, he survived. The copilot suffered fatal injuries. The larger debris from the vehicle fell in the intended operating area. There was no injury to any member of the public and no damage to property other than the aircraft itself. WK2, which had released the aircraft before the accident, and its crew members landed safely.

Subsequent investigation has confirmed that, apart from the effects of the premature feather unlock, SS2's flight systems performed as designed following SS2's release from WK2:

- "All [rocket motor] pressures climbed normally after ignition and stabilized at expected values up [until] the point the data link was lost."
- "No warnings or faults were noted during the accident flight that suggested pressurization system hardware anomalies."
- There were no "anomalous behaviors of the display system during the flight playback [of recorded data]."
- "[N]o anomalies were noted related to the pneumatics/ECS [Environmental Control System], flight control and electrical systems prior to the feather movement after the unlock occurred."
- "[T]he flight path of WK2 and SS2, and the debris from the breakup of SS2, remained within the mission's operations area (Restricted Area R2508). The key flight safety events (release from WK2 and rocket-powered flight), and SS2's predicted instantaneous impact point, remained within the operating area and outside of the mission's exclusion zones."

It is not known why the copilot, an experienced, well-trained, and capable flight test pilot prematurely opened the feather locks on SS2 that morning. Although several theories have been considered – that he was for some reason confused about the speed, or that he may have misread or not seen the speed display, or that he read the wrong data field – these theories do not appear to be supported by the known facts. Among other things, Scaled believes these theories are inconsistent with the fact that he properly called out the correct speed, 0.8 Mach.

III. <u>SS2'S FLIGHT CREW WAS WELL-QUALIFIED AND WELL-TRAINED</u>

The PF04 pilot and copilot were highly qualified and well respected test pilots, who had rigorously trained for the flight, including in numerous simulated flight sessions. Each had logged thousands of hours of flight time, including a number of previous flights on SS2, and was fully prepared for PF04. They each had engineering backgrounds and were regularly involved with the design of the aircraft, and each understood the flight procedures and the reasons for them.

A. The Pilot

The PF04 pilot has 23 years of flying experience and a reputation as an exemplary pilot. He has had no prior accidents.

He was hired by Scaled on December 16, 1996, as a flight test engineer, and worked his way up to his current position, Director of Flight Operations, a position he has held since June 27, 2008. Prior to working at Scaled, he was an aircraft dispatcher and ground instructor in Santa Barbara and a flight instructor in San Luis Obispo. He completed a Bachelor of Science Degree in Aerospace Engineering from California Polytechnic State University in 2001. He holds a number of pilot certifications and authorizations, including as a Flight Instructor, Commercial Pilot, and FAA Second Class Medical Certificate. He had nearly 3000 hours of total flying time prior to the October 31, 2014 accident. In 2004 and again in 2009, the Society of Experimental Test Pilots (SETP) awarded the pilot its Iven C. Kincheloe award for outstanding professional accomplishment in the conduct of flight testing.[2]

Prior to assuming the role of Director of Flight Operations, the PF04 pilot was a test pilot and engineer for the SS1 program. He had also previously held the position of Avionics Project Engineer for the SS2 program. As Director of Flight Operations, he had overall responsibility for flight test and normal flight operations. Similar to many test pilots at Scaled, he had significant experience at Scaled as a design and project engineer in addition to his flight testing responsibilities.

The PF04 pilot was very familiar with SS2. He was part of the initial Scaled cadre of test pilots on both the SS2 and WK2. He had flown 60 flights in WK2 as pilot in command, copilot, or instructor pilot beginning with its first flight on December 21, 2008. Prior to PF04, he had piloted WK2 as recently as July 22, 2014. He was the pilot of SS2 on 15 previous flights, beginning with the first glide flight[3] of SS2 on October 10, 2010 (GF01 – with the PF04 copilot). On the date of the accident, his most recent flight on SS2 was a glide flight on October 7, 2014 (GF30). While the PF04 flight was the first time he flew SS2 on a powered flight, he had previously flown one of SS1's powered flights.

Scaled does not believe that pre-accident activities or personal issues affected his performance on the day of PF04.

B. The Copilot

The PF04 copilot was also a highly-experienced pilot who had no prior accidents and was held in high regard by his peers not only as a pilot but as an engineer. At the time of the accident, he had roles both as a project engineer and as a test pilot for Scaled. In his test pilot role he reported to the Director of Flight Operations, the PF04 pilot.

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[2] "Iven C. Kincheloe Award," *at* https://www.setp.org/criteria/iven-c-kincheloe-award.html.

[3] Glide flights did not utilize SS2's rocket motor – the aircraft functioned like a traditional glider.

The copilot was hired by Scaled on January 17, 2000. Prior to his employment with Scaled, he was an engineer on the Visionaire Vantage airplane for Scaled Technology Works, a Scaled affiliate, from January 1998 to January 2000. Before that, he worked part time for the Boeing Company during the summers of 1996 and 1997 as a systems engineer and propulsion engineer. He earned a Bachelor of Science Degree in Aeronautical Engineering from California Polytechnic State University in December 1997. In 2013, SETP awarded the copilot and two of his test pilot colleagues at Scaled its Ray E. Tenhoff award for the most outstanding technical paper presented at the annual SETP Symposium.

The PF04 copilot was a certified Flight Instructor and Airline Transport Pilot. On December 31, 2013, he added an Airplane Single Engine Sea rating with Commercial privileges to his Airline Transport Pilot certificate. He had significant experience as a pilot and test pilot, and was one of Scaled's most experienced flight test engineers. In total, at the time of the accident, he had flown over 2100 hours, with almost 2000 hours as pilot in command.

The PF04 copilot was a dedicated member of the SS1 and SS2 programs. He was present in the control room for every SS1 flight. Based on his record, he was selected to be part of the initial group of test pilots on SS2 and WK2. He flew 18 flights in WK2 as copilot during the period from June 2009 to October 2014. He copiloted SS2 on 7 glide flights, beginning with the first glide flight of SS2 on October 10, 2010 (GF01 - flown with the PF04 pilot). His last time to copilot SS2 on a glide flight was August 28, 2014 (CF02 - again with the PF04 pilot). The PF04 copilot had been the copilot on one of SS2's previous three powered flights, the first powered flight (PF01) on April 29, 2013. He was chosen for PF04 because of his proven strengths as a pilot and his careful and methodical approach. He had received several commendations for his work and had recently received an excellence award.

Scaled does not believe that pre-accident activities or personal issues affected the copilot's performance on the day of PF04.

C. Test Pilot Training

Scaled and Virgin Galactic test pilots trained together in preparation for SS2 and WK2 flights. Through this process, the PF04 flight test crew received extensive and varied training – including through reviewing and revising written manuals, numerous simulation sessions, ground training, training on other aircraft, and crew resource management (CRM) training. Both the pilot and copilot met or exceeded all documented training requirements and had diligently prepared for the test flight.

1. Handbook and Procedures

Flight documentation, including the Pilot Operating Handbook (POH), Normal Procedures (NPs), and Emergency Procedures (EPs) provided comprehensive information on operating SS2 including potential hazards. Scaled created these materials with input from both Scaled and Virgin Galactic test pilots and design engineers. The materials were continually revised and updated throughout the life of the program. Among other things, prior to each flight, Scaled revised the POH, NPs, and EPs as needed based on input from flight simulations, and had revised each numerous times prior to PF04. These materials were regularly distributed to, reviewed by, and commented on by Scaled test pilots.

(a) Pilot Operating Handbook

Scaled's POH for SS2 "documents the configuration, systems, operating limitations, procedures and performance of the SpaceShipTwo suborbital space plane. The handbook also includes sections on Scaled's design philosophy and 'lessons learned' during design and development of the aircraft."

Revision D of the POH, dated September 3, 2013, dedicates 16 pages to the operation of the feather system. Within that section, it specifically notes that "During boost the feather locks are normally opened at 1.4 Mach after the gamma turn and if not open at 1.5 Mach a caution will annunciate. If the locks fail to open the boost should be aborted. . . . After reentry, the feather actuators are sufficient by themselves to hold the feather fully down without the feather locks engaged." The POH later again states that during a normal mission sequence, "After Gamma Turn at 1.4 Mach," the feather locks should be opened.

(b) Normal Procedures and Emergency Procedures

The NPs for SS2 define the normal pilot procedures for all phases of flight, and the EPs contained a series of checklists for test pilots to follow during various kinds of emergencies.

Drafting of the NPs and EPs relating to the feather system was a collaborative effort by Scaled engineers responsible for that system and Scaled and Virgin Galactic test pilots, including the pilot and copilot of the October 31 test flight. To inform their work, engineers sat in the SS2 and operated the feather system while SS2 was stationed in the hangar. Engineers also spent dedicated simulator sessions with the test pilots during which they worked on drafting the feather system NPs and EPs.

For the boost phase, the NPs indicate that the copilot should unlock when or just after the aircraft reached 1.4 Mach.

The EPs provided additional guidance relating to feather unlocking. They note that if either feather lock fails to unlock by 1.8 Mach, the crew should shut down the rocket motor and perform an unfeathered reentry. The EPs also warn that significant upward forces on an unlocked feather could be catastrophic. If the feather locks fail to close, the crew is directed to minimize Gs if SS2 is subsonic, or minimize angle of attack if SS2 is transonic or supersonic. The instruction recognizes the critical role of the feather locks and makes clear that that with sufficient loads or angle of attack, tail loads could exceed the feather actuators' retracting forces, indicating that the locks were critical for keeping the feather in place.

The EPs further state that significant upward forces on the tail can be catastrophic if the feather is unlocked at certain speeds. For example, if the crew is forced to attempt a feather down reentry, the EPs note that "[a] sudden feather up > 200 KEAS[4] will likely be catastrophic." In March 2014 notes from his review of an earlier version of the EPs, the October 31 test flight copilot wrote the words "should there be note about raising feather > 200 keas" with respect to a later section of the EPs, indicating he had reviewed and understood that specific risk. Other emails and handwritten meeting notes further demonstrate that he was regularly involved in reviewing and revising the EPs and NPs, and conscientiously reviewing them with other test pilots in the weeks prior to PF04.

2. Flight Test Card

Specific information for PF04 was identified on the PF04 flight test card. The card includes vehicle limitations, weight and balance information, performance information, mission timing, and flight crew procedures. From its July 2014 initial release through Revision U (the version used on October 31, 2014), the PF04 flight test card contained the specific procedure for unlocking the feather at 1.4 Mach. These procedures were repeatedly practiced during simulator sessions.

3. SS2 Simulator Training

The SS2 test pilots practiced flying the aircraft through a specially created simulator designed to replicate the SS2 cockpit. Scaled used this simulator both to simulate nominal flights as well as unexpected and emergency scenarios. Scaled and Virgin Galactic test pilots trained in the SS2 simulator, which was located at Scaled's facilities in Mojave, California. Scaled programmed the SS2 simulator to provide the same flight performance as the actual SS2. It has a dome-shaped spherical projection screen to re-create the scene that the flight crew would actually experience during flight and includes the following features:

- Detailed duplication of the SS2 cabin layout (including avionics, switches, controls, windows, and seats);
- Wrap around video simulation and sound effects;
- Detailed and precise SS2 flight dynamics;
- The ability to simulate both control forces and effectiveness in all flight regimes;
- The ability to simulate wind profiles;
- The ability to simulate thrust asymmetries;
- The ability to simulate a wide array of failure conditions.

Before each mission, a test pilot and flight test engineer used the simulator for initial mission planning. After the mission's test objectives were refined, the entire mission team (including the control-room personnel) conducted a number of full mission rehearsals (called "integrated simulations"), which included both normal and emergency scenarios. Test pilots also had access to the simulator for additional practice on their own or with another pilot, which the PF04 crew

[4] KEAS, or "knots equivalent airspeed," are a unit of measure of calibrated airspeed corrected for compressibility effects of altitude and airspeed. It is one way to measure how fast an aircraft is travelling.

utilized on a number of occasions. The SS2 simulator generated data that could be used to track flight crew proficiency.

In addition to its pilot training function, the simulator also serves as a valuable engineering development tool. Engineers are able to make changes to avionics and other hardware and software in the simulator before they decide whether to implement the changes in the actual SS2 and are also able to incorporate feedback from the test pilots.

4. Integrated Simulations for PF04

In preparation for PF04, Scaled conducted full team mission rehearsals using integrated simulations that involved scenario-based training in the SS2 simulator along with activation of the Ground Station, designed to replicate interaction between the aircraft and ground control. Scaled's policy is to conduct a minimum of three integrated simulations leading up to a boost flight. Leading up to PF04, Scaled conducted eight integrated flight simulation sessions throughout September and October of 2014. Representatives of the FAA attended and observed some of these integrated simulator sessions.

Each integrated session included multiple flight scenarios in which crew members were presented with a combination of emergency circumstances, including aborting flight, executing emergency procedures, and landing. The sessions began with a global briefing to the full mission team. The crew conducted separate debriefs after completing each flight scenario. At the end of the integrated simulation session, the crew conducted a global debrief, led by the simulation instructor, who was typically another pilot. In each of the debriefing sessions, the crew discussed their observations as a whole, including self-critiques. Based on evaluation of the results of those mission simulations by the responsible test pilots and engineers, Scaled would update the NPs, EPs, or flight test data cards, as necessary. Simulation participants also captured any changes in ground control mission notebooks.

5. Other Simulator Sessions

In addition to the formal integrated simulator sessions, the PF04 flight crew conducted training in the SS2 simulator multiple times leading up to PF04. According to login information from the simulator, the PF04 flight crew simulated over 100 flights together after the initial release of the specific procedures for PF04. During this same time period, the copilot simulated 6 additional flights on his own.

6. Flight Training

(a) Extra EA 300/L Training

The SS2 test pilots also received aerobatic training in an Extra EA300/L plane, which would be flown in extreme flight paths to train for "G" tolerance, condition against motion sickness, and practice recovery from unusual attitudes. The Extra EA300/L was operated by Virgin Galactic, and the training was conducted based on a test card syllabus. The syllabus included training in positive and negative "Gs", rapid "G" onset (Gamma turn simulation), adverse reentry "G" training, and disorientation and recovery training. Scaled's policy, consistent with its experimental permit application and applicable regulations, is to conduct a minimum of three training sessions in the Extra EA300/L in preparation for a powered flight, including gaining and maintaining "G" tolerance and upset recovery training, and the PF04 flight crew met those requirements.

In preparation for PF04, the PF04 pilot flew as a flight crew member on three Extra EA300/L flights: on October 2, 2014, October 9, 2014, and October 15, 2014. A Virgin Galactic test pilot instructed the crew on each of those flights. The PF04 copilot also flew as a flight crew member on three Extra EA300/L flights in preparation for PF04: on August 5, 2014, October 14, 2014, and October 21, 2014. A Virgin Galactic test pilot similarly instructed the crew on those flights.

(b) WK2 Training Flights

The SS2 flight crew also trained for SS2 flights by piloting WK2 to gain proficiency training and simulating glide through landing. The WK2 cockpit layout was similar (by design) to the SS2 cockpit and WK2 had a similar flight path and descent profile as SS2. SS2 test pilots conducted at least three WK2 simulated approaches for proficiency prior to an SS2 powered flight.

The PF04 pilot had flown 60 flights in WK2 as pilot, copilot, and instructor pilot from the period of December 2008 to July 2014. He last flew WK2 as a copilot on July 22, 2014 in preparation for upcoming SS2 glide flights and PF04. On that flight, he conducted two SS2-like approaches as pilot flying, and one as pilot monitoring. He also conducted one touch and go in WK2. On January 15, 2014, he conducted three SS2-like approaches as pilot flying, and four as pilot monitoring. He also conducted one touch and go and one full stop landing in WK2.

The PF04 copilot flew 18 flights in WK2 as copilot from the period June 2009 to October 2014, most recently as copilot on WK2 on October 7, 2014. During that flight he conducted one SS2-like approach as pilot flying and one as pilot monitoring. He also conducted one touch and go in WK2.

7. Crew Resource Management (CRM) Training

Scaled test pilots and engineers, including the PF04 copilot, attended CRM training by the National Test Pilot School (NTPS), including a lecture and two control room/simulator exercises (with an NTPS trainer behind the flight crew in the simulator) on May 3 and May 7, 2012, respectively, at Scaled. This course is "designed to review [for] flight test aircrew and control room members the coordination concepts and procedures, the necessary attitude which recognizes the importance of good aircrew coordination for effective mission accomplishment, and the skills to implement the crew coordination procedures. During the review of these topics, the mission of flight test is emphasized in the crew coordination process. Consequently, in class exercises and examples are centered on flight test scenarios." The NTPS provided an after action report to Scaled which indicated that "no one, including the newest guy in the room was shy about speaking up and asking questions or asserting a position" and that "this is exactly the attitude required for an efficient control room." Following the training, Scaled test pilots and engineers continued to focus on CRM and maximizing efficient and effective communication throughout missions.

IV. SPACESHIPTWO, AND IN PARTICULAR ITS FEATHER SYSTEM, WAS CAREFULLY DESIGNED, TESTED, AND MAINTAINED

A. SS2's Design

SS2, which evolved from the SS1 program, was carefully designed based on years of intensive research, analysis, and testing in an attempt to meet Virgin Galactic's performance and schedule requirements. The design utilized simple, robust systems to limit potential failure modes. SS2's systems were tested on over 50 flight tests prior to the October 31 test flight, including three prior rocket-powered flights, and they performed as they were designed to perform.

In particular, the feather system was rigorously evaluated during the design of SS2 and ultimately designed in accordance with Scaled's design philosophy. As it did with SS1, Scaled designed SS2 with actuators to extend and retract the left and right-side of the feather. Also like SS1, the design included separately-actuated locks to keep the feather retracted in place during those significant stages of flight when the feather actuators themselves were not sufficient to keep the feather in place, and feather deployment and the resulting forces on the craft could have catastrophic consequences. The feather system, including both the feather and feather locks, as well as the corresponding actuators, was critical to the safety of the aircraft and in particular to stabilize the aircraft during its safe reentry to earth. In light of these safety-critical functions, Scaled designed the feather system to be simple and to avoid complex components and mechanisms that could create additional potential failure modes and increase risk. This focus on simplicity and efficiency as a means to ensure safety and reliability was consistent with the company's design philosophy.

A key example of this focus on simplicity and reliability to enhance safety is the fact that the feather system did not rely on electrical components. Instead, the system used pneumatic actuators to open and close the feather and the feather locks, powered by an air supply that was also used to power other systems. Scaled engineers believed that dependency on other possible modes of actuation, such as electric or hydraulic power, could introduce additional complexity and potential failure modes into the feather system. For example, if the feather system operated on electrical power, a power loss might prevent the feather from opening, which would prevent the vehicle from a safe feathered reentry. The use of electric power also would have required the introduction of additional components, each of which could potentially fail. Electrical systems also increase the risk of fire that could spread to nearby systems and endanger the safety of the crew and vehicle.

As another example of simple design intended to enhance reliability and safety, the two feather assemblies were connected to a single structural torque tube, configured so that should one actuator fail pneumatically, the working actuator could supply the necessary force to operate both right and left feather booms.

Scaled designed the feather system's right and left pneumatic feather actuators to provide sufficient force to extend the feather near maximum apogee and to retract the feather during recovery, as well as to hold the feather in a retracted position during phases of flight when loads were low or were pushing the feather downwards into their retracted position rather than pushing them upwards. But the feather actuators were never intended to provide sufficient force to hold the feather in a retracted position during flight phases when high loads were pushing upwards, such as during the transonic portion of the boost phase.

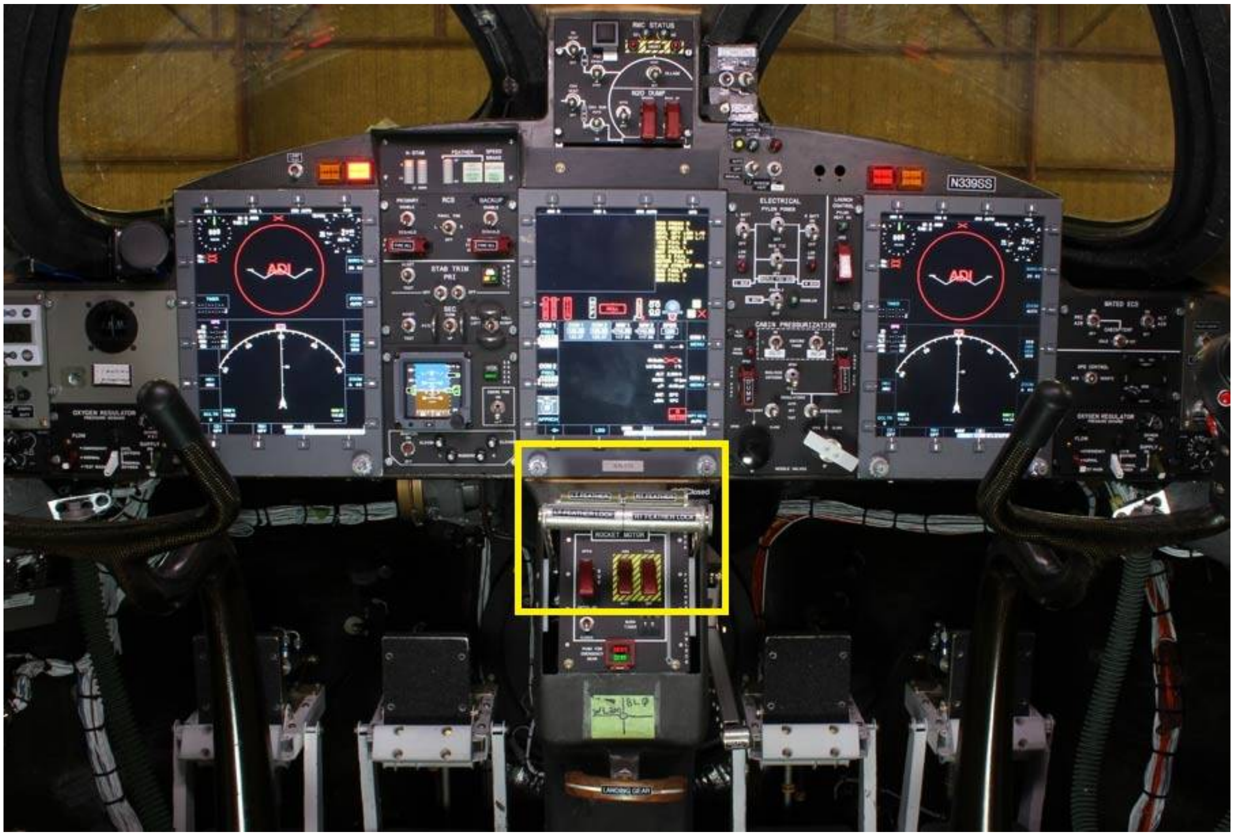
In nominal trajectories, feather opening moments were such that during the transonic zone and gamma turn maneuver, no reasonably-sized actuator could have withstood such loads and maintained the feather in place. Scaled engineers recognized early that any pneumatic actuator capable of sufficient downward force to maintain the feather in a retracted position at those loads would have been impractically large and far too heavy to meet the aircraft's design goals. As designed, SS2's feather actuators provided a feather retracting moment of approximately half of the peak feather opening moment resulting from loads on the vehicle. Feather locks – designed to keep the feather retracted under these strong opening moments – were thus a fundamental design feature of both SS1 and SS2.

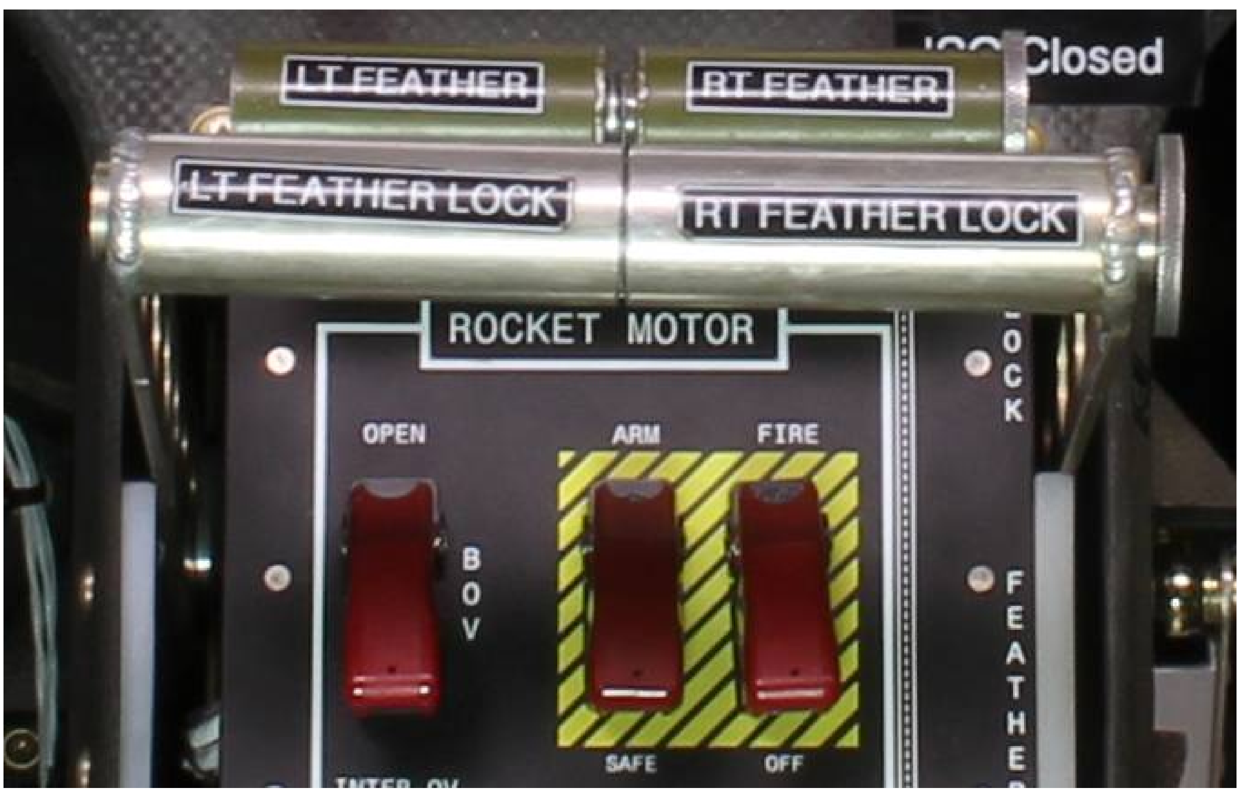
The feather lock system architecture was similar to that of the feather system. Like the feather itself, the right and left feather locks were powered by a pair of pneumatic actuators. The lock actuators were attached to hooks to hold the feather closed. The locks were interconnected with a steel cable to provide redundancy in the event of a pneumatic actuator failure on either side, *i.e.*, to allow both feather locks to function even if one actuator fails.

To extend the feather for reentry, the design principle for the cockpit controls was the same for both SS1 and SS2. The flight crew would first command unlock of the feather by pulling down on a pair of connected[5] feather lock handles located on the center console until they reached their mechanical stopping point. The locks then would unlock within a couple of seconds. In both the locked and unlocked positions, small gates that required a slight sideways force before the handles could be moved up or down held the handles in place, providing an additional mechanical precaution against inadvertent movement of the feather lock handle and resulting operation of the feather locks.

The feather itself was actuated in a separate procedure by pulling a large pull/slide handle rearward until it reached its stopping point. As shown below, the feather lock handles were positioned directly in front of the feather handles and were intentionally designed to make it difficult to access the feather handles while the feather lock handle was in the locked position.

[5] A pin ordinarily held the two handles together, but could be removed to allow independent movement of the handles in an emergency.





LT FEATHER
RT FEATHER
Closed
LT FEATHER LOCK
RT FEATHER LOCK
ROCKET MOTOR
OPEN
BOV
ARM
FIRE
SAFE
OFF

B. **Successful Flight Tests**

SS2's systems, including its feather system, had been extensively tested, inspected, and maintained throughout the life of the program and had a track record of successful performance. By the time of PF04, SS2 had flown over 50 test flights,[6] including 3 rocket powered flights (PFs), 30 glide flights (GFs), 2 cold flow glide flights (CFs),[7] and 19 captive carry flights (CCs).[8] Scaled designed these test flights to test the aircraft and its systems incrementally through "envelope expansion." The flight test program had demonstrated that the feather system worked as intended, and that Scaled test pilots understood how to use it and were capable of doing so.

1. Glide Flights

In 2010, following four successful captive carry flights, Scaled began flight testing SS2 during glide flights. The PF04 crew were the pilot and copilot on SS2's first glide flight in October 2010. SS2's first flight to use the feather system was the seventh glide flight (GF07), which took place on May 4, 2011, and was piloted by the PF04 pilot, following a dedicated Flight Readiness Review (FRR) that specifically addressed the feather system. This GF07 flight was successful and achieved all of its objectives including evaluation of the feather system itself, the stability and control the feather system afforded, and pilot proficiency at operating the feather system correctly.

A few months later, on September 29, 2011, during GF16, Scaled test pilots successfully demonstrated that the feather system could be used to stabilize SS2 during an emergency situation. The GF16 flight test card called for SS2 to enter a rapid descent after release from WK2. This procedure was intended to cause SS2 to accelerate as quickly as possible to test the vehicle's performance at high speed. At release, SS2 unexpectedly entered an inverted spin. The crew unlocked and actuated the feather, which stabilized the aircraft and allowed the crew to regain controlled flight. The crew then retracted the feather and successfully landed the aircraft.[9] The use of the feather on GF16 demonstrated that the feather functioned as intended by stabilizing the aircraft even after departure from controlled flight. It also demonstrated that the feather could be quickly operated by test pilots under emergency circumstances.

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[6] "SS2 Test Summaries," *at* http://www.scaled.com/projects/test_logs/35/model_339_spaceshiptwo.

[7] During cold flow flights, pilots would flow nitrous oxide through the propulsion system after release from WK2.

[8] During captive carry flights, SS2 remained mated to WK2 through the duration of the flight. SS2 had its own pilot and copilot during most of the captive carry flights.

[9] The PF04 copilot was part of GF16's ground crew.

2. Powered Flights

After a number of successful captive carry and glide test flights, on April 29, 2013, SS2 completed its first powered flight, with the PF04 copilot in that role. The milestone flight was a success. As reported in the test summary:

> The motor operated as designed and provided a strong, yet surprisingly smooth, acceleration through the sound barrier. The boost was terminated at the intended shutdown duration of 16 seconds [*i.e.*, 16 seconds after rocket boost was initiated]. Trajectory was nominal with [the flight crew] topping out at 1.3 Mach and 56,200 feet. Post shutdown glide was nominal. The vehicle and the team performed as expected – excellent!

Scaled's first powered flight test in which the feather was deployed was during the second powered flight, PF02, which occurred on September 5, 2013. The PF02 deceleration test point (Release + 33 to 38 seconds) was designed to explore high alpha (angle of attack) transonic stability at a lower dynamic pressure. During this test, the feather opened slightly for less than a second. Feather motion was not planned during the test, but this motion was consistent with the high tail loads expected during the test point. The preflight prediction closely matched the post flight loads estimate, but the opening moment during deceleration exceeded expectations briefly. The feather motion occurred at a lower speed than the maximum feather speed (from the POH), and at a fraction of the dynamic pressure of the PF04 feather event. After gathering the PF02 high alpha transonic data, PF03 returned to normal operating procedures, and targeted a lower flight path angle after burnout. On PF03, on January 10, 2014, the feather system functioned without incident, facilitating a safe reentry and landing.

C. <u>Maintenance</u>

As documented in the NTSB Structures Factual Report, SS2's feather system was regularly maintained in accordance with Scaled's SS2 Maintenance Plan. While Scaled noted a small number of maintenance issues with the feather system during an annual inspection of the SS2 in September-October 2014, all of them had been corrected and closed out prior to the October 31 test flight. Additionally, the feather system had recently undergone a successful leak check, which included exercising the feather locks, extending the feather and holding the feather positions, both extend and retract, for an hour to check for leaks in the system. Scaled does not believe that inadequate maintenance or maintenance issues played a role in the accident.

V. <u>SPACESHIPTWO'S FEATHER PROCEDURES WERE ANALYZED FOR SAFETY AND UNDERSTOOD BY SCALED TEST PILOTS AND ENGINEERS</u>

Throughout Scaled's safety assessment and pre-flight reviews, detailed in Part VI, *infra*, Scaled does not believe there were indications that the procedures developed could not, or would not, be followed.

Engineers and test pilots alike (including the two PF04 test pilots who were also engineers) understood the critical function of the feather locks during boost, and Scaled had developed a specific, safe procedure for the exact point at which the feather should be unlocked. Based on years of formal and informal discussions between Scaled test pilots and engineers regarding the feather system and related procedures, Scaled test pilots and engineers were aware of SS2's operating limits. Engineers and test pilots understood that the feather should not be unlocked too early, before the craft had passed through the transonic region, or the loads would cause the feather to deploy prematurely with likely catastrophic results. They understood that unlocking the feather too late could also have potentially catastrophic consequences: if the locks failed to open because of a malfunction or jam after it was too late to abort the mission, and the feather could not be deployed because they were permanently locked in place, the aircraft likely could not safely reenter. It was therefore critical to unlock the feather with sufficient time to abort the mission if the locks did not function properly and the feather could not be opened. To address these concerns, the SS2 team developed flight procedures that provided for unlock at 1.4 Mach. This provided a sufficient margin after passing through the transonic region (at around 1.0 Mach) so the loads would not force open the feather. It also provided sufficient time for the mission to be aborted and for the craft to land safely if the locks malfunctioned and failed to open and the feather could not be deployed.

Given that the Scaled engineers and test pilots working on the project understood and discussed these issues repeatedly, in face-to-face meetings, Flight Readiness Reviews (FRRs), and pre-flight briefings, throughout the investigation Scaled test pilots and engineers have stated that no one anticipated that the feather locks might be unlocked prematurely, prior to the designated 1.4 Mach speed on PF04, much less that this might occur early enough in relation to the transonic region that the feather might be deployed prematurely. Nor does Scaled believe there were any such indications during training. On the contrary, throughout the numerous simulator sessions leading up to PF04, there is no evidence of the feather locks being unlocked prior to 1.4 Mach.

A. <u>The SpaceShipTwo Team Understood That Unlocking Early Could Be Catastrophic</u>

SS2 engineers and test pilots were aware of the need for feather locks during the beginning of SS2's boost phase. The need for locks for safe flight during the transonic region was well-understood by the key engineers, who had worked on SS1, and repeatedly communicated to others on the program, including the test pilots. For example, a January 2007 presentation in the early stages of the SS2 program notes that "[a]fter 15 sec the feather actuators are strong enough to hold the feather closed without the locks during a nominal trajectory," and that "[i]f the pilot unlocks the feather after 20 sec the feather will not open since the aero loads are causing it to close."

During FRRs and pre-flight briefings, which the pilot and copilot attended, Scaled engineers and test pilots often referred to the reasons for the unlock of the feather locks, the timing of the unlock, and that the timing of the unlock procedure was critical to safety of the flight.

- For example, Scaled test pilots and engineers discussed the importance of feather locks at the time the aircraft was passing through the transonic region during the Spring 2011 FRR pertaining specifically to the feather system, which Scaled believes the pilot and copilot attended. A presentation by Scaled aerodynamicists included a chart detailing the "feather hinge moment," which is the torque that aerodynamic or inertial forces exert on the feather hinge, during a nominal boost trajectory. The chart indicated that locks are needed for the time frame during which the tail-up loads on the feather exceed the resistance provided by the feather actuator.

- Scaled test pilots and engineers, including the PF04 crew, extensively discussed the feather system during Scaled's July 2010 FRR for Captive Carry Flight number 3 (CC03). The engineer responsible for SS2's pneumatic systems (which included the feather system) discussed the design of the feather locks (including design requirements for holding the feather down during boost) and potential feather system failure modes. Additionally, Scaled's Systems Safety Analyst also discussed potential feather system failure modes during her discussion of Scaled's hazard analysis.

- In a July 2010 communication relating to that CC03 FRR sent by a Scaled design engineer to others on the SS2 team, including the PF04 flight crew, the engineer noted that the tail loads on SS2 "are not enough to open the feather even if the hooks were not engaged except during the pull-up portion of the boost phase."

- The need for locks during the boost phase was also reflected in SS2 flight test documentation, such as the POH, NPs, EPs, and flight test cards. Scaled test pilots regularly reviewed, revised, and discussed these materials throughout the life of the program.

Scaled's test pilots understood that unlocking too early during boost could be catastrophic. As noted in the NTSB Operations Group Chairman's Factual Report:

> The SS2 accident pilot knew the feather[] should not be unlocked prior to 1.40 Mach, . . . and said he believed it was common knowledge that the feather locks were required in the transonic region. Other Scaled Composites and Virgin Galactic pilots stated they were also aware of the hazards associated with the unlocking the feather early during boost. Multiple pilots stated that they never considered that a pilot would unlock the feather prior to 1.40 Mach during a boost flight.

B. Scaled's Development of the Procedural Mitigation to Unlock During Boost At 1.4 Mach

For SS1, flight procedures called for the feather to be unlocked near apogee, after upward loads on the tail had subsided, avoiding the risk of premature feathering during the boost phase. Unlike SS2, SS1 accepted the risk of certain single-point failures (such as the locks jamming or feather failing to open). If the crew did not identify these potential failures sufficiently before 1.8 Mach, the resulting unfeathered reentry would cause excessive speed, structural overload, and overheating, which could be catastrophic. Even if the craft could remain intact, the resulting G forces on the test pilots could be incapacitating. But Scaled did not intend for SS1 to be a prototype for a passenger-carrying vehicle, so it considered this slight risk tolerable on that program.

The SS2 vehicle, in contrast, was a prototype for a vehicle that Virgin Galactic would ultimately use to carry passengers, so Scaled modified its procedures to mitigate against the risk of these potentially catastrophic single-point failures. Early on in the SS2 program, Scaled developed a procedure to address the requirements of both needing the locks for a portion of boost, and unlocking soon enough to abort if necessary, avoiding an unfeathered reentry from apogee. Scaled identified the point in flight at which the flight crew could unlock the feather sufficiently late during boost where the loads on the vehicle would not force the feather open, but sufficiently early that the crew could abort the rocket motor boost and land safely if the locks jammed.

Scaled and Virgin Galactic evaluated and discussed alternatives for making the system more robust. The procedural mitigation offered a number of advantages over potential alternatives to mitigate the risk of the feather system failing. The procedural mitigation did not introduce additional, potential failure modes and added no weight to the vehicle. Also, the procedural mitigation could be repeatedly tested for reliability during sessions in the flight simulator.

The designation of 1.4 Mach as the specific speed at which the unlock should occur was a part of the unlock procedure for a nominal flight since Scaled began powered flights of SS2. After release and rocket motor boost, procedures provided for the copilot to unlock the feather at 1.4 Mach. If the lock system failed and the feather failed to unlock before 1.8 Mach, procedures provided for the crew to abort the rocket motor and reenter and land unfeathered.

Scaled identified the 1.4 Mach speed through aerodynamic modelling of loads on SS2. As noted, 1.4 Mach provided a significant safety margin beyond the portion of the transonic region where the tail-up loads could overcome the actuators. Scaled determined the upward lift on the tail booms shifted to a down force as the aircraft passed through the transonic region to supersonic flight. Modelling demonstrated that well before 1.4 Mach, SS2 would have tail-down loads that would keep the feather closed.

Having a procedure to unlock at 1.4 Mach also allowed a safety margin of 3-5 seconds, a standard, conservative estimate of pilot reaction time agreed upon for this procedure by Scaled test pilots and engineers, to shut down the motor and safely recover the vehicle if the locks failed to unlock. If the feather remained locked shortly after 1.4 Mach, the flight crew would receive an audible and visual caution reminding the crew to unlock the feather. If the locks failed to unlock before a certain speed, per emergency procedures, the crew was supposed to abort boost and proceed with unfeathered reentry and landing. The emergency procedures required an abort before the designated speed to limit the height of apogee, substantially reducing the risks associated with unfeathered reentry.[10]

C. <u>The Specific 1.4 Mach Procedure Was Well Known And Understood</u>

In addition to the catastrophic effects of unlocking early, Scaled test pilots and engineers knew and understood the specific requirement of unlocking at 1.4 Mach. Throughout the development

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[10] In formulating a safe margin to unlock, Scaled also considered the potential difference between the Mach number on the SS2 displays during trans- and supersonic flight and the "true" Mach number used in Scaled's modeling, which could vary by approximately .1 Mach depending on conditions.

of the program and the program procedures, Scaled test pilots discussed the 1.4 Mach unlocking procedure and agreed that the reaction times used in formulating the procedure were appropriate. The former Chief Aerodynamicist regularly discussed the appropriate Mach number with Scaled's test pilots. Scaled also evaluated this procedural mitigation in connection with its Systems Safety Assessments (SSAs), during FRRs, and during pre-flight briefings.[11]

The procedure was consistently documented and reviewed in advance of PF04. The NTSB System Safety Group found that SS2 program participants at Scaled and Virgin Galactic "regularly and repeatedly discussed" the procedural mitigation, including during the six integrated simulations in the weeks prior to PF04. The 1.4 Mach unlocking procedure first appeared in the SS2 NPs in November 2012, prior to any powered flight, and was repeated in each subsequent revision of the NPs as the intended unlock speed for nominal flights.[12] It also appeared on the initial release and every revision of the flight test card for PF04.

The pilot and copilot had practiced and memorized these procedures prior to PF04. The copilot did not need the pilot's verbal confirmation to unlock the feather through a "challenge-response" procedure[13] and it was not practical to execute a challenge-response procedure at that point in the flight. Having the pilot monitor Mach number and execute such a procedure for the feather locks would interfere with his other responsibilities at that time, including maintaining control of the vehicle and re-trimming the vehicle as SS2 transitioned to supersonic flight. Instead, the pilot and copilot memorized and repeatedly trained on these procedures to ensure that they would each execute their respective procedures at the right time and in the correct sequence.

The record shows that the unlock procedure was practiced repeatedly and without incident, including in a number of formal and informal simulator sessions. The NTSB investigation's review of notes and data from the PF04 integrated simulations found no evidence of unlocking prior to 1.4 Mach in simulator sessions. Evidence from the investigation showed that no one observing PF04 training events, including Scaled test pilots and engineers, Virgin Galactic employees, or FAA personnel, could recall observing any SS2 pilot unlock the feather prior to 1.4 Mach in a simulator session.

VI. SCALED'S ROBUST SAFETY PROCESSES AND CULTURE

Throughout Scaled's history, including during the years it was designing, manufacturing, and testing SS1 and SS2, Scaled has taken great pride in its intense focus on safety, safety processes,

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[11] Scaled's SSA and FRRs are discussed in Part VI, *infra*.

[12] Because of the limited duration of boost, for PF02 and PF03 the feather was unlocked at 1.2 and 1.3 Mach, respectively. Similarly, the PF01 procedures did not call for the feather being unlocked during boost because of an even more limited duration of the rocket motor burn.

[13] "Challenge-response" or "command-response" procedures can refer to a number of communication techniques between the pilot and copilot, such as the copilot calling "1.4 Mach, unlocking feather," pausing, and not unlocking until receiving verbal confirmation from the pilot.

and the safety culture of its management and employees. Scaled openly encourages all employees to thoroughly understand the design choices on its aircraft and to make design choices based on the primary interest of mission safety.

As explained in more detail below, Scaled spent over seven years conducting a rigorous systems safety assessment of SS2 using an industry-standard approach that had been used for years on passenger aircraft. Scaled regularly updated this analysis as systems and procedures changed. This was not the only form of safety review. Test pilots and engineers regularly reviewed potential hazards, including the risk of human error, to find appropriate mitigations. This review took many forms in many venues, including an FRR only days before the October 31 test flight.

A. Systems Safety Assessment Background

Scaled employed industry-recognized methods to assess the safety of SS2's systems. These formal methods included a Systems Safety Assessment (SSA), sometimes also referred to as a Systems Safety Analysis. Because SS2 was intended to be the prototype for a commercial passenger aircraft, redundant systems were incorporated.

Scaled began its SSA in 2006, and derived its SSA approach from existing industry best practices for certified aircraft. Scaled received guidance from the Drake Group (Drake), a nationally-respected aeronautics safety analysis consulting company that had helped conduct safety analyses on WK2. The process also heavily involved Scaled's in-house engineers. Scaled relied on FAA advisory circular AC 23.1309-1D, "System Safety Analysis and Assessment for Part 23 Airplanes" (the SSA Advisory Circular) and other published guidance available at the time.

B. Scaled's SSA Used Industry-Recognized Methodology

Scaled's SSA was comprised of several complementary analytical safety methods using an industry-recognized approach for safe operation of passenger aircraft. Once Scaled identified risks that could compromise a mission, it used a formal quantitative analysis, with conservative assumptions, to determine which systems required design changes and what, if any, additional mitigations needed to be put in place.

The SSA was routinely revised as systems and procedures were modified and improved. The SSA process was iterative, with the SSA influencing design and those design changes in turn being reanalyzed in accordance with the SSA. As of October 2014, Scaled had formally revised the SSA ten times since the beginning of the SS2 program.

1. Functional Hazard Analysis

The functional hazard analysis (FHA) was the first component of Scaled's SSA. The FHA was a structured process to identify potential hazards that could impair the ability of SS2 to safely complete a mission. To achieve this, the FHA "focused on 'mission safety' meaning the ability to complete (or abort) any particular mission while assuring the safety of the vehicle and crew."

Based on its prior experience and expertise and available guidance for commercial aircraft, Scaled structured its FHA based on aircraft functions. The SSA Advisory Circular defines an

FHA as "[a] systematic, comprehensive examination of airplane and system *functions* to identify potential minor, major, hazardous, and catastrophic failure conditions that may arise as a result of a malfunction or a failure to function." In accordance with this guidance, Scaled's FHA identified the aircraft functions of the SS2, conceived of functional failures for all phases of flight, and assessed the consequence of those functional failures.

By focusing on the safety of the crew and aircraft, rather than the uninvolved public, Scaled believed it was following a more rigorous process than that mandated by the FAA hazard analysis regulations for experimental suborbital rockets. Those regulations require a more limited hazard analysis than that required for regulated aircraft.

2. Fault Tree Analysis

The second component of Scaled's SSA was a fault tree analysis (FTA). After Scaled identified those failures that were potentially hazardous or catastrophic with respect to mission safety, Scaled used quantitative analysis to more precisely identify which hazards presented the greatest risks and how to mitigate them. Consistent with guidance in the SSA Advisory Circular, Scaled sought to reduce the probabilities of potentially hazardous failures to 1 in 100,000 (referred to as 1E-5), and potentially catastrophic failures to 1 in 1,000,000 (1E-6).

To ensure that SS2 systems were robust, Scaled used conservative estimated probabilities of failure for the components of each system. In assessing risk of component failure, Scaled used a probability of 1 in 1,000 (1E-3) for all events, which is conservative (that is, it uses a higher probability of failure) based on standard aerospace methodology. When the functional failure met the probability criteria using the conservative failure rate, there was no need for corrective action because those functional failures would also meet the target reliabilities with more realistic failure rates, which would be lower. For hazards requiring further analysis beyond the blanket conservative rate, Scaled conservatively estimated component-specific failure rates based on industry-standard reliability data, including manufacturer information, military specifications, and the Reliability Information Analysis Center's Non-Electronic Parts Reliability Data.

Scaled's FTA allowed Scaled to identify and mitigate specific risks. If a hazard did not pass the applicable probability criterion, Scaled either redesigned the contributing systems or put a mitigation in place. For example, the analysis considered the risk that the feather would fail to deploy properly and thereby fail to "[p]rovide . . . configuration for entry." Such a failure was classified as catastrophic because if the feather failed to deploy for reentry when SS2 was at or near apogee, the resulting hazard would likely be catastrophic for both the vehicle and its crew. As a result, under Scaled's SSA, the probability of that failure condition could not exceed 1 in 1,000,000 (1E-6). Because various proposed design changes to the feather system did not demonstrate order-of-magnitude improvements in reliability, Scaled instead implemented a procedural mitigation of unlocking the feather during boost, as discussed in Part V, *supra*, so that the crew could ensure that there would be sufficient time to abort the mission if the feather locks failed to open, and Scaled documented the mitigation as part of the SSA. Scaled repeated these steps on an iterative basis throughout the design development of SS2 and updated the FTA to account for improvements in systems design based on testing results.

3. Additional Safety Analysis

As an additional safety precaution, Scaled also performed a zonal safety analysis (ZSA) and common mode analysis (CMA), two additional industry standards for ensuring safety. As noted in the SSA Advisory Circular, ZSA and CMA are two types of "common cause" analyses, a risk assessment method that helps to ensure that potential failures are independent (*i.e.*, that single cause cannot give rise to multiple failures). ZSA analysis focuses on whether "equipment installations within each zone of the airplane are at an adequate safety standard regarding design and installation standards, interference between systems, and maintenance errors." Among other things, ZSA addresses whether the failure of one system could impact other systems in physical proximity. CMA analysis is "performed to confirm the assumed independence of the events that were considered in combination for a given failure condition," in other words, to analyze and ensure that circumstances giving rise to a failure and assumed to be independent are not in fact related. Scaled made additional design changes based on the results of these supplemental safety analyses.

C. Scaled's Evaluation of Hazards Created by Human Error and Software Error

Scaled's SSA endeavored to address all potential hazards, including the risk of human error, in accordance with FAA guidance. Scaled's FTA analyzed the possibility of human error in responding to functional hazards. In other words, should a certain function fail, Scaled considered whether the flight crew could respond correctly. Relying on the SSA Advisory Circular, Scaled assumed that standard pilot tasks would be performed correctly. In conformance with applicable guidance in the SSA Advisory Circular which recognizes that it is difficult to quantify the risk that test pilots will not conduct reasonable operations pursuant to procedure and to their training, Scaled's FHA and FTA did not separately analyze functional hazards initiated by human error. These analyses did not consider, for example, routine pilot tasks (*e.g.*, deploying the landing gear) being performed incorrectly (*e.g.*, at an inappropriate time such as mid-flight).

Scaled begins to mitigate against the risk of human error by hiring and robustly training capable and experienced test pilots. Scaled generally requires that its test pilots have at least 1,500 hours of flight time, as well as specific experience in jet and glider aircraft.[14] Scaled's multidisciplinary approach also requires that its test pilots be accomplished engineers, making them better able to understand and address potential hazards during test flights. The diverse skills of Scaled test pilots have been recognized by the test pilot community through a number of awards, including awards from the Society of Experimental Test Pilots for technical papers as well as flight testing. In January 2015, Virgin Galactic hired the Scaled pilot from the first powered flights of SS2, citing his "extraordinary capabilities."[15]

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[14] Waiver of 14 CFR 437.29 and 437.55(a) for Scaled Composites, LLC, 78 Fed. Reg. 42994, 42995 (July 18, 2013) (Waiver).

[15] "Virgin Galactic Appoints Mark Stucky As Pilot," *at* http://www.virgingalactic.com/press/virgin-galactic-appoints-mark-stucky-pilot/.

Scaled's approach to human error analysis is articulated in the "methodology" section of its SSA:

> Human error is reduced by testing processe[s] and procedures. The flight crew and control room crew run through many SIM (simulator) drills. These drills involve every kind of failure through the entire mission. These SIM sessions are designed to teach and prepare all crew involved on how to handle all kind[s] of situation[s]. Ground crew and Maintenance crews follow strict process and procedures for every change, test and pre\post flight operations. ERs, TRDs, Checklists and signoffs are required. . . . Given all the checks and balances Human error is not part of the FHA. In the FTA under high workload and very time sensitive events human error is a factor in the fault tree.

Scaled also considered software error in accordance with applicable guidance and regulations. In section 1.4.12 of its permit application, Scaled identified software-controlled systems in SS2. Scaled identified the rocket motor controller (RMC) as the one safety critical software controlled device, and that device was analyzed in accordance with Scaled's SSA, including through the FHA and FTA. The RMC went through a broad verification and validation plan.

D. <u>Other Safety Measures</u>

Through Scaled's flight test process, test pilots and engineers regularly reviewed and analyzed the design of the vehicle, flight procedures, and potential hazards, including the risk of human error. Scaled employed a number of safety initiatives to identify, communicate, and manage risk on its programs. Throughout each of these processes, Scaled maintained a philosophy that if any concerns were identified, the proposed flight test would not take place until those concerns were resolved.

1. Vibration Testing

In designing the rocket motor, Scaled was conscious of ensuring that the flight crew would be able to safely perform all required tasks. In May 2012, roughly one year before SS2's first powered flight, Scaled conducted specialized testing in order to develop "limits for SS2 vehicle vibration based on flight crew capability." During the tests, a test pilot would sit in a crew seat on a vibrating "shaker table" platform, wearing a parachute and helmet, and perform various tasks while undergoing different vibration levels, including reading the flight display. Seven test pilots and engineers, including the PF04 pilot, participated in the testing, and the results were provided to the rocket motor team to establish stability criteria for the rocket motor. Scaled's rocket motor design team was ultimately able to achieve acceptable levels of vibration based on the test results.

2. Scaled's Flight Readiness Review (FRR) Process

An important part of Scaled's safety process is its FRR process, in which a board of Scaled engineers with relevant subject matter expertise who do not work on the particular program under review, provides an independent, unbiased safety check prior to the start of flight testing or after significant changes to the vehicle. Scaled's President appoints a board Chair, who is independent from the project team. The FRR process is an industry-standard approach for ensuring that aircraft are safe to proceed with planned test flights.

The first FRR for a program consists of a comprehensive review of vehicle design, configuration, history, structure, systems, and flight plan. FRRs also cover potential hazards and procedural mitigations. The process includes presentation of the SSA and any modifications since the prior safety analysis. Subsequent FRRs focus on changes to structures, systems, weight, loads, and flight plan.

Before Scaled allows a flight test to proceed, all FRR participants, including test team and board members, must reach a consensus the aircraft is safe to flight test. The test team identifies risks and explains how those risks have been appropriately mitigated. By having independent subject matter experts on the board, the FRR should also uncover previously unidentified potential risks. To the extent any risks are identified during the FRR, the flight test cannot proceed until all FRR participants are satisfied that the risks have been appropriately mitigated or eliminated.

3. Safety Evaluation Specific to the Feather System

Scaled conducted an FRR specifically related to the feather system in connection with the first feathered glide flight of SS2 during March and April 2011. Before the FRR, engineers provided board members with a pre-FRR reading list to familiarize themselves with the program, the feather system, the SSA, and the aerodynamic principles on which the feather system was based. During the FRR, board members engaged in detailed discussions concerning the risks associated with the feather system, possible failure conditions, and mitigations that had been put in place. Because the FRR focused on the feather system, particular attention was given to the FHA section regarding “feather configuration.” Scaled test pilots and engineers also discussed loads on the feather during boost. While a sign-in sheet for this FRR could not be located, Scaled has concluded the PF04 copilot was in attendance, based on his work schedule as well as calendar and payroll record entries.

4. PF04’s FRR Process

Consistent with Scaled’s FRR process, the FRRs for PF04 featured robust vetting of questions and, consistent with the intent of the FRR process to prioritize safety over expediency, resulted in a change in the flight date to ensure all questions had been answered.

(a) PF04 FRR

The PF04 flight crew attended the internal FRRs related to PF04. They signed the attendance sheet for the initial FRR dated October 3, 2014. This initial FRR related primarily to changes in SS2 loads and new properties from the motor. The FRR also discussed the planned envelope expansion. The group reviewed the flight test card requirements, including the timing of feather unlock at 1.4 Mach.

Following the initial FRR, Scaled believed that additional aerodynamic modeling was necessary to address concerns relating primarily to potential changes in aerodynamic loads resulting from recent changes to the SS2 vehicle. Accordingly, despite having spent months planning, preparing, and training for PF04 in order to meet Virgin Galactic’s scheduling requirements, on

October 16 Scaled postponed PF04's October 23, 2014 flight while Scaled and Virgin Galactic worked together to address any outstanding concerns.

(b) October 2014 Town Hall

After Scaled's decision to delay PF04, Scaled invited Virgin Galactic to participate in an October 22, 2014 "town hall" discussion to address whether anyone had questions about the program "that have not been previously addressed." Over twenty representatives from the two companies met and engaged in wide-ranging discussion about a number of issues, including safety. Scaled engineers thought it was beneficial to have so focused a review at that time, shortly before the flight. The meeting touched on several safety-related aspects of the feather system, including the rationale for unlocking at 1.4 Mach. The group discussed the possibility of flutter during boost with the locks unlocked, feather-down reentry scenarios, the timing of feather unlock at 1.4 Mach, feather safety margins, vehicle stability in a feathered reentry, and feather lock loads. The meeting created a number of action items for Scaled engineers, all of which were fully cleared before the flight.

(c) PF04 Delta FRR

The PF04 crew attended an additional FRR for PF04 known as the Delta FRR on October 27, 2014, just four days before the flight. The Delta FRR covered changes from the initial PF04 FRR. These included SS2 loads, rocket motor qualification, nitrous oxide load and quantity, system characteristics and procedures, and several other modifications.

5. Pre-flight Checks

On the actual day of flight, Scaled followed additional procedures to ensure readiness. Early that morning, flight and ground crew members attended a briefing. The PF04 pilot and copilot were among those who attended the standard briefing the night before, as well as that morning's "delta briefing," which addressed any updates. The brief covered items such as weather, NOTAMs (i.e., so-called "Notices to Airmen" issued by aviation authorities as a form of alert), nitrous loading, and an additional review of the flight test data card (including the procedures during boost).

Scaled also designed flight check procedures to verify functionality of the feather system prior to each flight. Scaled mitigated the risk of feather lock failure by taking steps to make it less likely that the locks might jam. Pursuant to a standard procedure, the crew cycled the feather locks during the preflight and prerelease checks.

VII. SPACESHIPTWO COMPLIED WITH REGULATORY REQUIREMENTS

Scaled worked with the FAA[16] over the course of more than four years to ensure that SS2 complied with safety and regulatory requirements. During all SS2 flights, including PF04, SS2

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[16] Scaled's interactions with the FAA relating to SS2 were typically with the FAA's Office of Commercial Space Transportation, commonly known as AST. For ease of reference, this submission's use of "FAA" encompasses AST unless otherwise noted.

was flying pursuant to a valid Experimental Permit issued by the FAA, permitting Scaled to operate SS2 as a reusable suborbital rocket. During each flight, Scaled understood it was in full compliance with its permit. In January 2015, following its inspection to observe PF04, "ensure compliance with [Scaled's experimental permit] and its terms and conditions, and verify continued accuracy of representations contained in the experimental permit application," the FAA found Scaled to be compliant with applicable regulations and the terms and conditions of Scaled's permit, with the lone "issue" of using a "thumbs-up" instead of a verbal indication that all positions are go or no-go for launch.

A. Scaled's Pre-Application Consultation with the FAA

The FAA used the experimental permit process as a limited-term authorization to launch or reenter a suborbital rocket for research or training purposes. FAA regulations list a number of critical components required for an experimental permit application, including a hazard analysis. Throughout its safety assessment and development process, Scaled worked closely and transparently with the FAA. Scaled began consulting with the FAA in March of 2010. From March 2010 to January 24, 2012, Scaled had numerous communications with the FAA as a part of the pre-application consultation process. The pre-application process intends such consultations to allow Scaled and the FAA to identify potential issues relevant to the FAA's permitting decision. During this two-year period, Scaled provided the FAA with draft experimental permit materials, including two draft permit applications and its SSA. Beginning in January 2011, Scaled and Virgin Galactic provided the FAA with quarterly updates on the SS2 program. Scaled and the FAA also specifically discussed the SSA during this period. Throughout those discussions, Scaled understood that the FAA concurred with its SSA approach, as confirmed by the granting of the initial permit.

B. Scaled's Experimental Permit Applications and Renewals

Following these lengthy discussions with the FAA, Scaled submitted an experimental permit application on January 24, 2012. The application included Scaled's SSA in fulfillment of the hazard analysis requirement and further included a detailed explanation of Scaled's SSA approach.

On May 23, 2012, the FAA granted Scaled's application and issued Scaled a permit, permitting Scaled to proceed with SS2 test flights. The permit was subject to several terms, conditions, and limitations, which were not specifically related to the feather system or human error, including one condition (condition 8) related to Scaled's hazard analysis, requiring that "Scaled must submit an updated hazard analysis showing that all identified hazards have been mitigated to Scaled's acceptability criteria, including the Rocket Motor Controller and the Misleading Trajectory Guidance at Boost hazards."

In fulfillment of this condition, on March 6, 2013, before the first Experimental Permit expired, Scaled submitted an updated hazard analysis at the same time it submitted an application to renew and modify the Experimental Permit based on material changes to SS2's design. In addition to the revised hazard analysis required by condition 8 of the initial permit, Scaled also submitted a document titled "Clarification of Hazard Analyses Mitigations," and a document titled "Additional Information about Hazards." For the potentially catastrophic hazard of the feather failing to operate, Scaled noted that "the feather locks are tested before SS2 is released and are actuated early in the boost. If the locks don't actuate the boost is aborted and the feather isn't required for a safe landing." On April 23, 2013, prior to any powered flight of SS2, the FAA informed Scaled that the updates to the hazard analysis satisfied condition 8 of the initial permit.

The FAA approved Scaled's permit renewal application on May 22, 2013. The renewal removed the condition for Scaled to submit an updated hazard analysis, which had been satisfied and was no longer included as a term and condition of the permit.

C. The FAA's Issuance of a Waiver

Although Scaled understood it was in full compliance with all regulations, on July 18, 2013, nearly two months after the FAA granted Scaled's renewal application, the FAA published a notice of waiver in the Federal Register, waiving the requirement for Scaled to provide a hazard analysis that "identifies, mitigates, and verifies and validates mitigation measures for hazards created by software and human error." Scaled had not requested this waiver, as the FAA had previously determined that "Scaled's approach to demonstrating compliance [with the applicable regulations] was sufficiently rigorous to ensure public safety, and, in effect, the approach provided an equivalent level of safety." When the waiver was issued, Scaled's documentation of hazards that could result from human and software error analysis had not materially changed since the initial grant of Scaled's Experimental Permit.

The FAA's waiver notice indicated that the waiver was warranted under the applicable regulatory factors,[17] pointing to several attributes of the Scaled flight test program in finding that test flights would not endanger public health and safety or the safety of property:

> [T]he combination of [Scaled's] training program, incremental approach to flight testing, use of chase planes, and two-pilot model, as well as the limited duration of the permit and thus the waiver, the remoteness of its operating area and its use of a winged vehicle combine to allow the FAA to find that Scaled's activities will not jeopardize public health and safety or safety of property.[18]

The waiver did not explicitly list any conditions, and Scaled understood it was in full compliance with the FAA's requirements.

D. Scaled's 2014 Renewal Application and Permit Modification

The evidence demonstrates that the FAA reiterated its grant of the waiver on several occasions. On March 17, 2014, Scaled submitted an application to the FAA to renew its Experimental

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[17] The FAA may waive an experimental permit requirement under 14 C.F.R. § 404.5(b) when the waiver (1) will not jeopardize the public health and safety or the safety of property, (2) will not jeopardize national security and foreign policy interests of the United States, and (3) will be in the public interest. *See* 14 C.F.R § 404.5(b).

[18] Waiver at 42995.

Permit. On March 28, 2014, the FAA informed Scaled that the FAA had determined that additional information and clarification was needed to complete the evaluation, and provided Scaled with a list of items to be addressed, none of which involved human or software error. One item requested that Scaled update its SSA to address potential pilot incapacitation due to vibration, which was subsequently addressed as requested.

On May 21, 2014, the FAA granted Scaled's renewal application, and at the same time informed Scaled that it was again waiving the requirement to provide a formal hazard analysis that identifies, mitigates, and verifies and validates mitigation measures for all hazards, including those created by software and human error. The FAA noted that it did not believe Scaled's activities jeopardized public health and safety or property.

Similarly, when Scaled requested to modify the existing Experimental Permit to reflect design changes to SS2 (primarily related to the rocket motor) on July 16, 2014, the FAA granted this request and reiterated in a letter dated October 14, 2014 that it was again waiving the same hazard analysis requirements for the same reasons previously articulated.

E. <u>The FAA's Continual Monitoring of PF04 Pre-flight Activities</u>

Throughout its testing process, Scaled continued to work closely and transparently with the FAA. Between May and October of 2014, Scaled had numerous interactions with the FAA. The FAA was present for public safety related pre-operational, operational, and post-operational activities. FAA safety inspectors were present for numerous inspections in the build up to PF04, including integrated simulator sessions. SS2's most recent FAA Special Airworthiness Certificate was issued on October 1, 2014.

In short, Scaled was and believed itself to be operating in full compliance with all regulatory obligations at the time of PF04 and was operating pursuant to a valid Experimental Permit duly issued by the FAA.

VIII. <u>PROPOSED FINDINGS AND CONCLUSIONS</u>

A. <u>Proposed Findings</u>

1. The Powered Flight Four (PF04) pilot and copilot were properly certificated and qualified in accordance with applicable Federal Aviation Administration regulations at the time of PF04.

2. Scaled had received and was operating under a valid Experimental Permit and all other applicable regulations at the time of PF04. SpaceShipTwo was properly certified, equipped, and maintained in accordance with applicable regulations at the time of PF04.

3. Following release from WhiteKnightTwo, and prior to the feather unlock event, SpaceShipTwo's vehicle structures and systems, including its rocket motor, performed as designed.

4. There is no evidence of any pre-flight conduct issues or personal issues with respect to either the pilot or the copilot. All applicable crew rest requirements were satisfied. The

test pilots were provided ample rest opportunities and all indications are that they professionally managed their rest periods and took advantage of their opportunities for restful sleep. There is no evidence fatigue contributed to the accident.

5. Both the pilot and copilot were extensively trained. They met or exceeded all documented training requirements and had diligently prepared for the test flight. The PF04 flight crew regularly reviewed and simulated the procedures for PF04. During all of the simulator sessions leading up to PF04, there is no evidence that the feather was ever unlocked prematurely.

6. The SpaceShipTwo vehicle design was based on Virgin Galactic's performance requirements and was carefully considered in accordance with Scaled's proven philosophy to be safe and reliable by limiting and mitigating against potential failure modes. Scaled used a simple, robust, and proven design for the feather system after evaluating alternatives that would have introduced additional failure modes into the safety-critical feather system. SpaceShipTwo's feather system was properly maintained in accordance with the SpaceShipTwo maintenance plan, and had been successfully ground and flight tested multiple times prior to PF04.

7. Scaled mitigated the catastrophic risk of the feather failing to open by having the flight crew unlock the feather at 1.4 Mach following a detailed analysis of alternatives. Alternative mitigations introduced additional failure modes, and in any event, were not markedly safer than the procedural mitigation. The choice of the specific 1.4 Mach number provided a safe margin against unlocking both too early and too late.

8. The fact that the feather was supposed to be unlocked at 1.4 Mach was documented in numerous sources; was included in the flight test card procedures; was known to Scaled test pilots; and was rehearsed repeatedly without incident. Scaled and Virgin Galactic test pilots and engineers knew and understood that premature unlocking of the feather system could be catastrophic. The issue was repeatedly discussed by, among others, the former Chief Aerodynamicist, with test pilots and engineers, including those involved with PF04.

9. Consistent with industry standards and applicable Federal Aviation Administration guidance, Scaled conducted an extensive Systems Safety Assessment that included functional hazard assessment, fault tree analysis, zonal safety analysis, and common mode analysis. The manner in which Scaled considered the issues of human error and software error in its Systems Safety Assessment were consistent with available guidance.

10. There does not appear to have been any misrepresentation in the cockpit flight displays as to the speed of the aircraft or the coincidental depiction of readings that could have reasonably been interpreted as a 1.4 Mach indication. The copilot correctly called out a speed of 0.8 Mach just before he prematurely unlocked the feather locks.

11. Weather was not a factor in the accident.

12. During PF04, the feather locks were prematurely unlocked shortly after the .8 Mach call, within the transonic region, instead of at 1.4 Mach as provided for by flight procedures.

This allowed the feather to deploy, creating aerodynamic forces that caused the breakup of the vehicle.

B. Proposed Probable Cause

The probable cause of this accident was the unanticipated action of the copilot to unlock the feather locks at an airspeed that (1) was earlier than the Mach number for which the test flight was planned and for which the aircrew trained, and (2) was within a Mach number range that included aerodynamic forces on the feather booms sufficient to overpower the feather actuators, thus allowing the feather to open, which directly caused severe aerodynamic loads on the vehicle and the vehicle to break up.

IX. SCALED'S POST-ACCIDENT RECOMMENDATIONS

Following the accident, Scaled has extensively supported the NTSB investigation and undertaken its own efforts to learn from the accident and to continue to improve safety. These efforts have not uncovered evidence that a particular design or procedure caused the premature unlocking of the feather mechanism. Scaled recognizes that experimental flight testing in general, and space flight testing in particular, carry inherent risks. Scaled is committed, nonetheless, to the highest standards of safety. While no one can definitively conclude what led to the premature unlock, Scaled has strived to learn from this accident, to build on its robust processes and procedures, and identify areas in which safety can be further enhanced. In addition, Scaled hopes that the industry as a whole can also gain knowledge through the NTSB's and Scaled's efforts to understand as fully as possible the events leading up to the accident and incorporate that knowledge into future experimental flight testing. Continued innovation in aviation and space flight and dedication to safety demand as much.

Scaled recommends the following enhanced safety procedures and processes:

Training, Communication, and Documentation

- Continue to ensure documentation of and communication to the test team of any possibility of immediate catastrophic loss of the vehicle based on the flight crew exceeding operating limits. Make sure the Pilot Operating Handbook repeats this information and explains the rationale for all critical vehicle operating limitations.

- Continue to ensure and document that test pilots comply with program specific pilot training and currency requirements. This includes consideration of improved written training syllabus materials and improving pilot training records to include, as applicable, recurring Crew Resource Management, simulator sessions, transition, formation, chase, unusual attitude, spin awareness, elevated G, altitude chamber, life support, parachute, emergency egress, ejection seat, and survival training.

- Continue to ensure a formal methodology to document relevant flight test training simulator session data relating to human performance. This will aid in the further evaluation of flight crew workload, cockpit layout, and procedure design, and should enhance awareness of flight crew preparedness in an objective manner.

- Continue to ensure vehicle and procedure changes are disseminated to system safety engineers to re-assess hazards of vehicle and cockpit procedure modifications.

Human Performance and Procedures

- For any single action by the crew that could result in an immediate catastrophic occurrence, with an emphasis on actions that leave limited time for flight test crew to react, continue to evaluate and document whether additional mitigations are appropriate and to ensure that an appropriate mitigation method is employed.

- Engage a human performance expert or experts to help identify human performance needs, suggest additional processes, and further train staff on human performance, assisting in human performance analysis efforts. Enhance human performance considerations in design, build, training, and flight test efforts.

- Specifically address potential flight test crew human performance limitations in future systems safety assessment efforts. Focus additional attention on any single action by a crew member that could result in an immediate, catastrophic loss of the vehicle. Verify that mitigation of any hazard using flight test crew procedures continues to be carefully analyzed with respect to the possibility of human error.

Emergency Response

- Improve the understanding of all aspects of local emergency response assets, including any potential limitations. Define criteria for risk assessment of specific test flights that would trigger enhanced emergency response measures.

Scaled has already implemented the following actions on its programs:

Actions Already Implemented

- Immediately following the October 31, 2014 accident, Scaled grounded test aircraft on other programs. Return-to-flight reviews were then conducted focusing on risks, limits and operating procedures before returning the aircraft to flight test.

- Scaled has formally required recurring, return-to-flight reviews to be convened at the conclusion of the condition inspection of all Scaled aircraft. The meetings include a review of the vehicle's prior Flight Readiness Reviews. This will provide a refresher to the team of the rationale behind the operating limitations and potential hazards if operating limitations are exceeded.

- All Scaled test pilots have been assigned to report to the Director of Flight Operations, instead of other departments, to give the Director authority to directly manage test pilot workloads and priorities.

- Scaled has evaluated flight crew parachute systems, including emergency bailout oxygen bottle activation and parachute automatic deployment. Scaled is establishing a standard configuration for applicable flight crew parachute systems based on this evaluation.

- Scaled has standardized its curriculum for parachute training using an experienced parachutist as an instructor, and added an initial and annual recurrent training requirement for test pilots and test engineers in parachute functions and limitations.

- All training for each aircrew is now being documented in a central aircrew online training folder maintained by Scaled Flight Operations.

APPENDIX A

ACRONYMS AND ABBREVIATIONS

CC	captive carry flight
CF	cold flow glide flight
CMA	common mode analysis
CRM	crew resource management
ECS	environmental control system
EP	emergency procedures
ER	engineering request
FAA	Federal Aviation Administration
FHA	functional(/fault) hazard analysis
FRR	flight readiness review
FTA	fault tree analysis
G	gravity
GF	glide flight
KEAS	knots equivalent airspeed
NOTAM	notice to airmen
NP	normal procedures
NTPS	National Test Pilot School
NTSB	National Transportation Safety Board
PF	powered flight
PNF	pilot not flying
POH	pilot operating handbook
RMC	rocket motor controller
SETP	Society of Experimental Test Pilots
SIM	simulator
SS1	SpaceShipOne
SS2	SpaceShipTwo
SSA	systems safety assessment/analysis
VG	Virgin Galactic
WK2	WhiteKnightTwo
ZSA	zonal safety analysis

APPENDIX B

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