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Scaled Composites SpaceShipTwo, N339SS
Near Koehn Dry Lake, California
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Aerospace Accident Report

NTSB/AAR-15/02
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National
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Safety Board

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490 L'Enfant Plaza, S.W.
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National Transportation Safety Board. 2015. ***In-Flight Breakup During Test Flight, Scaled Composites SpaceShipTwo, N339SS, Near Koehn Dry Lake, California, October 31, 2014.*** **NTSB/AAR-15/02. Washington, DC.**

Abstract: This report discusses the October 31, 2014, crash involving the SpaceShipTwo (SS2) reusable suborbital rocket, N339SS, which was operated by Scaled Composites LLC. SS2 broke up into multiple pieces during a rocket-powered test flight and impacted terrain over a 5-mile area near Koehn Dry Lake, California. The pilot received serious injuries, and the copilot received fatal injuries. SS2 was destroyed, and no one on the ground was injured as a result of the falling debris. SS2 had been released from its launch vehicle, WhiteKnightTwo, N348MS, about 13 seconds before the structural breakup. Scaled was operating SS2 under an experimental permit issued by the Federal Aviation Administration's (FAA) Office of Commercial Space Transportation (AST) according to the provisions of 14 *Code of Federal Regulations* Part 437. Safety issues include the lack of human factors guidance for commercial space operators, the efficacy and timing of the preapplication consultation process, limited interactions between the FAA/AST and applicants during the experimental permit evaluation process, missed opportunities during the FAA/AST's evaluations of hazard analyses and waivers from regulatory requirements, limited inspector familiarity with commercial space operators, an incomplete commercial space flight database for mishap lessons learned, and the need for improved emergency response planning. Safety recommendations are addressed to the FAA and the Commercial Spaceflight Federation.

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Abbreviations

AC	advisory circular
ADC	air data computer
AFB	air force base
ARFF	aircraft rescue and firefighting
AST	Federal Aviation Administration Office of Commercial Space Transportation
ATC	air traffic control
ATP	airline transport pilot
CFR	*Code of Federal Regulations*
EMT	emergency medical technician
FAA	Federal Aviation Administration
FHA	functional hazard assessment
FRR	flight readiness review
FTA	fault tree analysis
IIP	instantaneous impact point
INS	inertial navigation system
KCFD	Kern County Fire Department
MFD	multifunctional display
MHV	Mojave Airport
NASA	National Aeronautics and Space Administration
nm	nautical mile
NTPS	National Test Pilot School

NTSB	National Transportation Safety Board
Nx	longitudinal acceleration
Nz	normal acceleration
PF	powered flight
PF01	first SpaceShipTwo powered flight test
PF02	second SpaceShipTwo powered flight test
PF03	third SpaceShipTwo powered flight test
PF04	fourth SpaceShipTwo powered flight test
PFD	primary flight display
POH	pilot operating handbook
RM2	rocket motor two
Scaled	Scaled Composites
SIP	safety inspection plan
SMS	safety management system
SODAS	Strap On Data Acquisition System
SS1	SpaceShipOne
SS2	SpaceShipTwo
SSA	systems safety analysis
UAV	unmanned aerial vehicle
WK2	WhiteKnightTwo

Executive Summary

On October 31, 2014, at 1007:32 Pacific daylight time, the SpaceShipTwo (SS2) reusable suborbital rocket, N339SS, operated by Scaled Composites LLC (Scaled), broke up into multiple pieces during a rocket-powered test flight and impacted terrain over a 5-mile area near Koehn Dry Lake, California. The pilot received serious injuries, and the copilot received fatal injuries. SS2 was destroyed, and no one on the ground was injured as a result of the falling debris. SS2 had been released from its launch vehicle, WhiteKnightTwo (WK2), N348MS, about 13 seconds before the structural breakup. Scaled was operating SS2 under an experimental permit issued by the Federal Aviation Administration's (FAA) Office of Commercial Space Transportation (AST) according to the provisions of 14 *Code of Federal Regulations* (CFR) Part 437.

Scaled had developed WK2 and was developing SS2 for Virgin Galactic, which planned to use the vehicles to conduct future commercial space suborbital operations. SS2 was equipped with a feather system that rotated a feather flap assembly with twin tailbooms upward from the vehicle's normal configuration (0º) to 60º to stabilize SS2's attitude and increase drag during reentry into the earth's atmosphere. The feather system included actuators to extend and retract the feather and locks to keep the feather in the retracted position when not in use.

After release from WK2 at an altitude of about 46,400 ft, SS2 entered the boost phase of flight. During this phase, SS2's rocket motor propels the vehicle from a gliding flight attitude to an almost-vertical attitude, and the vehicle accelerates from subsonic speeds, through the transonic region (0.9 to 1.1 Mach), to supersonic speeds. The flight test data card used during the accident flight indicated that the copilot was to unlock the feather during the boost phase when SS2 reached a speed of 1.4 Mach. (The feather was to be unlocked at this point in the flight to mitigate the hazard resulting from a reentry with the feather down due to a lock failure.) However, a forward-facing cockpit camera and flight data showed that the copilot unlocked the feather just after SS2 passed through a speed of 0.8 Mach. Afterward, the aerodynamic and inertial loads imposed on the feather flap assembly were sufficient to overcome the feather actuators, which were not designed to hold the feather in the retracted position during the transonic region. As a result, the feather extended uncommanded, causing the catastrophic structural failure.

Before Scaled received its experimental permit to conduct rocket-powered test flights for SS2, the company prepared an experimental permit application for the FAA/AST's review. One of the pertinent regulations relating to the issuance of an experimental permit is 14 CFR 437.55, "Hazard Analysis," which, among other things, requires the applicant to identify and describe those hazards that could result from human errors. In its SS2 hazard analysis, Scaled did not account for the possibility that a pilot might prematurely unlock the feather system, allowing the feather to extend under conditions that would cause a catastrophic failure of the vehicle structure. Instead, Scaled assumed that pilots would correctly operate the feather system every time because they would be properly trained through simulator sessions and would follow the normal and emergency procedures for a given situation. However, this accident demonstrated that

mistakes can occur even with a flight crewmember who had extensive flight test experience and had performed numerous preflight simulations during which the feather was unlocked at the proper speed of 1.4 Mach.

The FAA/AST evaluated Scaled's SS2 experimental permit applications and granted the initial SS2 permit in May 2012 and the first and second renewals of the permit in May 2013 and May 2014, respectively. After granting the first renewal of the permit, the FAA/AST conducted another review of the SS2 hazard analysis included in Scaled's application and determined that the hazard analysis did not meet the software and human error requirements of 14 CFR 437.55(a). As a result, in July 2013, the FAA/AST issued a waiver from these hazard analysis requirements for the first renewal of Scaled's experimental permit. Scaled did not request the waiver, participate in the waiver evaluation process, or have an opportunity to comment on the waiver before it was issued (except to identify proprietary information that should not be disclosed). In May and October 2014 (as part of the second renewal of Scaled's SS2 experimental permit and Scaled's application to modify the permit to reflect changes made to SS2, respectively), the FAA/AST issued additional waivers from the software and human error hazard analysis requirements of section 437.55(a).

The FAA/AST determined that each of the waivers was in the public interest and would not jeopardize public health and safety, safety of property, or US national security and foreign policy interests. The FAA/AST also determined that, even though Scaled's hazard analysis did not comply with software and human error regulatory requirements, specific mitigations that Scaled had in place would prevent hazards resulting from such errors. However, the FAA/AST issued the waivers without understanding whether the mitigations would adequately protect against a single human error with catastrophic consequences. In addition, the FAA/AST did not determine whether mitigations, other than those intended to protect against human error, were sufficient to ensure public safety.

The NTSB identified the following safety issues as a result of this accident investigation:

- **Lack of human factors guidance for commercial space operators.** Scaled did not emphasize human factors in the design, operational procedures, hazard analysis, and simulator training for SS2. For example, by not considering human error as a potential cause of uncommanded feather extension on the SS2 vehicle, Scaled missed opportunities to identify design and/or operational factors that could have mitigated the catastrophic consequences of a single human error during a high workload phase of flight. To prevent a similar situation from recurring, commercial space operators should fully consider human factors during a commercial space vehicle's design and operation. However, because commercial space flight is an emerging industry, no guidance currently exists specifically for commercial space operators that advises them to, among other things, obtain human factors expertise, consider human error in hazard analyses, ensure that hazard analyses avoid or adequately mitigate single-point failures, and ensure that flight crews are aware of known catastrophic hazards that could result from a single human error.

- **Efficacy and timing of the preapplication consultation process.** Experimental permit applicants are required to consult with the FAA/AST before formally submitting their applications, and individual operators can decide when to begin this process. The SS2 preapplication process began about 2 years before Scaled submitted its initial application but after the vehicle had been designed and manufactured. At that point, it could have been difficult and costly for Scaled to make changes to SS2 if the FAA/AST had found inadequacies in Scaled's hazard analysis during preapplication consultations. Thus, the experimental permit preapplication consultation process would be more effective if it were to begin during a commercial space vehicle's design so that concerns could be resolved and potential catastrophic hazards resulting from human error could be identified early in a vehicle's development.

- **Limited interactions between the FAA/AST and applicants during the experimental permit evaluation process.** As a part of the review of Scaled's experimental permit application, FAA/AST technical staff developed questions for Scaled technical staff related to SS2's design and operation, many of which were necessary to understand potential operational hazards and the design, operational, and management controls that would be needed to comply with FAA regulations to ensure public safety. However, some FAA/AST technical staff members reported that their questions that did not directly relate to public safety were filtered by FAA/AST management to reduce the burden on Scaled. The dividing line between the questions that the FAA/AST needs to ask to determine the risk to the public and those to assess mission objectives is not always apparent because certain aspects of a vehicle's design and operation could impact both public safety and mission safety assurance. Thus, more extensive interactions between FAA/AST technical staff and prospective experimental permit applicants during permit evaluations would help to perform this work more effectively in the future.

- **Missed opportunities during the FAA/AST's evaluations of hazard analyses and waivers from regulatory requirements.** The FAA/AST approved the initial and first renewal of the SS2 experimental permit without recognizing that the SS2 hazard analysis did not identify single flight crew tasks that, if performed incorrectly or at the wrong time, could result in a catastrophic hazard. Also, the FAA/AST did not consult with Scaled technical staff after determining that waivers would be necessary or ask Scaled to correct the areas of noncompliance. In addition, the FAA/AST issued the waivers without verifying that Scaled was performing the mitigations cited in the waiver or assessing the effectiveness of these mitigations.

- **Limited inspector familiarity with commercial space operators**. The FAA/AST conducts inspections before and during a commercial space flight to ensure compliance with federal regulations and the experimental permit and verify that the representations made in the experimental permit application are still accurate.

FAA/AST inspectors were assigned to individual launch operations and not to specific commercial space operators. The FAA/AST safety inspectors who were assigned to the accident test flight had not been assigned to previous Scaled test flights. As a result, the inspectors had limited time to understand Scaled's training, procedures, and operations before conducting safety inspections. FAA/AST inspectors who are assigned to commercial space operators (rather than individual commercial space launch operations) could become more familiar with the operators and could bring continuity and consistency to the inspection process.

- **Incomplete commercial space flight database for mishap lessons learned.** During 2010, the FAA/AST began efforts to create a mishap lessons learned database, the Commercial Space Transportation Lessons Learned System, but this database has not yet been fully developed. The aviation industry has databases documenting accident and incident findings and effective corrective actions, which have been highly beneficial in preventing accidents and reducing fatal accident rates. A fully implemented and transparent commercial space mishap database could not only benefit safety (by disseminating lessons learned) but could also promote growth while the industry is in its current formative stage.

- **Need for improved emergency response planning.** Scaled conducted its flight tests from Mojave Airport (MHV), Mojave, California. A helicopter that was specifically prepared for and tasked with supporting an emergency response to a potential SS2 accident was not prepositioned at MHV, even though that helicopter had been prepositioned at the airport for SS2's three previous powered flights. As a result, the helicopter was delayed in reaching the injured pilot. Another helicopter with advanced life support capabilities was located at MHV but was not placed on standby (before the accident flight) in case an accident were to occur. Thus, Scaled and local emergency response officials could improve their emergency readiness for future test flights by making better use of available helicopter assets. Other commercial space operators could benefit from taking the same action.

The National Transportation Safety Board determines that the probable cause of this accident was Scaled Composites' failure to consider and protect against the possibility that a single human error could result in a catastrophic hazard to the SpaceShipTwo vehicle. This failure set the stage for the copilot's premature unlocking of the feather system as a result of time pressure and vibration and loads that he had not recently experienced, which led to uncommanded feather extension and the subsequent aerodynamic overload and in-flight breakup of the vehicle.

As a result of this investigation, the NTSB makes safety recommendations to the FAA and the Commercial Spaceflight Federation.

1. Accident Investigation and Analysis

1.1 The Accident

On October 31, 2014, at 1007:32 Pacific daylight time, the SpaceShipTwo (SS2) reusable suborbital rocket, N339SS, operated by Scaled Composites LLC (Scaled), broke up into multiple pieces during a rocket-powered test flight and impacted terrain over a 5-mile area near Koehn Dry Lake, California.[1] The pilot received serious injuries, and the copilot received fatal injuries. SS2 was destroyed, and no one on the ground was injured as a result of the falling debris. SS2 had been released from its launch vehicle, WhiteKnightTwo (WK2), N348MS, about 13 seconds before the structural breakup. Scaled was operating SS2 under an experimental permit issued by the Federal Aviation Administration's (FAA) Office of Commercial Space Transportation (AST) according to the provisions of 14 *Code of Federal Regulations* (CFR) Part 437.[2]

The National Transportation Safety Board (NTSB) is charged by statute with conducting transportation accident and incident investigations for the purpose of improving transportation safety for the public. A memorandum that sets forth the NTSB's authority to investigate this accident appears in appendix A.

1.1.1 Background Information

Scaled was responsible for developing a "reliable, reusable, and affordable suborbital commercial space tourism system for Virgin Galactic."[3] Accordingly, Scaled developed and built WK2 as the high-altitude launch platform and SS2 as the reusable suborbital rocket. Figure 1 shows SS2, and figure 2 shows WK2 with SS2 mated.

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[1] All times in this report are Pacific daylight time based on a 24-hour clock. The main wreckage sites were located within a 5-mile area. (All miles in this report are expressed as statute miles unless otherwise noted.) Smaller, lightweight pieces of wreckage were found northeast of the main wreckage sites. The inclusion of this wreckage increased the total length of the wreckage area to about 33 miles, as discussed in section 1.1.4.

[2] Title 14 CFR Part 400 addresses commercial space transportation activities conducted in the United States or performed by a US citizen, and Part 437 addresses experimental permits for such activities. According to 14 CFR 437.9, "Issuance of an Experimental Permit," an experimental permit authorizes an unlimited number of launches and reentries for a particular suborbital rocket design. According to 14 CFR 401.5, "Definitions," a suborbital rocket is "a vehicle, rocket-propelled in whole or in part, intended for flight on a suborbital trajectory, and the thrust of which is greater than its lift for the majority of the rocket-powered portion of its ascent."

[3] Before Scaled received its experimental permit to conduct SS2 rocket-powered test flights, the company prepared an experimental permit application for the FAA/AST's review. Information from the SS2 experimental permit application appears throughout this report. (The SS2 experimental permit history is discussed in section 1.4.2.1.) At the time of the accident, Scaled planned to deliver SS2 to Virgin Galactic in early 2015 after completing flight testing. Virgin Galactic planned to use SS2 and WK2 for commercial space suborbital operations from a spaceport in southern New Mexico. Before the accident, The Spaceship Company, an aerospace production company that Virgin Galactic and Scaled founded, began building a second SS2 vehicle, and Virgin Galactic planned to begin testing this vehicle in 2015. (In October 2012, Virgin Galactic acquired Scaled's interest in The Spaceship Company.) The Spaceship Company took possession of WK2 from Scaled in February 2014.

Source: Scaled Composites.

Figure 1. SpaceShipTwo.

Source: Scaled Composites.

Figure 2. WhiteKnightTwo with SpaceShipTwo mated.

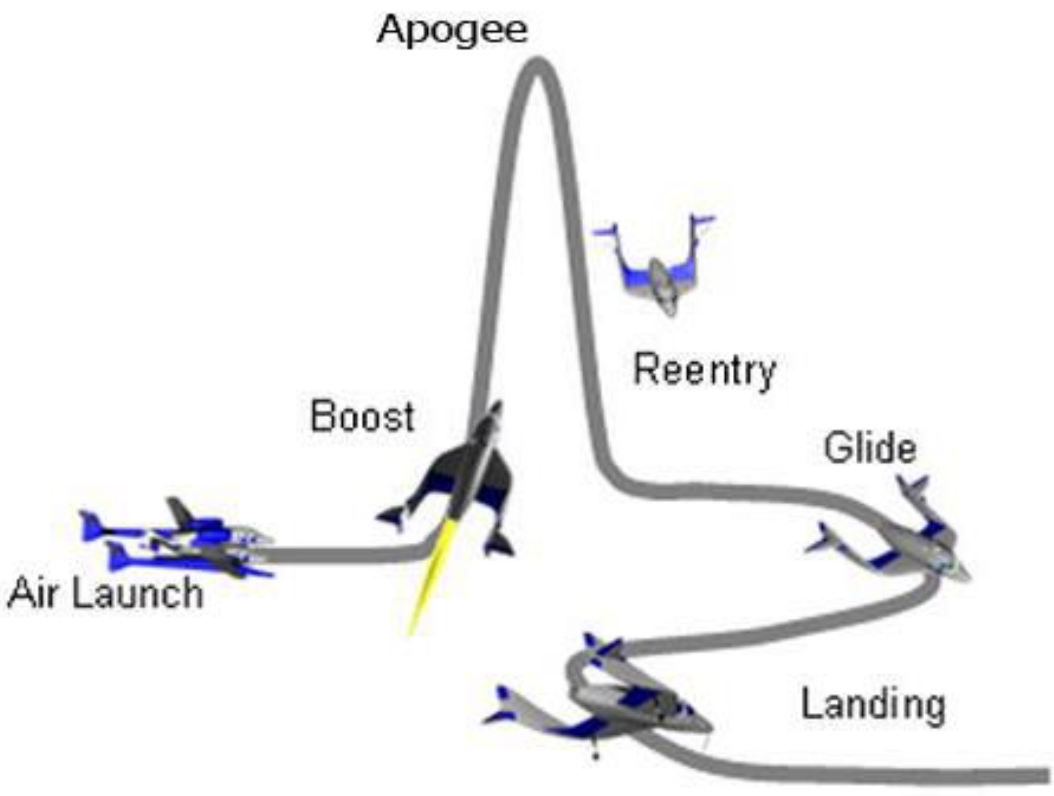
The design mission for SS2 consisted of the following phases:

- air launch from WK2, which occurs at an altitude of about 50,000 ft;
- boost, during which SS2's rocket motor propels the vehicle from a gliding flight attitude to an almost-vertical attitude—the maneuver during which SS2 pitches up from horizontal to vertical flight is referred to as the "gamma turn," which occurs after SS2 accelerates from subsonic speeds, through the transonic region, to supersonic speeds;[4]
- apogee (maximum altitude), which occurs at an altitude of about 360,000 ft or above—the rocket motor is cut off at an altitude of about 150,000 ft, after which SS2 coasts to apogee;
- reentry, which occurs with SS2 in a "feathered" configuration to stabilize SS2's attitude and increase drag;[5]
- glide, which follows SS2's transition from a feathered to an unfeathered configuration; and
- landing (unpowered).

Figure 3 illustrates the different phases of the SS2 design mission. Figures 4 and 5 show the SS2 normal (unfeathered) and feathered configurations, respectively.

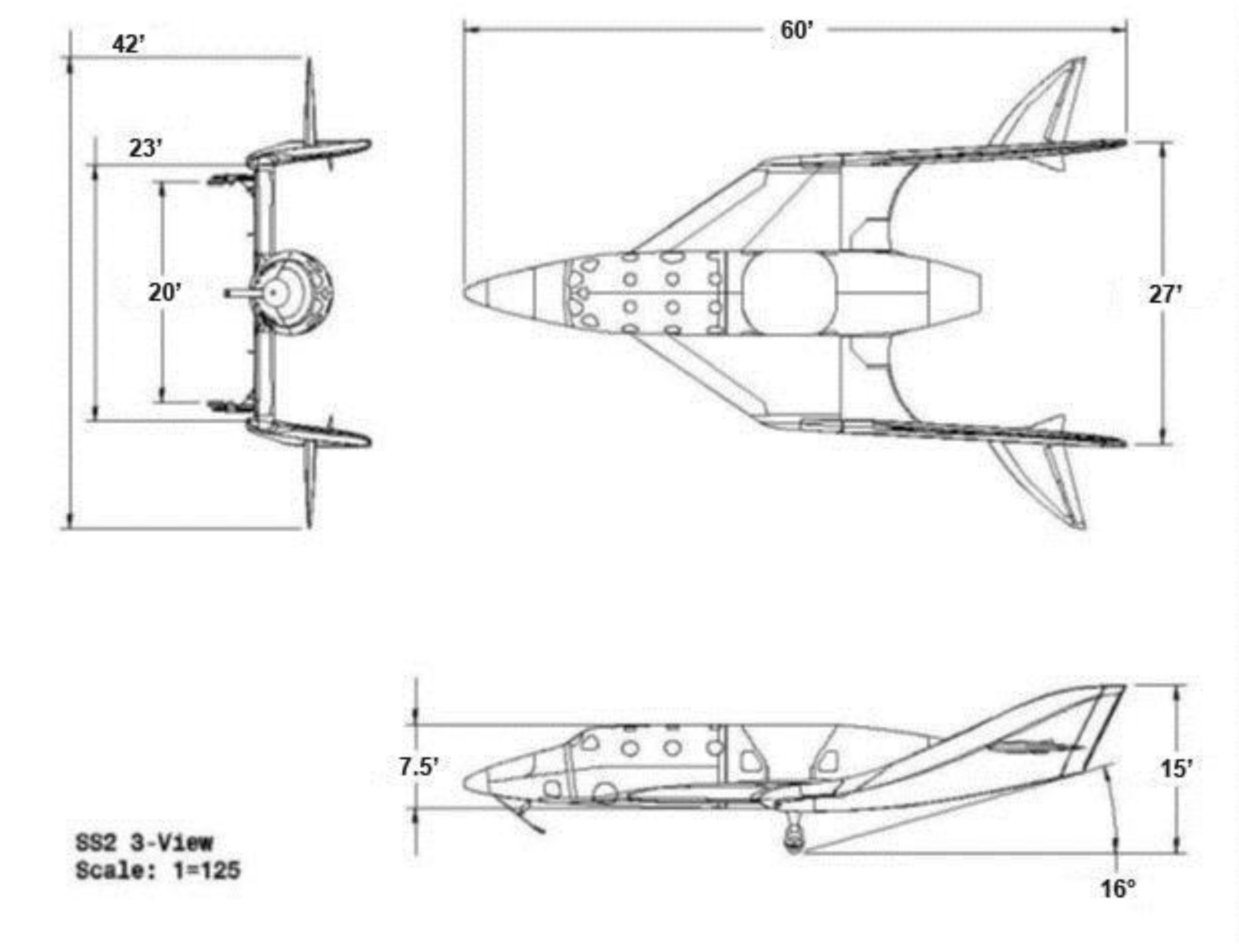
[4] During a postaccident interview, a Scaled design engineer described the transonic region as 0.9 to 1.1 Mach. (The Mach number is the ratio between an aircraft's speed and the speed of sound.) The handbook *Aerodynamics for Naval Aviators* stated that, during the transonic region, "it is very probable that flow on the aircraft components may be partly subsonic [speeds below 0.75 Mach] and partly supersonic [speeds above 1.2 Mach]" (Hurt 1965).

[5] For reentry into the earth's atmosphere, SS2 was equipped with a feather system that rotated a feather flap assembly with twin tailbooms upward from the vehicle's normal configuration (0º) to 60º. The feather system included actuators to extend and retract the feather and locks to keep the feather in the retracted position when not in use. The feather was designed to be manually controlled and pneumatically extended as the indicated airspeed decreased below 20 knots equivalent airspeed and the vehicle neared apogee. Section 1.3.2 provides additional information about SS2's feather system.



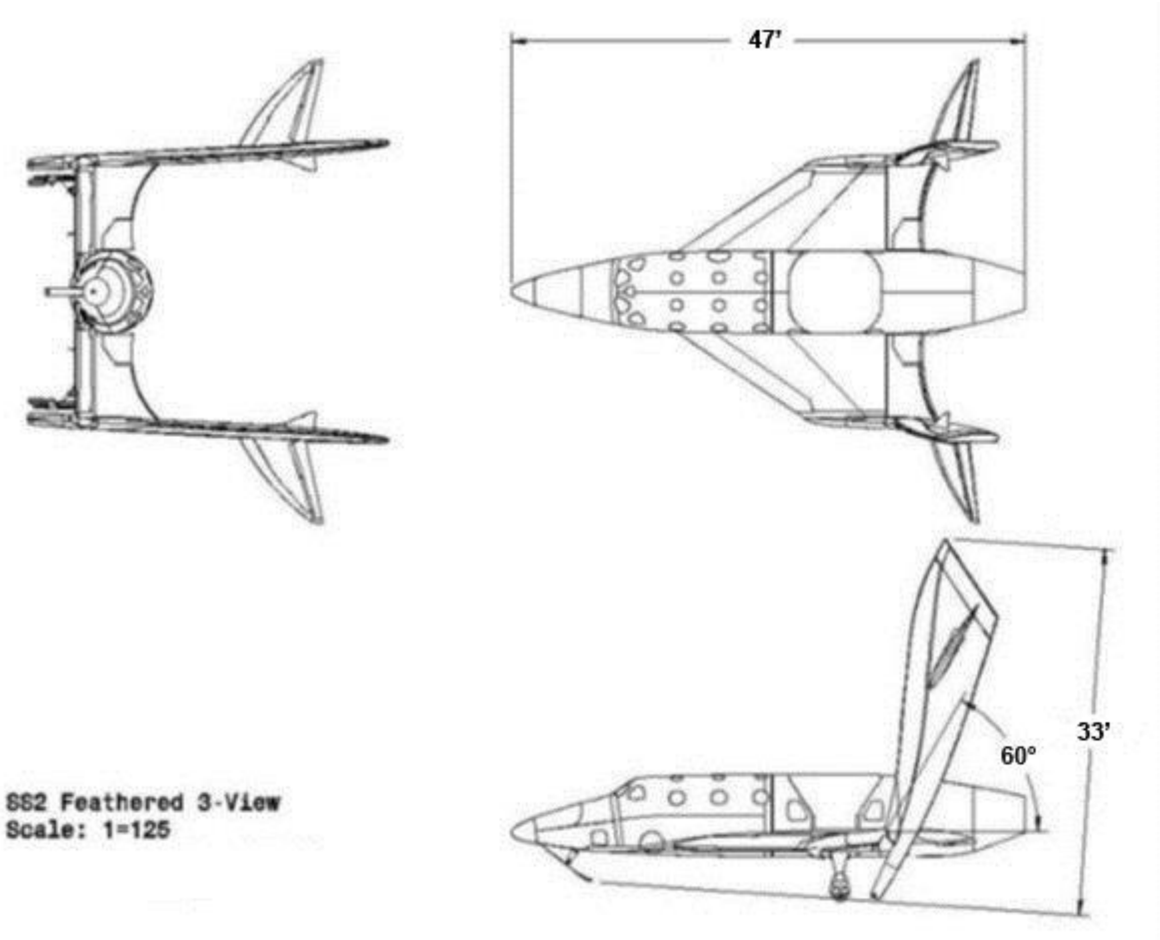
Source: Scaled Composites.

Figure 3. SpaceShipTwo design mission.



Source: Scaled Composites.

Figure 4. Engineering drawings showing SpaceShipTwo's normal (unfeathered) configuration.



Source: Scaled Composites.

Figure 5. Engineering drawings showing SpaceShipTwo's feathered configuration.

During the accident flight, SS2 was flown by two Scaled test pilots. The pilot (in the left seat) was the pilot flying and the pilot-in-command, and the copilot (in the right seat) was the pilot monitoring. WK2 was flown by two test pilots, and a flight test engineer was also aboard. In addition, on the day of the accident, Scaled used an Extra EA-300L single-engine aerobatic airplane, N24GA, as a chase plane.[6]

The accident flight occurred during SS2's fourth powered flight (PF) test (referred to as PF04). The objectives of PF04 included conducting a 38-second burn of a new rocket motor (discussed in section 1.3.3) and a feathered reentry at a speed that exceeded 1.0 Mach (1.2 Mach was planned). The three previous SS2 PF tests occurred on April 29, 2013 (PF01),

[6] For the accident flight, the WK2 pilot was the Virgin Galactic chief pilot, who was acting at the time as a Scaled flight crewmember. The WK2 copilot was a Scaled test pilot, and the flight test engineer was Scaled's SS2 program manager. The Extra EA-300L was operated by Virgin Galactic and was flown by a Virgin Galactic test pilot. A professional photographer was also aboard that airplane.

September 5, 2013 (PF02), and January 10, 2014 (PF03).[7] In addition, SS2 completed 30 glide flights between October 10, 2010, and October 7, 2014.[8]

WK2 (with SS2 mated) was operating from Mojave Airport (MHV), Mojave, California.[9] The PF04 test conductor (a Virgin Galactic test pilot), a test assistant (a Scaled test pilot), and engineers from both companies supported the mission from a control room at Scaled's facilities at MHV. FAA/AST inspectors monitored the flight from Scaled's control room.

Numerous data sources captured the events leading up to the accident. For example, SS2 contained a flight test data instrumentation system, referred to as the Strap On Data Acquisition System (SODAS), that captured critical flight data and used SS2's telemetry system to stream the data to a ground station.[10] These data were displayed in Scaled's control room. The telemetry system included a downlink for two onboard cameras, which were mounted on the left inboard tailboom pointed toward the rocket motor and at the top center of the cockpit pointed forward over the shoulders of the flight crew. In addition, cameras mounted on WK2's right tailboom and release pylon captured SS2's flight, and several ground-based camera systems captured imagery of the flight.

1.1.2 History of Flight

On the day of the accident, the flight crews for WK2 and SS2 and other test team members participated in a briefing from 0500 to 0600. About 0730, the WK2 and SS2 flight crews began their preflight duties at the staging area where the vehicles were located. The pilot and the copilot entered SS2 at 0815:45. WK2 (with SS2 mated) departed at 0919:30.

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[7] The amount of time in between PF03 and PF04 (more than 9 months) was partly due to modifications to the rocket motor.

[8] For these flights, SS2 glided to a landing after release from WK2; the rocket motor was not ignited. During all glide flights, SS2 operated under a special airworthiness certificate. Appendix B provides detailed information about SS2's flights.

[9] MHV is located about 70 miles northeast of Los Angeles, California, at an elevation of 2,801 ft mean sea level. (All altitudes in this report are expressed as mean sea level unless otherwise indicated.) Two of the three runways at MHV support Scaled's operations. The SS2 experimental permit authorized Scaled to conduct "pre-flight and post-flight ground operations at Mojave Air and Space Port," which owns MHV.

[10] The NTSB retained for review 662 parameters captured by the telemetry system. Appendix C describes the numerous recording devices associated with the SS2 investigation, the types of data recorded, and the data recovery results. Appendix D contains the cockpit image recorder transcript. The NTSB relied heavily on the available information from these data sources to accurately determine the events preceding the accident.

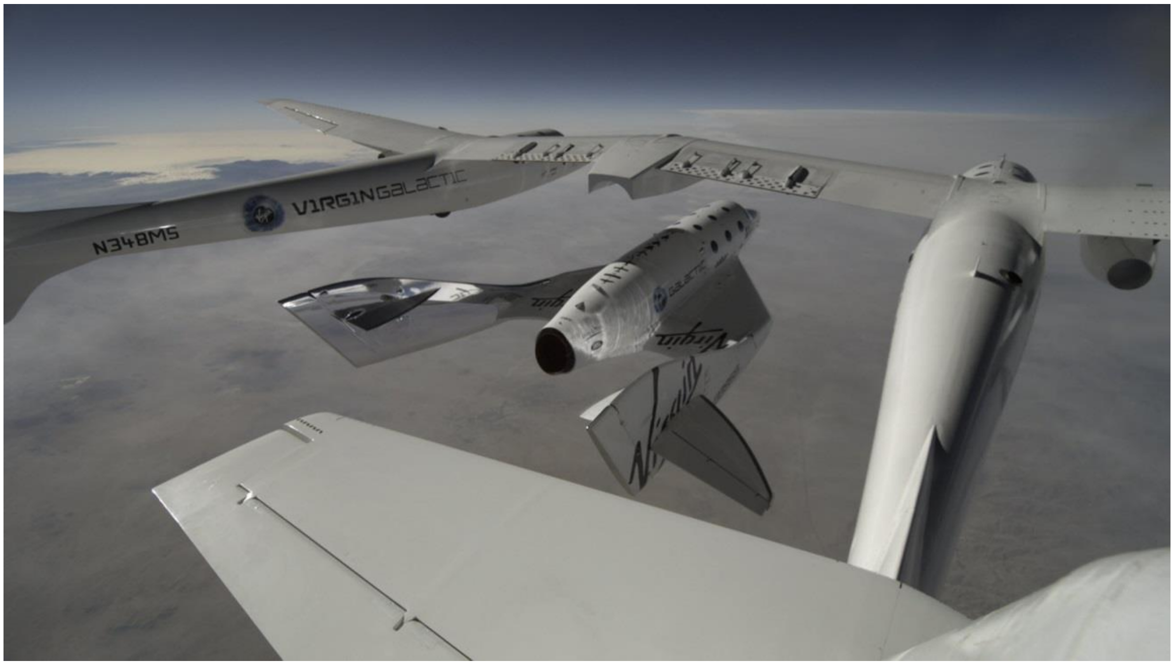
Video from the cockpit image recorder showed that, at 0958:45, the SS2 copilot started the L-10 (launch minus 10 minutes) checklist. As part of this checklist, the copilot verified the operation of the feather locks, including the feather lock and unlock indications on the multifunctional display (MFD) in the cockpit.[11] No anomalies were detected.[12] At 1003:26, the copilot started the L-4 (launch minus 4 minutes) checklist to prepare SS2 for release from WK2. At 1005:39, the pilot briefed the tasks during the boost phase, stating "alright, you're clear to arm, uh, at pylon release, I'll call for fire, and . . . call the pitch up, pitch down, trim, feather unlock one point four."

At 1006:53, the copilot stated that SS2 was 30 seconds from release, and, at 1006:54, a transmission from the control room indicated that SS2 was ready for release. At 1006:57, the pilot stated that the control stick was in the forward position (to maximize separation from WK2 after release), and, at 1007:00, the copilot stated that the launch pylon switch was armed and that the release push button had illuminated (in yellow).[13] At 1007:16, the WK2 copilot began a countdown to the release of SS2. Telemetry data showed that, at 1007:19.1, SS2 released from WK2; about the same time, one of the SS2 pilots commented "clean release." WK2's altitude at the time of SS2 release was about 46,400 ft. Figure 6 shows SS2 after release from WK2 (as captured by the WK2 tailboom camera). After SS2 release, WK2 continued climbing to maximize separation from SS2 before returning to level flight after separation was confirmed.

[11] The SS2 cockpit contained three MFDs—left, right, and center units—that Scaled designed, built, and programmed to provide flight crews with flight, navigation, and system information. The upper half of the left and right displays were normally configured as primary flight displays (PFD). The center display was normally set to the MFD display configuration, and the lower half of each MFD could be reconfigured by a flight crew to display various system pages. In the MFD configuration, the upper right portion of the center display showed crew alert (advisory, caution, and warning) messages.

[12] The feather locks were also cycled during a preflight check to ensure proper operation of the feather lock system. No anomalies with the feather locks were detected during the preflight check.

[13] The launch pylon attached SS2 to WK2. Both SS2 and WK2 were equipped with a launch pylon arm switch and a release push button. The SS2 flight crew armed the launch pylon switch, and the WK2 flight crew (specifically, the WK2 copilot) released SS2 after a countdown to release. After release, the SS2 flight crew armed and fired the rocket motor.



Source: Virgin Galactic.

Figure 6. SpaceShipTwo release from WhiteKnightTwo.

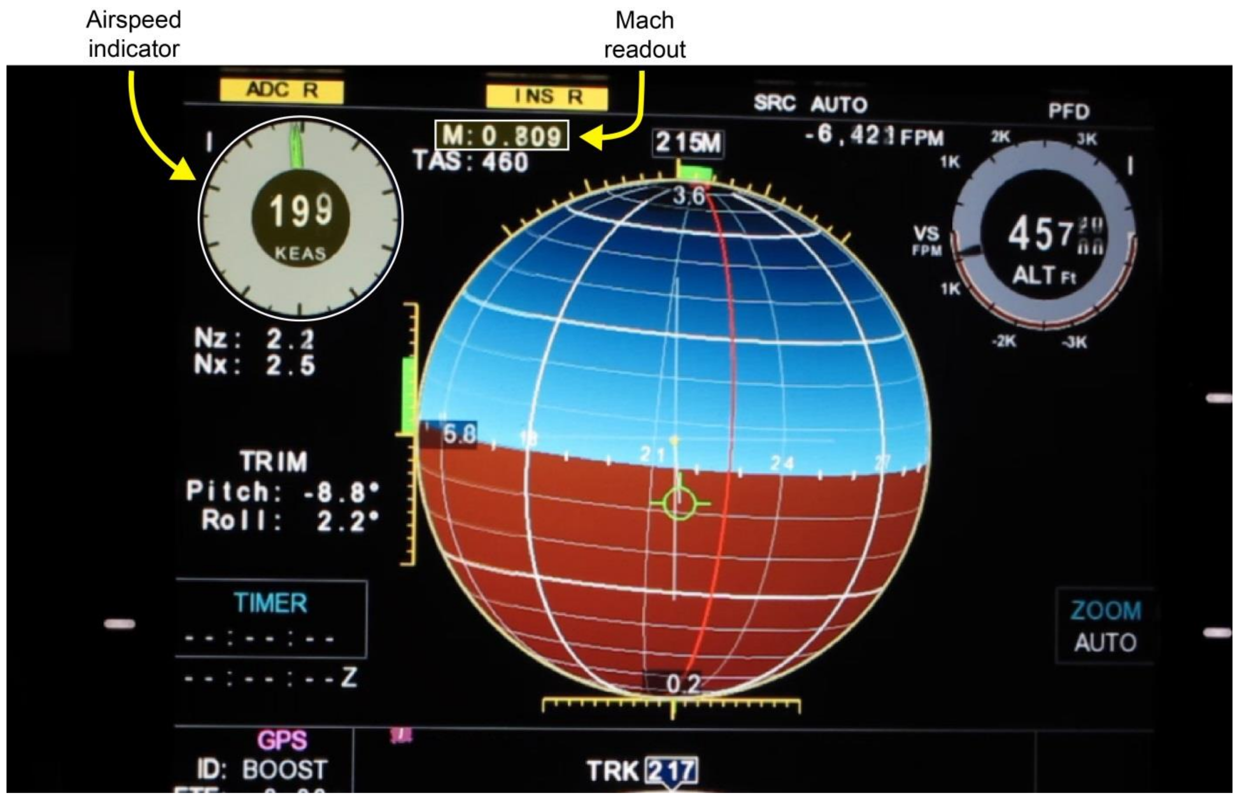
At 1007:19.5, the pilot commanded the copilot to fire the rocket motor. The copilot flipped the "arm" and "fire" switches on the rocket motor control panel, and, at 1007:21.6, the rocket motor started. At 1007:24.5, the pilot commented, "good light."

At 1007:26.9, the copilot made a callout indicating that the vehicle had reached a speed of 0.8 Mach, consistent with the first step on the PF04 flight test data card for the maneuver referred to as "RM2 [rocket motor two] burn" during the boost phase.[14] This and other tasks during the boost phase of flight were memorized due to the dynamic nature of this phase. The purpose of the copilot's 0.8 Mach callout was to alert the pilot that a transonic "bobble" would be occurring as the vehicle accelerated through the transonic region and became supersonic.[15] SS2 pilots stated that the pilot monitoring would determine when to make the 0.8 Mach callout by referencing the digital Mach readout from the upper left portion of the PFD and/or noticing

[14] A flight test data card was standard for every flight and was mission specific. The PF04 flight test data card (revision U) was available to the pilots in the cockpit. The test card included information about vehicle restrictions and limitations, weight and balance, SS2 performance, the mission timeline, and expected pilot and copilot actions during the various phases of flight. Page 7 of the flight test data card included the expected pilot and copilot callouts and actions during the boost phase of flight.

[15] The transonic bobble results from a nose-up motion as the center of lift shifts forward in the transonic region (with supersonic flow over parts of the vehicle) followed by a nose-down motion as the center of lift shifts aft when the vehicle becomes fully supersonic.

the change in background color (from black to gray) on the airspeed indicator that occurs when SS2 reaches a speed above 0.8 Mach, as shown in figure 7.[16]



Source: Scaled Composites.

Figure 7. Primary flight display.

Note: This photograph was taken during a postaccident test and not during the accident flight. The circle around the airspeed indicator and the box around the Mach readout were added to the figure for emphasis.

The PF04 flight test data card indicated that, after the transonic bobble, the pilot was to trim the horizontal stabilizers to -14º (vehicle nose up), and the copilot was to announce the pitch trim position until it reached -14º (the gamma turn setting).[17] The flight test data card showed that the next step was for the copilot to unlock the feather by moving the feather lock handle

[16] Immediately before the copilot's 0.8 Mach callout, the background color of the airspeed and altitude indicators on each pilot's PFD changed from black to gray, indicating that the information source changed from the air data computer (ADC) to the inertial navigation system (INS). The PFD displays were in the AUTO mode. With the AUTO mode, the source of airspeed, altitude, Mach, and vertical speed information would change from the ADC to the INS when SS2's airspeed was above 0.8 Mach, altitude was above 60,000 ft, or feather was extended. An indication in the upper left and right corners of the display would also show an "A" for ADC data or an "I" for INS data.

[17] A trimmable horizontal stabilizer was attached to the outboard side of each tailboom. SS2's horizontal stabilizers are full flying surfaces during supersonic flight and have manual elevon (combination elevator and aileron) surfaces for subsonic flight.

from the locked to the unlocked position when SS2 reached a speed of 1.4 Mach. The copilot did not need to wait for the pilot's instruction to unlock the feather.[18]

The cockpit image recorder showed that, 0.5 second after making the 0.8 Mach callout (1007:27.4), the copilot's left hand was on the feather lock handle.[19] At 1007:28.4, the copilot stated, "unlocking," and the cockpit image recording showed the copilot move the feather lock handle to the right and out of the detent and then down from the locked to the unlocked position.[20] At the time that the copilot stated "unlocking," the displayed speed was about 0.82 Mach.

Telemetry data showed that, at 1007:29.5, both the left and right feather lock positions transitioned from locked to not locked. Immediately afterward, the "FEATHER NOT LOCKED" light illuminated in the cockpit. Telemetry data also showed that the feather started to move at 1007:30.6. The cockpit image recording showed that neither pilot moved another feather handle in the cockpit that would have deployed the feather.

At 1007:31.4, the pilot stated "pitch up," followed by the same comment from the copilot. Figure 8 shows the feather position at 1007:32.0 (as recorded by the SS2 tailboom camera), which was just before the start of SS2's in-flight breakup at an altitude of 46,000 ft. The cockpit image recording ended at 1007:32.8, and the telemetry system data stream ended at 1007:35.

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[18] During postaccident interviews, Scaled engineers and test pilots stated that, because of the high workload during the boost phase of flight, the speed for unlocking the feather was not cross-checked by the pilot flying.

[19] The feather lock handle is shown in figure 12 in section 1.3.2.

[20] The feather lock handle had a detent on the cockpit pedestal structure that acted as a gate. To unlock the handle, a pilot had to move the handle to the right (to bypass the detent) and then down.

Source: Scaled Composites.

Figure 8. Feather position immediately before in-flight breakup.

Note: The movement of the feather can be seen by the angle of the left and right tailbooms compared with the position of the fuselage.

Video evidence (from the SS2 tailboom camera and ground-based camera systems) showed that SS2's structural breakup began in the aft end of the vehicle near the location where the wing and feather flap assembly joined together. During the breakup sequence, the pilot was thrown from the vehicle while still restrained in his seat. During his descent to the ground, the pilot released himself from his seat, and his parachute deployed automatically.[21] The copilot was found restrained in his seat with the cockpit wreckage.[22]

During a postaccident interview with the NTSB, the pilot recalled a very violent, large pitch up with high G forces.[23] He heard a loud "bang" followed very quickly by signs of a rapid cabin depressurization. He also heard a sound in the background that was similar to "paper fluttering in the wind," which he believed was the pieces of the cabin coming apart. That sound was followed by a period in which he had no recollection, which he attributed to a loss of consciousness resulting from the unexpected onset of high G forces.

[21] The pilot reported that he did not pull the parachute system's ripcord handle, and evidence showed that the parachute's automatic activation device deployed the parachute after the pilot had separated from his seat.

[22] The coroner's section of the Kern County (California) Sheriff's Office performed an autopsy on the copilot, which determined that his cause of death was multiple blunt force trauma.

[23] G is a unit of measurement of acceleration; 1 G is equivalent to the acceleration caused by the earth's gravity (about 32.2 ft/sec^2).

The next things the pilot remembered were being outside of SS2, seeing a wide expanse of desert from a high altitude, and falling in a stabilized position. He unfastened his seat belt without difficulty, which allowed him to separate from his seat, and assumed the free-fall position (with his arms out and legs apart). He then experienced another period of unconsciousness (or an absence of memory) until being brought back to consciousness when the parachute opened automatically. He recalled reaching for the emergency oxygen system several times but stated that he did not get any oxygen flow.[24] After descending to the ground, he heard WK2 and the chase plane overhead, and then helicopters landed with emergency response personnel aboard.[25] The first emergency response helicopter landed about 1052, 45 minutes after the accident, as discussed in section 1.1.3.

The pilot stated that he was unaware during the flight that the copilot had unlocked the feather early. The pilot also stated that he and the copilot briefed “multiple” times that the copilot was to unlock the feather at 1.4 Mach. (As stated earlier, the pilot briefed “feather unlock one point four” just before the boost phase of the accident flight.)

Weather was not a factor in this accident. The reported and simulated wind conditions were typical for SS2’s operating altitudes, visual meteorological conditions prevailed at the time of the accident, and the pilots relayed no concerns about the weather during the flight.[26]

1.1.2.1 Analysis of Copilot’s Actions During Flight

During the boost phase of flight, the copilot’s initial responsibility, according to the PF04 flight test data card, was to make a callout at 0.8 Mach to prepare the pilot for the upcoming transonic bobble.[27] To determine when the vehicle had reached 0.8 Mach, the copilot could have referenced the digital Mach readout in the upper left portion of the PFD and to the right of the airspeed indicator and/or noticed the background color of the airspeed indicator change from black to gray as the ADC transitioned to the INS (as previously shown in figure 7).

Instrumentation data and the cockpit image recording showed that, at 1007:26.8, the PFD transitioned from the ADC to the INS, and the airspeed indicator background turned gray. Immediately before the transition, when the ADC was the source for Mach information, the PFD showed that the Mach speed was 0.795. Immediately after the transition (1007:26.9), the copilot

[24] The pilot could not clearly recall when, during his descent, he attempted to activate the emergency oxygen system but stated that he tried to activate it multiple times. Section 1.5 discusses the parachute system, including the emergency oxygen system.

[25] Afterward, WK2 and the chase plane descended and landed uneventfully at MHV. The actions of the WK2 pilots and the operation of the WK2 vehicle were not factors in this accident.

[26] According to upper air data from Edwards Air Force Base (AFB), Edwards, California, at 0500 the wind at an altitude of about 46,000 ft was from 235º at 54 knots. (Edwards AFB is an official upper air sounding site located about 25 miles south of the accident site.) Automated surface observations from Edwards AFB at 0958 indicated clear skies above 25,000 ft (above ground level). The NTSB performed a weather research and forecasting model simulation to determine the wind speed near the accident site about the time of the accident. The simulation showed that the wind speed at 44,500 ft ranged between 67 and 73 knots at 1010 and 1020. The simulation also showed a very low potential for weak turbulence (and no potential for stronger turbulence) at an altitude of 47,000 ft.

[27] The accident pilots might have stated “pitch up” toward the end of the flight because they were expecting SS2 to pitch up and then down during the transonic bobble.

made the 0.8 Mach callout in anticipation of the vehicle reaching 0.8 Mach. At that point, the Mach readout showed 0.705, which was lower than the previously displayed speed due to the different calculations that the ADC and the INS use to compute speeds.[28] Although the copilot might have associated the change of the airspeed indicator background color as a cue of the impending need to make the 0.8 Mach callout, the Mach readout would have been a more reliable source for Mach information. Thus, the copilot was most likely using the Mach indication to make the callout.

The 0.8 Mach callout was intended to be only a verbal indication from the copilot to the pilot; the callout did not require the copilot to take any physical action. The next steps on the PF04 flight test data card were for the pilot to begin trimming the horizontal stabilizers; the copilot to call out the pitch trim positions; and, at 1.4 Mach, the copilot to move the feather lock handle to unlock the feather. However, the cockpit image recording showed that the copilot began moving the feather lock handle to the full unlocked position just after the 0.8 Mach callout, when SS2's speed was 0.82 Mach, which occurred about 9.8 seconds after release. The NTSB's postaccident simulator tests showed that SS2 would likely have reached 1.4 Mach between 23 and 26 seconds after release.[29]

Because the copilot moved the feather lock handle prematurely, the NTSB considered whether he might have misread another digital indication near the digital Mach readout. The copilot would not have needed to refer to SS2's normal and longitudinal acceleration values (Nz and Nx, respectively) to accomplish his tasks during the boost phase; however, the Nz and Nx indications appeared below the airspeed indicator, and the Mach readout appeared to the right of the airspeed indicator in the same size and color font as Nz and Nx.[30]

When the copilot made the 0.8 Mach callout (at 1007:26.9), the PFD displayed Mach at 0.705 with Nz at 1.0 and Nx at 2.4. When the copilot's left hand was on the feather lock handle (at 1007:27.4), the PFD depicted 0.75 Mach with Nz at 1.3 and Nx at 2.5. When the copilot stated "unlocking" and the cockpit image recording showed him beginning to move the feather lock handle out of the detent and toward the unlocked position (at 1007:28.4), the PFD indicated 0.82 Mach with Nz at 2.3 and Nx at 2.5.

Because the Nz and Nx values were above 0.8 when the copilot made the 0.8 Mach callout, it is unlikely that he confused the Nz and Nx values for Mach at that time. Between the time of the copilot's 0.8 Mach callout and his statement that he was unlocking the feather, Nx remained relatively constant, so it is also unlikely that he misinterpreted the Nx value as the Mach indication. Even though Nz passed through a reading of 1.4 before the copilot stated that he was unlocking the feather, he would not likely have been attending to both the Mach and Nz indications in close succession and thus misinterpreted the Nz value as the Mach indication.

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[28] The INS computes SS2's speed relative to the earth, and the ADC computes the vehicle's speed relative to air. Because SS2 was flying into a headwind, the speed relative to the earth was less than the speed relative to air.

[29] The NTSB observed multiple test runs in Scaled's SS2 simulator. One objective of the tests was to document the timing from release to the 0.8 Mach callout and release to 1.4 Mach.

[30] The SS2 avionics project engineer did not recall any discussion on font size or the use of any reference for determining font size.

In addition, the copilot flew SS2 on previous glide flights and one previous powered flight (PF01), so he was familiar with the location of the Mach readout on the PFD. Scaled's SS2 simulator logs showed that, during 13 days of simulator work between August 12 (after the initial release of the PF04 flight test data card) and October 30, 2014 (the day before the accident), the copilot participated in 112 SS2 simulator runs (65 of which occurred during the month leading up to PF04), so he would have been familiar with the 0.8 Mach callout procedure.[31] There were no indications, from simulator logs and notes and postaccident interviews with pilots who flew with the copilot or observed him in the simulator, that he had previously misread information on the PFD or had mistakenly used the information from another PFD indication as the basis for making the 0.8 Mach callout. Although the feather was not unlocked during PF01 due to the limited boost time, before PF04 the copilot performed numerous simulations in which the feather was unlocked at 1.4 Mach, and there were no reports that he unlocked the feather before the appropriate speed during training.[32]

The NTSB concludes that, although the copilot made the required 0.8 Mach callout at the correct point in the flight, he incorrectly unlocked the feather immediately afterward instead of waiting until SS2 reached the required speed of 1.4 Mach. The copilot's action of unlocking the feather after the 0.8 Mach callout (which was inconsistent with his training and the steps on the PF04 flight test data card) occurred during a particularly dynamic and high workload phase of flight. Workload is characterized not only by task demands but also by mental, physical, and temporal (time) demands (Hart and Staveland 1988). With high workload, cognitive resources are limited, and performance decrements can occur.

Because of the dynamic nature of the boost phase, the copilot memorized his three tasks to be accomplished during that phase: calling out 0.8 Mach, calling out the pitch trim position in degrees as the pilot trimmed the horizontal stabilizers, and unlocking the feather at 1.4 Mach.[33] In addition to recalling these tasks from memory, each of the tasks needed to be accomplished in a limited time frame.[34] Postaccident simulator testing showed that the 0.8 Mach callout occurred about 8 to 10 seconds after release, the trim callouts occurred less than 2 seconds after 0.8 Mach, and 1.4 Mach occurred about 13 to 14 seconds after the trim callouts. As explained further in section 1.3.2.1, if the feather was not unlocked by the time SS2's speed reached 1.5 Mach, a caution message would annunciate on the center MFD.[35] Also, if the feather was still not unlocked by the time that SS2's speed reached 1.8 Mach, the flight would have to be aborted to

[31] A Scaled test pilot stated that the simulator replicated the bobble during transonic flight. Section 1.4.1.1 discusses further information about the flight crew's simulator training.

[32] During a simulator run on October 27, 2014, the copilot unlocked the feather after 1.4 Mach (after he received a caution message on the MFD); this situation was debriefed afterward.

[33] The cockpit image recording showed that the copilot had the PF04 flight test data card on his kneeboard but that he did not appear to reference the test card after release from WK2. (The cockpit image recording showed that the copilot had referenced the SS2 normal procedures manual to complete the prerelease checklists.) Scaled test pilots confirmed that pilots would not reference the flight test data card during the boost phase of flights because of the high workload.

[34] Time pressure has been shown to increase the rate at which an individual must process information, which can lead to cognitive overload. To compensate for time pressure, there is often a tradeoff of speed versus accuracy; specifically, the individual might work and make decisions quickly at the expense of reviewing all available information, which will degrade performance (Driskell and Salas 1996).

[35] The NTSB's postaccident simulator tests showed that about 2.7 seconds elapsed between 1.4 and 1.5 Mach.

mitigate the hazard resulting from a potential reentry with the feather down due to a lock failure. Because of the importance of unlocking the feather before 1.8 Mach, the copilot might have been anxious to unlock the feather to avoid aborting the flight. Thus, time pressure was likely a stressor that contributed to the copilot incorrectly recalling the sequence of his tasks and unlocking the feather prematurely.

Another stressor during the boost phase that could have contributed to the copilot's workload was the operational environment, specifically, the vibration and loads. Between the time of the copilot's 0.8 Mach callout and his movement of the feather lock handle toward the unlocked position, Nz increased from 1.0 to 2.3 Gs, and Nx increased from 2.4 to 2.5 Gs. The cockpit image recording showed that the pilots' voices were strained and that the copilot did not initially place his hand on the feather lock handle in the correct place. After adjusting his hand, the copilot appeared to be leaning forward and into a downward unlocking motion with his left arm and shoulder, which was likely the result of the vibration and loads that he experienced with the rocket motor ignited.

The vibration levels during the flight would not have impeded the copilot's ability to read the PFD because, as shown on the cockpit image recording, the copilot did not have his head on the seat headrest; keeping his head off the headrest would have minimized any degrading effects of vibration. However, the copilot did not have recent experience with the vibration and loads that occurred during the flight. The vibration and loads experienced during powered flight were not replicated in the simulator (as discussed in section 1.4.1.5), and the copilot had not flown SS2 under power since PF01 in April 2013. The lack of recent experience with powered flight vibration and loads could have increased the copilot's stress and thus his workload during a critical phase of flight.

The NTSB concludes that the copilot was experiencing high workload as a result of recalling tasks from memory while performing under time pressure and with vibration and loads that he had not recently experienced, which increased the opportunity for errors. The NTSB notes that Scaled did not recognize and mitigate the possibility that a test pilot could unlock the feather early, as discussed in section 1.4.1.

1.1.3 Emergency Response

The Extra EA-300L chase plane pilot witnessed the accident and made numerous notifications to Scaled, air traffic control (ATC), and other aircraft during the 45 minutes after the in-flight breakup of SS2 became apparent (at 1007:36). The chase plane pilot reported observing a parachute at 1010:06, which indicated to him that at least one pilot had most likely survived the accident. About 1.5 minutes later, the chase plane pilot reported that the main sections of SS2 were on the ground and then requested that search and rescue forces respond to the Koehn Dry Lake area.

The MHV airport manager and the Kern County Fire Department (KCFD) on-scene commander at MHV learned about the accident as they listened to the transmissions between Scaled's control room and the SS2 flight crew. After the accident, the MHV airport manager drove directly to the National Test Pilot School (NTPS), which was located at MHV, and arranged for the school's UH-1N helicopter to launch to the accident site. Because this helicopter was not part of the preplanned response (as discussed in the next section), the helicopter had to be pulled from its hangar and preflighted. The NTPS helicopter, which departed about 1041 with a pilot, an MHV firefighter/emergency medical technician (EMT), and a flight surgeon aboard, was the first helicopter to land at the pilot's location, arriving about 1052.

About 1007, the KCFD on-scene commander at MHV sent a text message to the pilot of a KCFD UH-1H helicopter (referred to as helicopter 408), indicating that there were problems with the test flight and that he should "get ready" to respond. About 1018, the on-scene commander sent another text message to the pilot of helicopter 408, instructing him to launch to the accident scene. The helicopter pilot reported that, because this method of dispatch was not standard operating procedure, he had to await dispatch instructions from the Kern County Emergency Communications Center, which provided dispatch instructions about 1023, 5 minutes after the on-scene commander's instruction to launch. Helicopter 408 departed from KCFD's helibase in Keene, California, about 1030 with a pilot, an EMT/paramedic, and the KCFD captain among those aboard and arrived at the pilot's location about 1057.

The medical personnel from the NTPS and KCFD helicopters approached the pilot, and the MHV firefighter/EMT immediately requested, through the KCFD captain, the dispatch of a Mercy Air Bell 407 helicopter.[36] The medical personnel began administering first aid and preparing the pilot for transport to a local hospital.

At the time of the accident, the Mercy Air helicopter was conducting a maintenance test flight over MHV. The helicopter landed at Mercy Air's hangar a few minutes after the NTPS helicopter departed for the accident site and was immediately put back into service. The Kern County Emergency Communications Center placed the Mercy Air helicopter on standby. A Mercy Air flight nurse called the center and asked if the helicopter should launch, but she was told that the helicopter should remain on standby. About 1100, Mercy Air personnel heard a request over the radio for the helicopter to respond to the accident site, and the emergency communications center dispatched the helicopter at that time. The helicopter departed with a pilot, flight nurse, and flight paramedic aboard and arrived at the pilot's location about 1116. The pilot was placed into the Mercy Air helicopter, which departed the accident site about 1123 and arrived at a local hospital about 1153, 1 hour 46 minutes after the accident.

1.1.3.1 Analysis of Emergency Response

Consistent with the routine established for previous powered flights, Scaled provided a safety briefing to MHV personnel and local emergency responders 3 days before PF04 was to occur. The briefing discussed the PF04 planned timeline of events, operation locations, risks, safety zones, and contingency and emergency operations. The briefing also included a PowerPoint presentation; one slide stated that, if an in-flight emergency were to occur, the

[36] Mercy Air was a full-service air medical transport system that operated an advanced life support helicopter at MHV. The helicopter was operated under contract to KCFD and could only be dispatched through the Kern County Emergency Communications Center.

control room should immediately contact ATC and follow the established mishap response protocols.[37]

In addition, the MHV airport manager provided a briefing to the local emergency responders about 0600 on the day of the flight. According to PowerPoint slides from the briefing, the KCFD assistant chief would direct an off-airport response, and helicopter 408 would be one of the KCFD assets that would respond. However, KCFD helicopter 408 was not prepositioned at MHV, even though a KCFD helicopter had been prepositioned at MHV for the three previous SS2 powered flights. According to Scaled, during the October 28, 2014, safety briefing, a KCFD representative suggested keeping helicopter 408 at its base in Keene (about 37 miles from MHV) for PF04 to minimize response times in case the helicopter were to be dispatched to a situation near the helibase. None of the meeting attendees, which included representatives from Scaled, Virgin Galactic, MHV, the Kern County Sheriff's Office, and the FAA/AST, objected to this suggestion.

The MHV airport manager stated that one of the main reasons for prepositioning a KCFD helicopter at MHV for the previous SS2 powered flights was because of the frequency of localized morning fog in Keene, which could hinder emergency response operations.[38] According to the pilot of KCFD helicopter 408, he received notification about PF04 the night before the flight and was told to remain on standby in Keene. The helicopter pilot reported that he normally received notification of an SS2 powered flight about 2 to 4 days before the flight was scheduled to occur.

The MHV airport manager believed that the Mercy Air helicopter was on standby for the test flight. However, during a postaccident interview, the Mercy Air lead pilot and the flight nurse who responded to the accident stated that Mercy Air staff was not included in briefings before test flights or other activities at MHV and was not on standby for PF04.

Figure 9 is a timeline of the emergency response to the SS2 accident. The timeline shows that the first helicopter (the NTPS helicopter) arrived at the pilot's location 45 minutes after the accident and that the helicopter transporting the pilot to the hospital (the Mercy Air helicopter) departed the scene 1 hour 16 minutes after the accident.

[37] To meet its obligations under 14 CFR 431.45, 437.41, and 437.75(b), Scaled developed a mishap investigation plan and an emergency response plan for the SS2 program. According to the emergency response plan, if a mishap were to occur, Scaled was to notify the MHV ATC tower, which would notify the East Kern Airport District aircraft rescue and firefighting (ARFF) at MHV. ARFF would then notify the Kern County Emergency Communications Center about the mishap, which would initiate a three-engine response from KCFD, the Kern County Sheriff's Office, and the California Highway Patrol.

[38] It is unknown whether the test flight would have occurred if KCFD helicopter 408 would have been unable to fly due to weather on the morning of the accident.

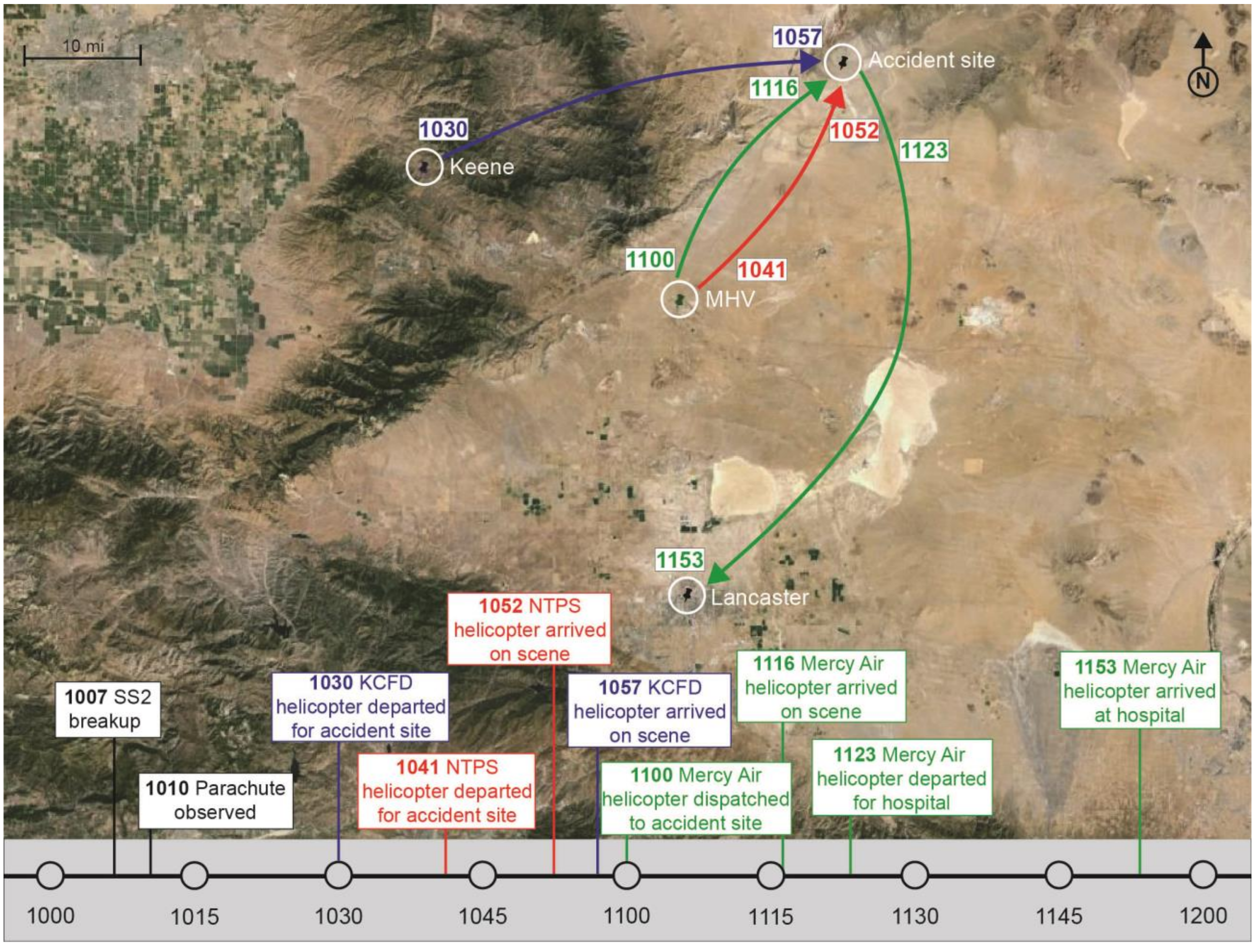

Figure 9. Emergency response timeline.

The NTSB is concerned that Scaled conducted a high-risk flight test without the on-airport presence of a helicopter that was specifically prepared for and tasked with supporting an emergency response. The KCFD helicopter, which was not prepositioned at MHV but was a designated asset for responding to an off-airport emergency, arrived at the injured pilot's location 39 minutes after the on-scene commander's instruction to respond to the accident. The Mercy Air helicopter, which was located at MHV and had advanced life support capabilities, arrived at the injured pilot's location 16 minutes after being dispatched, even though the helicopter was not designated to be part of the preplanned response to a potential accident. The NTSB determined that, if Mercy Air had been briefed ahead of time about the flight and dispatched immediately after the Extra EA-300L chase plane pilot observed a parachute, the Mercy Air helicopter could have arrived at the pilot's location about 45 minutes earlier.[39] The NTSB concludes that Scaled Composites and local emergency response officials could improve their emergency readiness for future test flights by making better use of available helicopter assets.

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[39] This estimate is based on the time that the KCFD helicopter was instructed to launch to the accident scene and the flight time from Mercy Air's hangar to the injured pilot's location.

Other commercial space operators could benefit from the emergency response lessons learned from this accident investigation. According to its website, the Commercial Spaceflight Federation's mission is to "promote the development of commercial human spaceflight, pursue ever higher levels of safety, and share best practices and expertise throughout the industry." Members of the Commercial Spaceflight Federation include commercial space flight developers, operators, and spaceports; thus, the Commercial Spaceflight Federation is in an ideal position to provide information to numerous commercial space flight organizations about the importance of emergency response procedures and planning.[40] Therefore, the NTSB recommends that the Commercial Spaceflight Federation advise commercial space operators to work with local emergency response partners to revise emergency response procedures and planning to ensure that helicopter and other resources are appropriately deployed during flights.

1.1.4 Wreckage and Instantaneous Impact Point Information

The main wreckage sites were contained within a 2.5-square mile area that was about 5 miles long by 0.5 mile wide. The main wreckage sites comprised the following major individual impact sites (from southwest to northeast): (1) rocket motor, (2) forward pressure tank, (3) cockpit and nose section, (4) left feather actuator, (5) main oxidizer tank and wings, (6) pilot's seat, (7) left tailboom, (8) torque tube, (9) right tailboom, and (10) pilot's parachute. As previously stated, smaller, lightweight pieces of wreckage were also found between the main wreckage sites and the Ridgecrest, California, area (northeast of the main wreckage sites).[41] The inclusion of this wreckage increased the total length of the wreckage path to about 33 miles.

According to 14 CFR 401.5, the instantaneous impact point (IIP) is "an impact point, following thrust termination of a launch vehicle, calculated in the absence of atmospheric drag effects."[42] Title 14 CFR 437.57, "Operating Area Containment," stated that, during each permitted flight, a reusable suborbital rocket's IIP must be contained within an operating area that (1) is large enough to contain each planned trajectory and all expected vehicle dispersions and (2) has enough unpopulated or sparsely populated area to perform key flight-safety events.[43] Section 437.57 also stated that the IIP could not contain, or be adjacent to, a densely populated area or large concentrations of members of the public and significant automobile, railway, or waterborne vessel traffic. In addition, section 437.57 stated that the IIP must remain outside any

[40] Scaled, Virgin Galactic, and the Mojave Air and Space Port are members of the Commercial Spaceflight Federation. Additional information about the Commercial Spaceflight Federation appears on its website (www.commercialspaceflight.org, accessed June 15, 2015).

[41] The most distant fragment was found about 27 miles northeast of SS2's breakup point. This and other lightweight pieces of debris from the vehicle were carried northeast by the wind.

[42] The *Guide to the Identification of Safety-Critical Hardware Items for Reusable Launch Vehicle (RLV) Developers* stated that "the Instantaneous Impact Point (IIP) is the location on the earth's surface where the vehicle would impact if it were to stop thrusting at any given moment. The IIP is used in recognition of the fact that in the event of catastrophic failure, the vehicle is unlikely to impact at the point directly below where the failure occurred. Its energy will carry it away from that point" (American Institute of Aeronautics and Astronautics 2005).

[43] Release from WK2 and ignition of a primary rocket motor are considered to be key flight-safety events according to 14 CFR 437.59, "Key Flight-Safety Event Limitations."

exclusion zone (within an operating area) designated by the FAA to protect public health and safety, safety of property, or US foreign policy or national security interests.[44]

SS2 flight operations for PF04 were to occur within restricted airspace in an area referred to as R-2508. In its experimental permit application, Scaled indicated that this area, which was created to contain military and civilian flight test activities, was "ideal" for SS2 operations because it was away from most high-density population areas and had "well-documented procedures and processes for test flights" and air traffic controllers who were "well-trained in test flight operations." Thirteen exclusion zones within R-2508 were in effect for PF04.

SS2 pilots could monitor the vehicle's position within R-2508 using the MFD, which continuously calculated the IIP from inertial data. The IIP was displayed on the moving map page of the MFD as a small yellow circle, which allowed the pilots to visually follow the IIP relative to the operating area boundaries. The MFD also calculated the distance between the IIP and the nearest operating area boundary.[45]

As part of the vehicle performance study for this accident, the NTSB reviewed the latitude and longitude coordinates of SS2's IIP, which were computed by SS2 inertial data and recorded in the telemetry data; the R-2508 restricted airspace, including the 13 exclusion zones; and WK2's and SS2's flightpaths. The study showed that, throughout PF04, SS2's IIP and the key flight-safety events (release from WK2 and rocket-powered flight) remained within R-2508 and outside of the exclusion zones, as required. The study further found that the main wreckage locations (described earlier in this section) were also within R-2508 and outside of the exclusion zones.[46] Figure 10 depicts this information. The NTSB concludes that SS2's IIP on the day of the accident was consistent with the requirements of 14 CFR 437.57.

[44] Title 14 CFR 437.57(c) states, "the FAA may prohibit a reusable suborbital rocket's instantaneous impact point from traversing certain areas within an operating area by designating one or more areas as exclusion areas, if necessary to protect public health and safety, safety of property, or foreign policy or national security interests of the United States. An exclusion area may be confined to a specific phase of flight." In this report, the term "exclusion zone" is synonymous with the term "exclusion area."

[45] The MFD would generate a caution message if the calculated distance to the boundary was less than a specified threshold. The MFD would generate a warning message if the IIP was calculated to be on or outside the operating area boundary.

[46] The most distant fragment was found on a golf course inside the Ridgecrest exclusion zone, but 14 CFR Part 437 regulations require that only the IIP and key flight-safety events remain outside exclusion zones.

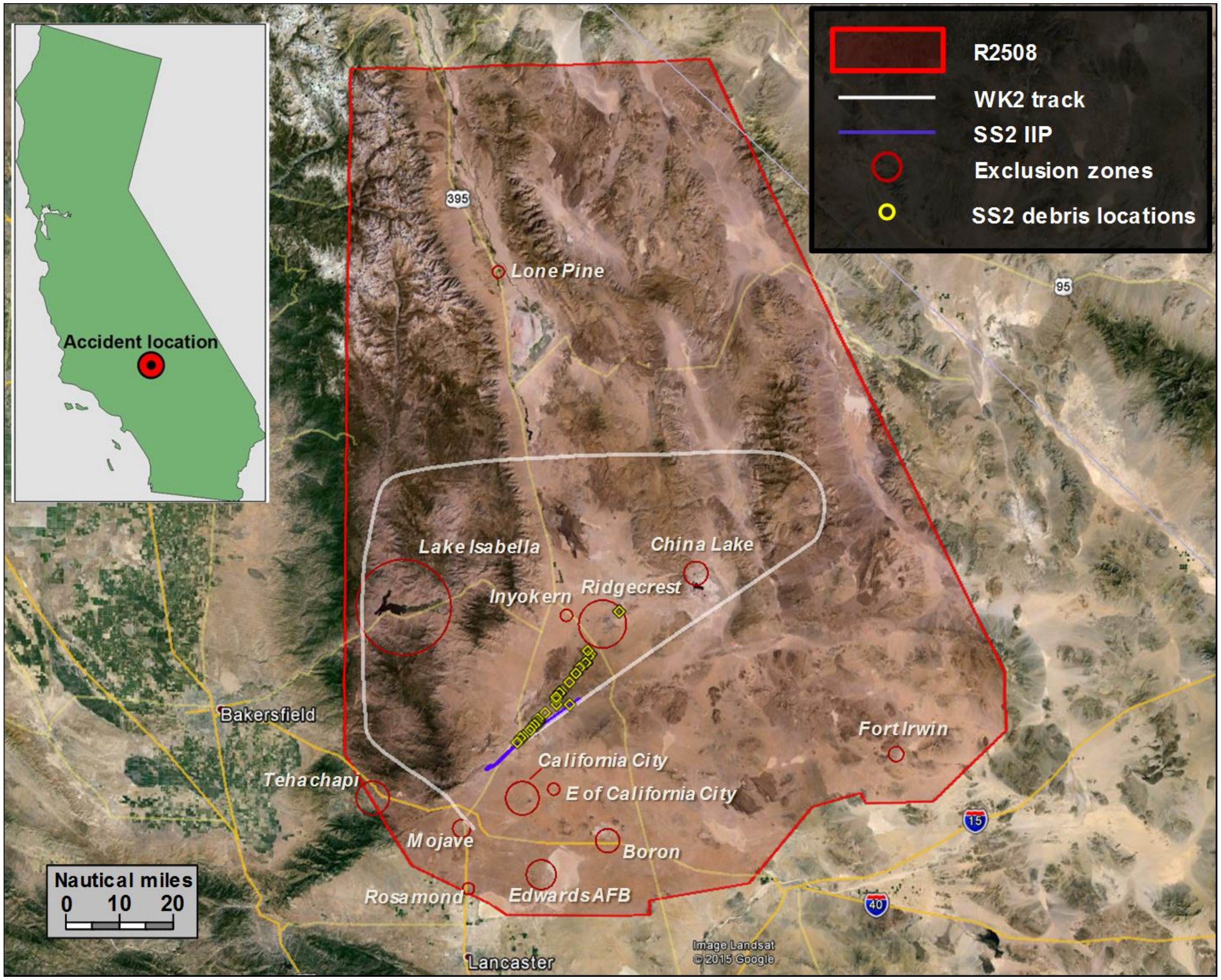

Figure 10. R-2508 operating area and main wreckage locations.

1.2 Flight Crew Information

The accident pilot and copilot were part of the initial cadre of test pilots for WK2 and SS2. Scaled records showed that the pilot and copilot had flown together in SS2 three times before the accident flight—on October 10, 2010, for the first glide flight; June 26, 2012, for the 17th glide flight; and August 28, 2014, for the second cold flow flight.[47] Additional information about the pilot and copilot appears in the sections that follow.

1.2.1 Certifications and Experience

1.2.1.1 The Pilot

The pilot, age 43, held a commercial pilot certificate with ratings for airplane single-engine and multiengine land, instrument airplane, and glider. He had FAA authorization to operate the SpaceShipOne (SS1), Proteus, SS2, and WK2 experimental aircraft as the pilot-in-command.[48] He also held a flight instructor certificate with ratings for airplane single-engine and multiengine instrument airplane. According to FAA records, the pilot added the SS2 experimental authorization to his commercial pilot certificate on January 17, 2014, and his flight instructor certificate was renewed on October 25, 2014. A review of FAA records for the pilot indicated no previous aviation-related accidents, incidents, or enforcement actions. The pilot held a second-class medical certificate, dated August 22, 2014, with no limitations.[49]

The pilot was hired by Scaled in December 1996 as a design engineer. He had been a test pilot for the SS1 program and was responsible for developing the simulator, avionics/navigation system, and ground control system for the program. The pilot transitioned to the WK2 program in December 2008 and the SS2 program in July 2010. In addition to his role as a test pilot with the SS2 program, the pilot was Scaled's director of flight operations. He had been in that position since June 2008. His responsibilities included overseeing flight test and normal flight operations, selecting and managing flight crews, scheduling flight crews, and providing training and currency opportunities for flight crews. He was also responsible for flight operations safety. A review of employee records did not reveal any disciplinary actions against the pilot.

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[47] Scaled conducted cold flow tests in April 2013 and August 2014. During these tests, nitrous oxide flowed through SS2's propulsion system (with no fuel present) after release from WK2. Afterward, SS2 glided to a landing.

[48] An FAA authorization to operate an experimental aircraft as a pilot-in-command is similar to a type rating. The eligibility and application for and the issuance and limitations of an FAA authorization are also similar to a type rating. At the time of the accident, the pilot's most recent FAA authorization for SS2 was dated January 17, 2014; WK2 was dated October 2, 2013; Proteus was dated January 8, 2014; and SS1 was dated October 1, 2004. These authorizations did not have an expiration date. SS1, the predecessor to SS2, was developed and built by Scaled as a suborbital vehicle that used a feather configuration for reentering the atmosphere. (WhiteKnight, the predecessor to WK2, was the launch platform for SS1.) SS1's last flight occurred on October 4, 2004. Scaled's website (www.scaled.com, accessed June 15, 2015) contains information about the Proteus experimental aircraft.

[49] For rocket-powered flight tests in which WK2 and SS2 were operating as a launch system under an FAA/AST experimental permit, SS2 pilots (and WK2 pilots) were required to meet the provisions of 14 CFR Part 460, "Human Space Flight Requirements," Subpart A, "Launch and Reentry With Crew." Scaled required SS2 test pilots to have a commercial pilot certificate with an instrument rating and a current second-class medical certificate, which met the provisions of section 460.5, "Crew Qualifications and Training," paragraphs (c)(1) and (e), respectively.

The accident pilot was the pilot of SS2 for 13 glide flights between October 10, 2010, and August 28, 2014.[50] He was also an instructor pilot, occupying the right seat of SS2, for the glide flights on July 29 and October 7, 2014. PF04 was the accident pilot's first powered test flight aboard SS2. He was the pilot during a powered test flight aboard SS1 on April 8, 2004.

According to Scaled records, the pilot had accumulated 2,980 hours total flying time, including 2,550 hours as pilot-in-command and 49 hours in SS2. He had flown 42 hours in the last 90 days, 2 hours in the last 30 days, and 0.7 hour in the 24 hours before the accident.[51] Scaled pilot training records showed that the accident pilot received SS2 systems and procedures ground training on November 26, 2013.

1.2.1.2 The Copilot

The copilot, age 39, held an airline transport pilot (ATP) certificate with a rating for airplane multiengine land and commercial pilot privileges for airplane single-engine land and sea and glider. He had FAA authorization to operate the Proteus and Ares experimental aircraft as the pilot-in-command.[52] He also held a flight instructor certificate with ratings for airplane single-engine and multiengine instrument airplane. According to FAA records, the copilot received his ATP certificate on December 16, 2013, and his flight instructor certificate was renewed on June 3, 2014. A review of FAA records for the copilot indicated no previous aviation-related accidents, incidents, or enforcement actions. The copilot held a second-class medical certificate, dated May 22, 2014, with the limitation that he must wear corrective lenses. The cockpit image recording showed that the copilot was wearing glasses during the accident flight.

The copilot was hired by Scaled in January 2000 as an engineer in the company's flight test data analysis department. He transitioned to the WK2 program in June 2009 and the SS2 program in July 2010. In addition to his role as a test pilot with the SS2 program, the copilot was a project engineer for two other Scaled programs. A review of employee records did not reveal any disciplinary actions against the copilot. He had received commendations for his performance at work and was part of a Scaled team that received two awards in 2014.

The accident copilot was the copilot of SS2 on seven glide flights occurring between October 10, 2010, and August 28, 2014.[53] He had been the copilot of SS2 for PF01 in April 2013.

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[50] The accident pilot was also the WK2 pilot for 11 SS2 glide flights occurring between October 28, 2010, and August 11, 2012. In addition, he was the pilot, copilot, or instructor pilot for 60 WK2 flights between December 2008 and July 2014.

[51] The pilot's flight time for the 30 days and 24 hours before the accident included the time during the accident flight when SS2 was mated to WK2.

[52] At the time of the accident, the copilot's most recent FAA authorizations to operate the Proteus and Ares experimental aircraft were dated January 14, 2013, and August 23, 2013, respectively. These authorizations did not have an expiration date. Scaled's website (www.scaled.com, accessed June 15, 2015) contains information about the Proteus and Ares experimental aircraft.

[53] The accident copilot was also the copilot of WK2 for seven SS2 glide flights occurring between November 17, 2010, and October 7, 2014. In addition, he was the copilot for 18 WK2 flights between June 2009 and October 2014.

According to Scaled records, the copilot had accumulated 2,154 hours total flying time, including 32 hours in SS2. He had flown 43 hours in the last 90 days, 21 hours in the last 30 days, and 0.7 hour in the 24 hours before the accident.[54] Scaled pilot training records showed that the copilot received ground training on SS2 cautions and warnings and emergency procedures on September 3, 2013. He also received WK2 systems ground training from May 17 to 20, 2013.

1.2.1.3 Analysis of Flight Crew Certifications and Experience

According to the human space flight requirements of 14 CFR 460.5, pilots are required to "possess and carry an FAA pilot certificate with an instrument rating" and "possess aeronautical knowledge, experience, and skills necessary to pilot and control the launch or reentry vehicle that will operate in the National Airspace System." The pilot's commercial pilot certificate and the copilot's ATP certificate exceeded the minimum certification requirements of section 460.5. Also, both pilots were experienced in several multicrew experimental aircraft, had significant flight test experience with multiple aircraft while employed at Scaled, and were part of the initial cadre of test pilots for SS2 and WK2. In addition, the pilot participated in the SS1 program, the copilot flew on SS2's first powered flight, and both pilots had glide flight experience in SS2. Thus, the NTSB concludes that the pilot and copilot were properly certificated and qualified.

1.2.2 Medical, Pathological, and Rest Information

The pilot and the copilot did not take any prescription or nonprescription medication in the 72 hours before the accident that might have affected their performance on the day of the accident. They had no major changes to their health, financial situation, or personal lives that would have impacted their performance on the day of the accident. Specimens taken from the pilot and the copilot, which were sent to the FAA's Civil Aerospace Medical Institute for toxicological testing, were negative for ethanol and drugs.

The NTSB determined the pilot's and copilot's preaccident activities through postaccident interviews, Scaled records, and cell phone records. According to this information, the pilot and copilot had opportunities to obtain adequate sleep in the days before the accident, and their schedules met the rest requirements of 14 CFR 437.51, "Rest Rules for Vehicle Safety Operations Personnel." No evidence suggested that the copilot was fatigued on the morning of the accident, and he performed his duties as expected until unlocking the feather system early.[55] Also, the copilot's wife described him as healthy, and he had no known medical or behavioral conditions that might have affected his performance. Thus, the NTSB concludes that fatigue and medical and pathological issues were not factors in this accident.

[54] The copilot's flight time for the 30 days and 24 hours before the accident includes the time during the accident flight when SS2 was mated to WK2.

[55] The copilot's wife stated that, on the night before the accident, the copilot went to sleep about 2100 and fell asleep immediately. She also stated that he woke up on the day of the accident about 0300 and that he slept well.

1.3 Vehicle Information

1.3.1 Overview

The SS2 reusable suborbital rocket was manufactured in June 2010. Before the accident flight, SS2 had accumulated 83 hours of flight time while coupled to WK2 and about 6.3 hours of glide and powered flight time while decoupled from WK2. FAA records showed that SS2's first special airworthiness certificate was issued on June 30, 2010, and that SS2's most recent special airworthiness certificate was issued on October 1, 2014.[56]

SS2 had a low-wing, twin-tailboom, outboard horizontal tail, and extension-only tricycle landing gear configuration.[57] SS2's primary airframe structures—the nose, cabin, aft fuselage, wing, feather flap assembly, and horizontal stabilizers—were constructed with composite materials. The aft one-third of the wing surface and the tailbooms comprised the feather flap assembly structure (discussed in the next section). The aft fuselage contained the rocket motor system (discussed in section 1.3.3) and the pylon structure that attached SS2 to WK2. SS2 was about 60 ft long with a wingspan of about 23 ft, a height of about 15 ft at the tail, and a fuselage diameter of 7.5 ft. At the time of the accident, SS2 had two seats for the pilots, but Scaled designed the vehicle to be configured with six additional forward-facing seats in the cabin (three seats on the left side and three seats on the right side).

SS2's primary flight control system consisted of elevons for pitch and roll control and rudders for yaw control. The electrical system (after release from WK2) was powered by two main battery packs and one emergency battery pack. The pneumatic system consisted of four high-pressure bottles that supplied dry, compressed air to various systems, including the feather system. Two bottles were located in the leading edges of each wing. Telemetry data for the flight control system, the electrical system, and the pneumatic system showed no anomalies before the feather movement.

1.3.2 Feather System

The feather system was designed to pivot a feather flap assembly upward from SS2's normal configuration (0º) to 60º to slow the vehicle during the reentry phase of flight.[58] The feather system was also designed to retract the feather flap assembly at the end of the reentry phase (which would occur at an altitude of about 60,000 ft) to aerodynamically configure SS2 for its glide to a landing.[59] The feather flap assembly included the left and right tailbooms, left and right feather flaps, and a torque tube structure in the aft fuselage that connected both sides of the feather flap assembly. The assembly attached to the wing rear spar at two outboard and two

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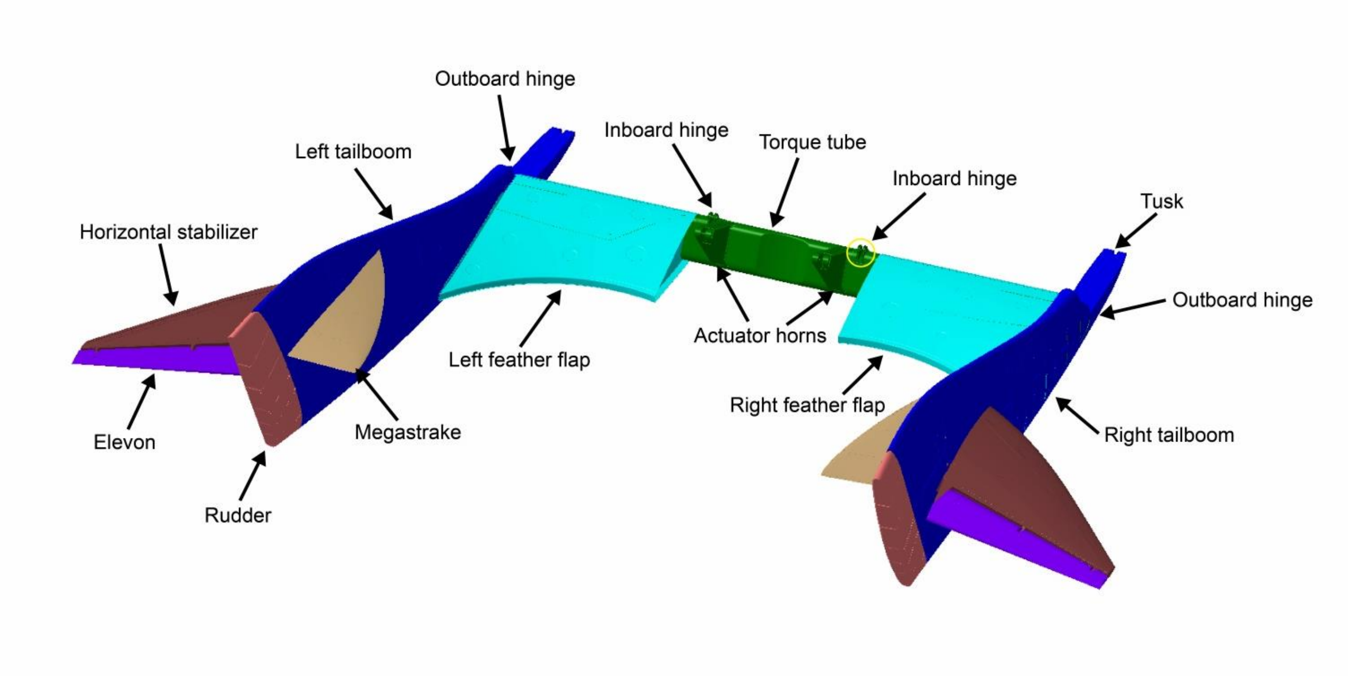
[56] WK2 was manufactured in 2008, and its most recent special airworthiness certificate was issued June 30, 2014. A special airworthiness certificate has an expiration date, which is generally 1 year from the date of issuance. As a result, an operator must obtain a new special airworthiness certificate before the first flight after an expiration date.

[57] The SS2 landing gear was retracted during takeoff.

[58] The design of the SS2 feather system was based on the design of the SS1 feather system. During SS1 flights, the feather was unlocked immediately before feather extension during the reentry phase.

[59] After the feather was retracted, the MFD would display an "OK TO LOCK" message, and a light on the backup LED indicator panel (on the pilot's side next to the caution and warning indicator lights) would illuminate.

inboard hinges (located in the wingtips and the aft fuselage, respectively). Figure 11 shows the external components of the feather flap assembly.



Source: Virgin Galactic.

Figure 11. Feather flap assembly.

Identical left and right feather lock actuators were mounted on the wing forward spar and were connected to lock hooks. In the normal (unfeathered) configuration, the feather lock hooks engaged hardened steel lock pins at the forward end of the tusks (tailboom structure forward of the hinge line) to secure the feather in the retracted position. Identical left and right feather actuators were mounted in the aft fuselage, with the forward ends of the feather actuators connected to the feather horns on the torque tube. For the feathered configuration, the feather actuators would extend, and the torque tube would rotate to extend the feather flap assembly. The feather locks and feather actuators were controlled by SS2's pneumatic system.

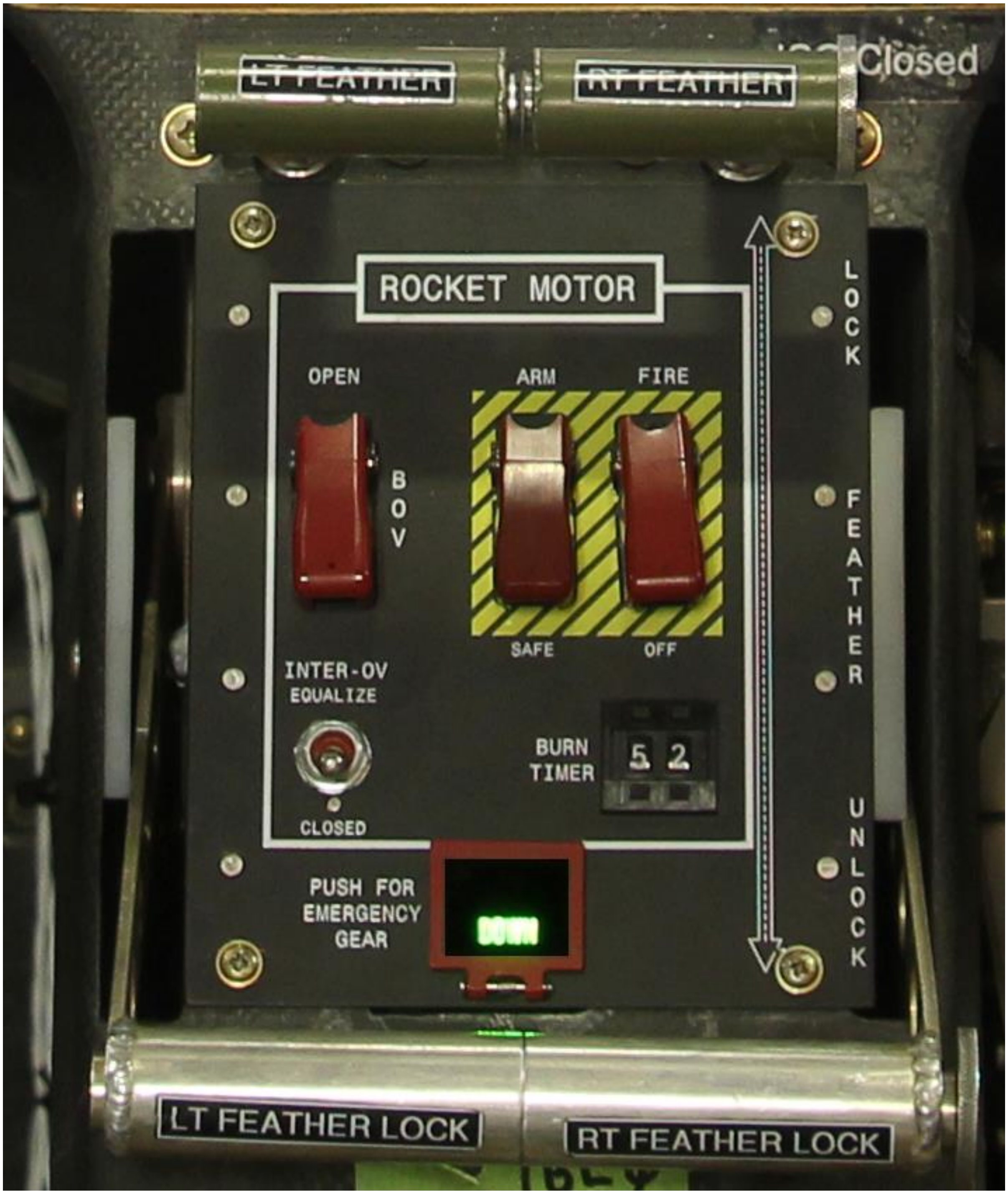
To operate the feather system, the pilot monitoring would unlock the system by moving the feather lock handle (on the center pedestal) to the right and downward to the unlocked position, as shown in figure 12. The pilot monitoring would then extend the feather by pulling the feather handle outward.[60] To retract and secure the feather, the pilot monitoring would push the feather handle inward, as shown in figure 12, and would then move the feather lock handle to the right and upward to the locked position.[61] Scaled's former chief aerodynamicist (who developed the feather system) stated that a pilot would not unknowingly unlock the feather because moving the feather lock handle around a detent and downward required "a bit of

[60] The design of the feather lock handle required it to be in the unlocked position before the feather handle could be extended.

[61] The center MFD continuously displayed SS2's lock status and feather position. (The backup LED indicator panel also displayed the lock status and feather position.) The center MFD had an optionally selectable feather system page to provide additional feather system indications.

force."[62] (The amount of force was not quantified.) The feather lock handle controlled the position of the left and right feather locks, and the feather handle controlled the position of the left and right feather actuators. The feather lock handle was designed to be placed in either the locked or the unlocked position, and the feather handle was designed to be placed in either the extended or the retracted position; no intermediate positions were available.

[62] The former chief aerodynamicist was the SS2 project engineer for most of the build phase, the flight test group lead, and the test conductor for PF01 through PF03. He left Scaled on October 9, 2014, but continued to work for the company as a consultant.



Source: Scaled Composites.

Figure 12. Feather lock handle and feather handle.

Note: The left feather lock and left feather handles were normally connected via a steel pin to the right feather lock and right feather handles, respectively. Thus, this report refers to the left and right feather lock handles as a single feather lock handle and the left and right feather handles as a single feather handle (except in the discussion in this section about the handles as found in the wreckage). The feather lock handle (at the bottom of the figure) is shown in the unlocked position, and the feather handle (at the top of the figure) is shown in the retracted position. The rocket motor arm and fire switches (discussed in section 1.1.2) are shown in the center of the figure.

During postaccident discussions with the NTSB, Scaled engineers indicated that the design of the feather lock system was intended “to hold the feathers in the retracted position during all phases of flight except when the feathers were intended to be extended.” Scaled also indicated (in a January 23, 2015, document that responded to NTSB questions) that “the portions of the trajectory when the feather was not intended to be extended” included the transonic region and the gamma turn maneuver. Scaled further indicated that the design parameters for the feather actuators “were selected such that the feather retracting forces provided by the actuators were adequate to retract the feathers during the recovery phase of flight (after re-entry) and less than the feather extending forces caused by aerodynamic loads during the transonic flight regime and gamma-turn maneuver.”[63]

Both feather lock handles were recovered with the wreckage. The left handle was attached to part of the center pedestal structure, and the right handle had separated from the structure. Examination of the center pedestal structure determined that the left handle was recovered in the locked position. The position of the right handle could not be determined because of impact damage. The cockpit image recording and flight data showed that, before the feather movement, the copilot placed the feather lock handle in the unlocked position and that the lock handle remained in the unlocked position. Thus, the position of the left handle as found on scene was most likely the result of the vehicle breakup.

Both feather handles were recovered in the wreckage, but their positions could not be determined. As stated in section 1.1.2, the cockpit image recording and flight data showed that neither flight crewmember extended the feather handles. Thus, the feather extension (as seen on the SS2 tailboom video) was uncommanded.

Several feather system components—including left and right feather actuators, left and right pneumatic system pressure regulators, and left and right feather enable valves—were scanned by x-ray computed tomography to document their internal condition.[64] No anomalies that could have affected the feather system were found. After the x-ray scanning, teardown inspections of these components were performed, and no anomalies were noted.

1.3.2.1 Reasons for Unlocking Feather During Boost Phase

SS2 pilots were required to unlock the feather during the boost phase of flight (after the gamma turn) to ensure that the feather could be extended during the reentry phase. According to postaccident interviews with Scaled engineers, unlocking the feather during the boost phase would mitigate the hazard resulting from the feather remaining locked (because of a jammed or nonoperational feather lock) by allowing the pilots to detect the failure of the feather to unlock in time to abort the mission (by shutting down the rocket motor) and return safely to MHV in the unfeathered configuration. The mission would have to be aborted before 1.8 Mach because, after this point, an unfeathered reentry would have a much greater risk due to the higher apogee of the

[63] The NTSB notes that, during a nominal flight, the feather, after being unlocked, would have to be held in the retracted position by the feather actuators (and not by the feather locks) before the point at which the feather was to be extended (during the deceleration through the transonic region after the gamma turn and the rocket motor burn).

[64] The feather enable valves were located on the cockpit floor between the pilot seats, and each valve handle was connected to a lanyard. If a lanyard were pulled, the respective valve handle would rotate to the vent position, and the pneumatic lines for that side would vent to the atmosphere.

vehicle and the resulting high G loads, high speeds, flutter, and high heat loads on the vehicle. The design of the feather system included a caution message that would annunciate on the center MFD (along with an aural annunciation) if the feather was not unlocked before 1.5 Mach so that a pilot could take the required action before 1.8 Mach.

During discussions with the NTSB, Scaled engineers indicated that the Mach number for unlocking the feather system was "chosen to provide a safety margin at the lower end of the scale to prevent premature unlocking, and at the higher end of the scale to allow adequate time to abort." Postaccident interviews and the flight test data cards for PF02 and PF03 indicated that the feather was to be unlocked at 1.2 and 1.3 Mach, respectively, because of the rocket motor burn time during those flights, as further discussed in section 1.3.3. (The feather was not unlocked during PF01.) Scaled's former chief aerodynamicist stated that 1.4 Mach was established as the speed for unlocking the feather during PF04 because that speed provided (1) a sufficient margin of safety from the flight regime during which there would be an upward lift on the tail (from 0.8 to 1.0 Mach, after which there would be a down force on the tail) and (2) enough time for the pilots to take action by 1.8 Mach if the feather did not unlock.

Scaled engineers stated that, if the feather were unlocked during the transonic region, the large lifting force generated by the tail (acting to extend the feather) could overpower the resistance capability of the feather actuators (acting to keep the feather retracted). The WK2 pilot for PF04 (who was the SS2 pilot for PF03), among others, stated that the feather was to be unlocked at 1.4 Mach because, at that point, the substantial down force on the tail and the loads on the actuators would be holding down the feather without the locks engaged.

The SS2 accident pilot knew that the feather was not to be unlocked before 1.4 Mach but could not remember if that information was conveyed in a design review or during informal discussions. He stated that the requirement for feather locks in the transonic region "came up many times" and believed that this information was "common knowledge." Other Scaled and Virgin Galactic pilots stated they were also aware of the requirement not to unlock the feather during the transonic region. Scaled's vice president/general manager stated that the company had not considered the possibility that a pilot would unlock the feather before 1.4 Mach.

The NTSB could find only two written references involving the accident pilots (an e-mail from 2010 and a presentation slide from the April 2011 Feather Flight Readiness Review [FRR]) that addressed the excessive tail loads during the transonic region and the inability of the feather actuators to hold the feather in place under such loads.[65] Neither of these references discussed the catastrophic risk of unlocking the feather before 1.4 Mach. A second presentation at the April 2011 Feather FRR informed meeting participants that uncommanded feather operation during the boost phase would be catastrophic, but this finding was based on the assumption that "the feather has been unlocked, so only the feather actuation has to fail uncommanded." Thus, although some evidence indicated that SS2 pilots were made aware that the feather should not be

[65] The NTSB asked to review the sign-in sheet for the meeting during which this presentation was made, but Scaled could not find the sign-in sheet. However, the meeting invitation was sent to both pilots, the copilot's calendar on the day of the briefing showed the meeting, and his timecard for that day indicated that he worked 4 hours on the SS2 program at the time that the meeting was held. The pilot was most likely at the presentation because he was Scaled's director of flight operations and an SS2 pilot. Section 1.4 describes FRRs and other SS2 reviews that Scaled performed.

unlocked before the designated Mach speed, there was insufficient evidence to determine whether the pilots fully understood the potential consequences of unlocking the feather early.

1.3.2.2 Feather Moments During Accident Flight

The vehicle performance study for this accident included computations of the feather moments during PF04. The feather moment is the torque that aerodynamic and inertial forces produce about the feather hinge, acting to either extend (opening moment) or retract (closing moment) the feather. To compute the PF04 feather moments, the NTSB used selected data from a three-degree-of-freedom simulation program called the "trajectory code," which was one of Scaled's primary analytic tools for modeling SS2's handling qualities and feather moments during flight (including the transonic region and gamma turn). In addition to flight simulations, the trajectory code included computations for vehicle loads, including the feather moments. The aerodynamic database for the trajectory code was based on computational fluid dynamics studies that were updated with flight test data from SS2 glide and powered test flights. The aerodynamic database included data for a combination of Mach number, angle-of-attack, and horizontal stabilizer positions at the retracted, midpoint, and extended feather positions.

The vehicle performance study found that, when the feather was unlocked at 1007:29.5, the total feather opening moment exceeded the total closing moment provided by the feather actuators.[66] At 1007:30.0, the opening moment decreased below the closing moment actuator capability. The opening moment then increased again above the closing moment actuator capability and continued increasing when the feather started to move at 1007:30.6. The oscillation in the feather opening moment was consistent with the delay of about 1.1 seconds between the unlocking of the feather and the movement of the feather toward the extended position.[67] Thus, the study showed that, shortly after the feather was unlocked, the feather opening moments were sufficient to open the feather by overcoming the closing moments provided by the feather actuators.

In addition, the vehicle performance study determined the total feather moments for the three previous powered flights, which were also computed using Scaled's trajectory code. The accident flight and previous powered flights were conducted with shorter-than-nominal motor burn times compared with the design mission, and SS2 decelerated through the transonic region at lower-than-nominal altitudes. The computations for PF02 and PF03 (during which the feather was to be unlocked at a speed of 1.2 and 1.3 Mach, respectively, per the flight test data cards) showed that the feather moment at the time that the feather was unlocked was a closing moment. Thus, when the feather was unlocked during the boost phase, aerodynamic forces and the feather actuators held the feather in the retracted position.[68]

The vehicle performance study further determined that, during the boost phase for PF02 and PF03, as SS2 decelerated from supersonic speeds back through the transonic region (during

[66] As previously stated, at 1007:29.5 both the left and right feather lock positions transitioned from locked to not locked.

[67] The aerodynamic database used in the trajectory code was not designed to model small feather deflections. As a result, once the feather started to move, the computed feather moments were unreliable.

[68] As previously stated, the feather was not unlocked during PF01. The feather was unlocked during PF02 at 1.31 Mach and during PF03 at 1.36 Mach.

SS2's ascent but after the rocket motor had burned and while the feather was still closed), the feather moment increased again and became an opening moment. Although during PF02 and PF03 there was a large closing moment at the time that the feather was unlocked, significant opening moments occurred as SS2 decelerated through the transonic region at a lower-than-nominal altitude. For example, the deceleration test point for PF02 was designed to explore high angle-of-attack transonic stability at a lower dynamic pressure. For this test, SS2 was deliberately operated near the edge of its feather-unlocked operating envelope. During the test, the opening moment briefly exceeded the feather actuators' capabilities (while the feather was unlocked) and resulted in a small uncommanded feather motion (about 0.8º) for less than 1 second.[69] PF03 was conducted according to normal procedures, and a feather opening moment within the feather actuators' capabilities occurred with no observed uncommanded feather motion.

1.3.2.3 In-Flight Breakup Sequence

When the feather was locked, the aerodynamic and inertial loads imposed on the feather flap assembly were reacted through the four feather flap hinges, the two feather actuators, and the two feather locks. After the feather was unlocked, all of the aerodynamic and inertial loads were being reacted by only the four feather flap hinges and the two feather actuators. The feather flap assembly began moving relative to the wing 1.7 seconds after the feather lock handle reached the full unlocked position. At this point, the loads imposed on the vehicle were sufficient to overcome the feather actuators.

Video imagery showed that the forward end of the vehicle then began to pitch up. The pitch rate increased rapidly, and the vehicle essentially folded in half about the feather flap hinge line, causing a catastrophic structural failure. Video imagery also showed that the first evidence of the in-flight breakup occurred at 1007:32.13 (about 13 seconds after SS2's release from WK2) when the feather flap became displaced from the trailing edge of the wing, which was the beginning of a failure at the feather flap hinges.[70] The localized stress in the wing side of the inboard feather flap hinge fittings was sufficient to fracture the inboard hinges at 1007:32.18.[71] The right and left tailbooms and the torque tube separated from the vehicle between 1007:32.4 and 1007:33.4. The rocket motor case/throat/nozzle assembly and the nose and crew station separated immediately afterward (at 1007:33.5 and 1007:33.6, respectively).[72]

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[69] During a nominal mission profile, the loads would be within the operating envelope of the feather actuators because SS2 decelerates through the transonic region at a higher altitude (and in thinner air) than when the vehicle accelerates through the transonic region.

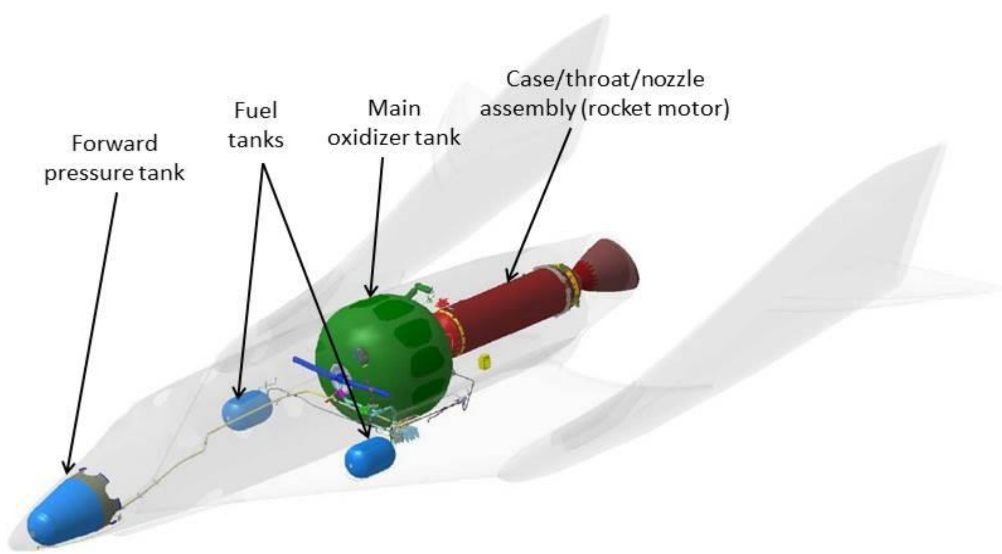
[70] The video evidence in this section was based on information from several cameras, each of which had different time bases. The NTSB Group Chairman's *External Imagery Factual Report* (accessed July 29, 2015), which can be found at www.ntsb.gov, provides information about time correlation among the cameras.

[71] The left and right inboard feather flap hinges fractured in a similar manner, and the fracture surfaces had damage and deformation consistent with shear overload.

[72] The aft torque tube sections that remained attached to the left and right tailbooms showed fracture surfaces indicative of positive overload. The part of the case/throat/nozzle assembly that had separated from the aft fuselage structure showed fractures that were consistent with overstress separation.

1.3.3 Propulsion System

SS2 had a hybrid rocket motor that used nylon fuel grain and nitrous oxide to generate thrust. The main components of the propulsion system, as shown in figure 13, were the main oxidizer tank, which contained the nitrous oxide; the forward pressure tank, which fed helium to the main oxidizer tank to pressurize the nitrous oxide; the case/throat/nozzle assembly, which contained the nylon fuel grain; and two fuel tanks to improve combustion stability during rocket burn.[73] The rocket motor controller (located in the aft fuselage) monitored and sequenced propulsion system functions and could abort the rocket motor burn if failures in the propulsion system were detected. A review of instrumentation data found that, after the feather began to move at 1007:30.6, an "RMC [rocket motor controller] ABORT" warning was displayed on the MFD (at 1007:33.0).



Source: Scaled Composites.

Figure 13. SpaceShipTwo's propulsion system.

[73] The case/throat/nozzle assembly was replaced for each flight, but the forward pressure tank, the main oxidizer tank, and most of the associated parts were designed to be reusable.

PF04 was the first SS2 powered flight to use a fuel injection system and a nylon fuel grain (RM2).[74] The change to a nylon fuel grain resulted in a thrust increase from previous powered flights. Also, as previously stated, a 38-second rocket motor burn time was planned for PF04. A 16-second burn of the rocket motor occurred during PF01, and a 20-second burn occurred during PF02 and PF03.

Examination of the propulsion hardware showed no propulsion system anomalies before the in-flight breakup. Sectioning of the case/throat/nozzle assembly showed that the fuel grain burned evenly without any indications of preimpact fuel cracks or localized hot spots. Propulsion system pressure parameters from the telemetry system and the rocket motor controller internal memory showed that rocket ignition was normal and that pressure values climbed and stabilized at nominal levels before the accident.

1.3.4 Analysis of Vehicle Information

The recovered vehicle components showed no evidence of any structural, system, or rocket motor failures before the in-flight breakup.

Flight data for the feather lock system showed that the system operated as commanded by the copilot: the feather locks unlocked after the copilot moved the feather lock handle to the unlocked position. The aerodynamic loads on the vehicle (with the feather locks unlocked) resulted in an opening moment that was greater than the closing moment provided by the feather actuators. As a result, the feather began to extend. The feather actuator examinations and flight data showed that the actuators functioned as designed. Thus, the NTSB concludes that the unlocking of the feather during the transonic region resulted in uncommanded feather operation because the external aerodynamic loads on the feather flap assembly were greater than the capability of the feather actuators to hold the assembly in the unfeathered position with the locks disengaged.

1.3.5 Maintenance and Inspection Information

Scaled developed maintenance and inspection programs for SS2, even though no such requirement existed under 14 CFR Part 437. For example, between June 26, 2010, and October 1, 2014, Scaled performed five conditional inspections of the vehicle according to the company's SS2 inspection plan, which Scaled created for the special airworthiness certificate. The last conditional inspection included servicing and detailed inspections of the feather system components, including the feather actuators. Two discrepancies related to the feather system were noted during the conditional inspection, which were corrected and closed before the inspection was completed.[75] Also during the inspection, the feather lock and feather actuator valves were modified according to an engineering change to add valve lock tubes to the supply ports (to prevent a blockage from occurring in the ports that could restrict airflow to the system). The paperwork for the conditional inspections was signed off with no discrepancies. Other

[74] The SS2 simulator software for PF04 was updated to reflect the additional thrust resulting from the nylon fuel grain.

[75] One discrepancy was related to damage to the right feather actuator cap, which occurred during reinstallation. The other discrepancy was related to a failure of a wire connection on the feather up actuator position switch.

examinations of the feather system before the accident included a leak check on October 8, 2014, during which no anomalies were noted.

Title 14 CFR 437.21, which discussed general requirements to obtain an experimental permit, stated in paragraph (d) that, before the FAA/AST could issue an experimental permit, the vehicle had to be made available for inspection. The FAA/AST inspected SS2 on April 11, 2012, and determined that all vehicle components were installed as represented in Scaled's experimental permit application except for the propulsion system components, which were not installed at the time. The FAA/AST performed an inspection on April 15, 2013, with the propulsion system installed. The FAA/AST determined that the propulsion system was installed as represented in the permit application (except for the rocket motor case/throat/nozzle assembly and igniters, which were not installed at the time), and that the vehicle inspection was complete.

1.3.6 SpaceShipTwo Data Sources

SS2's flight test data instrumentation system, referred to as SODAS, was the main source of flight data used during the investigation of this accident. SODAS telemetered data from SS2 to ground-based stations and was the only source of information for numerous vehicle performance and system operating status parameters. Without SODAS, critical investigative data, including the status of the feather and Mach numbers, would have been unavailable to the NTSB.

As part of the investigation of this accident, the NTSB attempted to locate and recover five onboard high-definition cameras and their associated solid-state media recording devices, but only two of the five recording devices were located within the vehicle wreckage, and the information from only one recording device was successfully recovered. None of the data or image recording devices installed on the accident vehicle were designed or required to meet or exceed any existing flight recorder survivability standards for commercial airplanes.

In addition to data telemetry, SODAS telemetered the video from two of the onboard high-definition cameras, one of which was the cockpit image recorder. Without the video from inside the cockpit, the NTSB's ability to determine and analyze flight crew actions would have been significantly hampered.

SODAS was installed on the accident vehicle specifically to support instrumented flight test activities; as a result, the data system might not be installed on the SS2 vehicle currently under construction (and any subsequent SS2 vehicles) once in commercial service. Thus, if an accident or incident involving a future SS2 vehicle in commercial service were to occur, it is not clear whether SODAS and the other data-rich recording devices installed on the accident vehicle would be available to aid the resulting investigation.

1.4 Organizational and SpaceShipTwo Program Information

1.4.1 Scaled Composites

Scaled Composites LLC is a proof-of-concept and prototyping aerospace development company headquartered at MHV. The company, which was founded in 1982, is currently a wholly owned subsidiary of Northrop Grumman Corporation. Scaled's staff includes test pilots, engineers, analysts, and technicians.

Scaled test pilots were assigned to the engineering department and reported to the director of flight operations (the accident pilot), who reported to the vice president of engineering. At the time of the accident, four Scaled test pilots were assigned to the SS2 test program. The SS2 test pilots provided flight operations technical support for vehicle and payload system development; prepared flight test plans, data cards, and pilot operating handbook (POH) revisions; supported ground tests and documented test results; participated in pre- and postflight briefings; and flew test flights as a pilot or copilot. Test pilot assignments were part time and had to be coordinated with other company responsibilities.[76]

Scaled indicated that preparation for PF04 began immediately after PF03 in January 2014. PF04 was originally scheduled for October 23, 2014, but was rescheduled because of concerns that were unrelated to the feather system or pilot procedures. Scaled's vice president of engineering stated that there was pressure to have PF04 completed on October 31, 2014, but that the pressure was not "undue or unreasonable."[77]

Scaled performed several flight and test reviews before PF04, including three FRRs on October 3, 27, and 29, 2014. According to a Scaled document, during FRRs the "test team reviews [the vehicle] configuration and [the] changes for a specific test or series of test[s] with [the] intent of getting management buy-in on the risks" that the team has identified.[78] Another objective of FRRs was to determine "potential unidentified risks through the use of independent/outside sets of eyes and subject matter experts." According to postaccident interviews with participants at these FRRs, the feather system was not discussed. A review of the action items from the FRRs showed several items associated with the feather system, none of which were related to pilot procedures for operating the system.

Scaled also performed two test readiness reviews on September 30 and October 8, 2014. The Scaled document stated that a test readiness review was the "ground test equivalent of an FRR." In addition, Scaled held a Tier 1B town hall meeting to "provide an opportunity to ask questions" and "discover unknown issues that could delay the remaining [SS2 program]

[76] In his role as a project engineer on two other Scaled programs, the copilot reported to the engineering manager, who reported to the vice president of engineering.

[77] Postaccident interviews revealed that the pressure to complete PF04 on October 31, 2014, was due to a desire to maintain the program schedule, especially given that PF04 had already been delayed. Scaled's vice president of engineering stated that this pressure had to be balanced with the pressure to safely perform the flight. No one interviewed expressed any concerns about PF04 proceeding on October 31.

[78] The NTSB asked Scaled to provide a document that detailed the flight and test reviews performed before PF04. Scaled's document to the NTSB was dated February 27, 2015.

schedule."[79] Scaled, Virgin Galactic, and The Spaceship Company personnel attended this meeting.

1.4.1.1 Simulator and Flight Training

Scaled and Virgin Galactic test pilots trained together to prepare for SS2 glide and powered flights. In its experimental permit application, Scaled stated that it would take a "three prong approach to training SS2 pilots." As such, SS2 pilots were trained in the SS2 simulator, the WK2 aircraft, and the Extra EA-300L aerobatic airplane.

Scaled's SS2 simulator replicated the SS2 cockpit and was a fixed-base (no motion) simulator.[80] The SS2 experimental permit application stated that Scaled's simulator had "great fidelity" with the SS2 vehicle because the simulator duplicated the SS2 cockpit layout; included "detailed and precise" SS2 flight dynamics; and had the ability to simulate control forces and effectiveness in all flight regimes, wind profiles, thrust asymmetries, and "a huge array" of failure conditions. Before each mission, a test pilot and a flight test engineer would use the simulator for mission planning and test point specifications. Afterward, the entire mission team, including control room personnel, would conduct full mission rehearsals—referred to as integrated simulations—during which the team would practice normal and emergency procedures and abort scenarios in the simulator so that the flight crew would be well trained to respond in a timely manner to issues that could arise during a flight. Scaled required the team to conduct at least three integrated simulations before each SS2 powered flight. Scaled's records showed that, between September 22 and October 27, 2014, eight integrated simulation sessions were held to prepare for PF04. A review of the notes and data from these integrated simulations found no instances of the feather being unlocked during the boost phase before 1.4 Mach.

Scaled's simulator logs showed that, for PF04, one or both of the accident pilots trained in the SS2 simulator 34 times between August 12 and October 30, 2014. The accident pilots trained together during 14 of these sessions, 5 of which were integrated simulations.[81] Between October 27 and 30, 2014, the accident pilots trained together in the simulator three times (including one integrated simulation), the accident pilot trained two other times, and the accident copilot trained one other time. (Multiple runs occurred during each of the simulator sessions discussed in this paragraph.)

The SS2 simulator did not model uncommanded feather deployment with the feather unlocked. As a result, if a pilot were to unlock the feather early in the simulator, the pilot would not receive direct feedback regarding the catastrophic results of that action during an actual flight.

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[79] Tier 1B was the official name of the program to test and evaluate the WK2 and SS2 vehicles and their systems.

[80] Virgin Galactic also had a fixed-base (no motion) simulator located at its facility. At the time of the accident, the cockpit configuration of that simulator replicated the WK2 cockpit (in the right fuselage), which was similar to the SS2 cockpit configuration.

[81] Two of the eight integrated simulations involved only the accident pilot, and one integrated simulation involved two other pilots.

The experimental permit application also stated that SS2 pilots would use WK2 to train for proficiency during simulated release through touchdown. The WK2 cockpit layout was similar to the SS2 cockpit. Also, with its gear down, inboard speedbrakes extended, and engines set to 75% N2 (engine high pressure spool speed), WK2 had a similar flightpath and descent profile as SS2. Scaled required SS2 pilots to fly at least three simulated approaches in WK2 for proficiency before a powered flight.[82] Section 1.2.1 discussed the accident pilots' WK2 flight time, which included flights to prepare for PF04, the last of which occurred on July 22, 2014, for the pilot and October 7, 2014, for the copilot.

In addition, SS2 pilots received aerobatic training in the Extra EA-300L airplane before SS2 flights. The training included G tolerance and upset recovery training. Scaled required a minimum of three aerobatic training flights to prepare for an SS2 powered flight. A Virgin Galactic test pilot was the instructor pilot for the Extra EA-300L training flights. The accident pilot received aerobatic training in the Extra EA-300L to prepare for PF04 during three flights between October 2 and 15, 2014, and the accident copilot received this training during three flights between August 5 and October 21, 2014.

1.4.1.2 Written Guidance

In addition to the PF04 flight test data card, Scaled's *SpaceShipTwo (SS2) Pilot Operating Handbook* (dated September 3, 2013) contained information about the speed at which the copilot was to unlock the feather.[83] For example, page 102 of the SS2 POH indicated that a nominal mission sequence included unlocking the feather after the gamma turn at 1.4 Mach. Also, page 165 of the POH stated, "at 1.4 Mach the feather should be unlocked and if both hooks do not unlock the boost must immediately be aborted."

Test pilots, engineers, and managers involved with the SS2 program were aware that unlocking the feather during transonic flight could be catastrophic, but no warning, caution, or limitation in the SS2 POH specified the risk of unlocking the feather before 1.4 Mach. Page 103 of the POH contained a warning indicating that inadvertently actuating the feather while cycling the feather locks (during the preflight and L-10 checks) would likely result in catastrophic failure of the mated pair (WK2 and SS2). However, the POH did not indicate that unlocking the feather during transonic flight would allow the aerodynamic forces on the SS2 vehicle to overpower the resistance capability of the feather actuators and thus result in a catastrophic failure of the vehicle.[84]

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[82] Scaled did not specify any time period during which this training and the Extra EA-300L training were required to be performed, and no such requirement was specified in 14 CFR 460.5.

[83] Scaled's *M339 SpaceShipTwo Normal Procedures* manual (dated October 14, 2014) also contained information about the speed at which the copilot was to unlock the feather. Specifically, page 37 stated that, during the boost phase of flight, at a speed greater than 1.4 Mach, the pilot not flying (the pilot monitoring) was to unlock the feather. The procedure to unlock the feather at 1.4 Mach first appeared in the SS2 normal procedures in November 2012, after Scaled incorporated rocket system components into SS2's design. The 1.4 Mach feather unlocking procedure has been a part of each subsequent revision of the SS2 normal procedures.

[84] Scaled's *M339 SpaceShipTwo Emergency Procedures* manual (dated October 14, 2014) included a warning that "a sudden feather up [at] >200 KEAS [knots equivalent airspeed]" during a feather down reentry "will likely be catastrophic." However, the NTSB's review of the SS2 emergency procedures did not find a warning stating that uncommanded feather movement during transonic flight would also be catastrophic.

1.4.1.3 SpaceShipTwo Systems Safety Analysis

Scaled's experimental permit application indicated that the company performed a comprehensive systems safety analysis (SSA) for SS2 and RM2 to comply with the requirements of 14 CFR 437.29 and 437.55(a), "Hazard Analysis."[85] Section 437.29 required an experimental permit applicant to perform a hazard analysis that complies with section 437.55(a) and provide the FAA/AST with all results of each step of the hazard analysis. Section 437.55(a) required an applicant to perform a hazard analysis that, among other things, identifies and describes those hazards that result from component, subsystem, or system failures or faults; software errors; environmental conditions; human errors; design inadequacies; or procedural deficiencies.

Scaled's document, "Systems Safety Analysis Approach," dated February 14, 2011, stated that Scaled derived its SSA process for SS2 from "several sources of industry best practices including those related to experimental aircraft and certificated aircraft." Scaled also stated that its SSA process was equivalent to the process outlined in Advisory Circular (AC) 437.55-1, "Hazard Analysis for the Launch or Reentry of a Reusable Suborbital Rocket Under an Experimental Permit," which the FAA/AST issued in April 2007.[86] The AC stated that a hazard analysis must address human errors, including "decision errors, such as using flight controls at the wrong time" and "skill-based errors, such as improperly following a procedure." Scaled stated that the SSA process for SS2 met the requirements of 14 CFR 437.55 because (1) "the design of the vehicles is such that mission assurance results in the protection of public health and safety, and property," (2) "the approach is similar to [the approach provided in] AC 437-55," and (3) "the approach is derived from industry practice for certificated aircraft, which have higher standards than experimental aircraft."

Scaled's SSA included a functional hazard assessment (FHA) and a fault tree analysis (FTA).[87] Scaled indicated that it performed its FHA according to the guidance in AC 23.1309-1D, "System Safety Analysis and Assessment for Part 23 Airplanes," which applied directly to certificated aircraft and indirectly to experimental aircraft.[88] Scaled's first FHA document, dated December 8, 2011, provided background information (purpose, methodology, and definitions) about the FHA and discussed the analysis related to WK2. The second FHA document, dated December 20, 2011, contained the analysis related to SS2 and RM2.[89] Both FHA documents identified specific vehicle functions, determined the safety-critical failure

[85] One of Scaled's hazard analysis documents defined an SSA as "a systematic, comprehensive evaluation of an implemented system, its architecture and its installation to show compliance with the safety requirements."

[86] The FAA/AST published AC 437.55-1 to provide experimental permit applicants with an acceptable, but not the only, approach for demonstrating compliance with the hazard analysis requirements of 14 CFR 437.55(a). The AC described steps to identify and describe hazards, determine and assess the risk for each hazard, identify and describe risk elimination and mitigation, and validate and verify risk elimination and mitigation measures.

[87] An FHA is a systematic, top-down, comprehensive examination of vehicle and system functions to identify potential minor, major, hazardous, and catastrophic failure conditions that could arise from a malfunction or a failure to function. One of Scaled's FHA documents defined catastrophic failure conditions as those "that are expected to result in multiple fatalities of the occupants, or incapacitation or fatal injury to a flight crewmember, normally with the loss of the vehicle." An FTA is a deductive failure analysis that focuses on one particular undesired event and provides a method for determining the causes of the event.

[88] AC 437.55-1 cited AC 23.1309-1C, "Equipment, Systems, and Installations in Part 23 Airplanes," as a reference document. AC 23.1309-1D, dated January 16, 2009, was in effect at the time that Scaled performed its hazard analysis. (That version of the AC was replaced by version 1E on November 17, 2011.)

[89] The first and second FHA documents were updated on February 11 and October 2, 2014, respectively.

modes for the functions and the effects that the failure modes could impose on the vehicle and its occupants, applied a classification to the failure modes, and identified mitigation measures to reduce the risk associated with each failure mode.

One of the vehicle functions identified in the SS2 FHA was "provide feather configuration." For this function, Scaled identified "uncommanded feather operation" as a catastrophic hazard during the boost phase, with the "probable loss of aircraft" as the resulting effect on the vehicle and flight crew. Because uncommanded feather operation was classified as a catastrophic hazard, Scaled performed an FTA to identify and analyze potential failure conditions. Scaled's FTA assumed that the flight crew would be properly trained through simulator sessions and that the crew would follow the normal and emergency procedures for a given situation. These assumptions relied on the flight crew to correctly operate the feather system during every flight.

Scaled stated that its FTA for the hazard involving uncommanded feather operation during the boost phase, dated June 21, 2011, was developed with the assumption that the flight crew would release the feather locks at the appropriate time because they were trained in the SS2 simulator before all flights. The FTA showed that, after the feather locks were released, a failure involving both the left and right feather actuation systems would need to occur for the feather to move uncommanded. Scaled's analysis showed that the probability of failure for the hazard involving uncommanded feather operation during the boost phase met the "extremely remote" criteria in 14 CFR 437.55(a) and Scaled's quantitative requirement of 1×10^{-6}.[90] As a result, Scaled determined that the feather system design was adequate and that no mitigations were needed to ensure that the feather would remain retracted during the boost phase.

1.4.1.3.1 Adequacy of Scaled Composites' Systems Safety Analysis

The NTSB's review of the SSA determined that Scaled accounted for human error in its FTA only in response to another failure; specifically, the FTA assumed that a pilot would incorrectly respond while attempting to mitigate another failure. As a result, the SSA did not account for single flight crew tasks that, if performed incorrectly or at the wrong time, could result in a catastrophic hazard, as required by 14 CFR 437.55(a). Specifically, Scaled did not account for the possibility that a pilot might unlock the feather prematurely during the boost phase, allowing the feather to extend under conditions that would cause a catastrophic failure of the vehicle structure. Instead, Scaled assumed that pilots would perform the unlocking task correctly every time.

The NTSB notes that AC 23.1309-1D, which Scaled used in developing its SSA, included provisions for an applicant to assume correct flight crew action in demonstrating compliance with applicable regulations. Specifically, AC 23.1309-1D stated, "for the purposes of quantitative analysis, a probability of one can be assumed for flight crew and maintenance tasks that have been evaluated and found to be reasonable."[91] An aircraft type certificate applicant would typically use this guidance during bench, ground, and flight testing to validate that the

[90] AC 437.55-1 defined "extremely remote" as "so unlikely, it can be assumed occurrence may not be experienced, with a likelihood of occurrence less than 10^{-6} in any one mission."

[91] A "probability of one" means that a flight crewmember will take the correct action all of the time for a flight crew task that has been found to be reasonable.

intended flight crew procedures and human factor design assumptions made during the safety assessment process (among other factors) were correct.

Because SS2 was in the experimental flight test stage, the flight crew procedures related to the feather system unlocking task were evolving over the course of multiple flight tests. In particular, the physical cue that initiated the unlocking task, the Mach number, was modified with each successive powered flight test (starting with PF02 because the feather was not unlocked during PF01). Although Scaled had its test pilots execute the unlocking task during simulator training preparation before flight tests, validation of the "reasonableness" of the task did not include some important human factors considerations. For example, as discussed in section 1.4.1.5, the SS2 simulator was not capable of modeling the accelerations and vibrations that pilots would experience during actual flight tests, which are more severe than the accelerations and vibrations that pilots would typically experience during training.

Because of limitations with available test equipment, including simulators, it is reasonable to expect that a commercial space manufacturer might need to rely on flight testing to evaluate the factors, such as acceleration rates, that might impact a pilot's ability to perform flight test procedures. However, when the flight test evaluation includes a single pilot task that, if performed incorrectly or at the wrong time, would result in a catastrophic condition (without sufficient time for a pilot to recover before such a condition occurs), as occurred during PF04, this vulnerability should be identified as part of an applicant's safety assessment process. Once the vulnerability is identified, selected measures to mitigate the effects of a related human error to reduce the risk of a flight test accident should be validated to ensure their effectiveness.[92]

Scaled stated that it relied on pilot training to reduce the possibility of a pilot making an error with the unlocking task, but the NTSB notes that it is difficult to effectively validate training alone as a sufficient measure to fully eliminate the occurrence of such a single human error because many factors independent of training can influence human performance. System safety practitioners often refer to the system safety design order of precedence, which indicates that the largest potential for safety improvements comes from design and engineering enhancements, followed by engineered features or devices, warning devices, and training and procedures (Department of Defense 2012, section 4.3.4(a) through (e); Air Force Safety Agency 2000, section 3.3; and FAA 2000, section 3.6). In this case, Scaled relied exclusively on the lowest mitigation strategy (training) to address the risk associated with premature unlocking of the feather.

In addition, Scaled did not perform task-specific validation measures consistent with those in AC 23.1309-1D. Although the unlocking task was directly associated with a catastrophic hazard, Scaled did not evaluate this task to determine a specific training protocol that would measurably and reliably reduce the possibility that the task would be performed incorrectly. Thus, although Scaled's actions, during the development of the SSA, to seek out and use proven methodologies from aviation industry guidance were commendable, Scaled's assumptions

[92] AC 437.55-1 defined validation as "an evaluation to determine whether each safety measure derived from a system safety process is correct, complete, consistent, unambiguous, verifiable, and technically feasible. Validation is the process that ensures that the implemented safety measure is right."

regarding pilot performance were not rigorously verified and validated, consistent with that guidance, as part of the SSA process.[93]

Human error associated with tasks that can significantly impact safety is most reliably addressed using task-specific procedural and/or design mitigations that use redundancy or error checking to reduce the severity of an outcome because the possibility of a single human error cannot be reliably predicted or eliminated. For example, if Scaled had incorporated a pilot flying/pilot monitoring challenge and response protocol for the unlocking task (given the safety consequences if the task were performed incorrectly), the task would have been redundant because both pilots would have been included in the recognition and response decision-making of the task. In addition, Scaled could have validated the use of this procedure to mitigate the risk of unlocking the feather early and verified the effectiveness of the procedure through structured simulator trials before flight crews performed this procedure during flight.

The NTSB concludes that, although Scaled Composites' SSA correctly identified that uncommanded feather operation would be catastrophic during the boost phase of flight and that multiple independent system failures had to occur to result in this hazard, the SSA process was inadequate because it resulted in an analysis that failed to (1) identify that a single human error could lead to unintended feather operation during the boost phase and (2) consider the need to more rigorously verify and validate the effectiveness of the planned mitigation measures.

1.4.1.4 Design and Operational Considerations

The SS2 feather system had no design barrier that prevented a flight crewmember from erroneously unlocking the feather during the transonic region, and the system provided no annunciation on the MFD to prompt pilot action when it was appropriate to unlock the feather. According to the SS2 program manager, no safeguards were built into the feather system design because Scaled counted on the pilot "to do the right thing" and dealing with redundancies was "complex." However, a vehicle system design that accounts for the possibility of a single human error and provides an independent measure to mitigate the consequences when such an error occurs would be the most effective and reliable means for managing the safety risk associated with a catastrophic failure condition.

The NTSB notes that Scaled considered design mitigations for other aspects of the feather system. For example, if the feather remained locked after SS2 accelerated through a speed of 1.8 Mach, the pilots would have to make a high-risk feather-down reentry. As a result, Scaled developed the procedural mitigation to unlock the feather at 1.4 Mach (after the gamma turn during the boost phase) and programmed the MFD to provide pilots with an aural and a visual annunciation if the feather was not unlocked by 1.5 Mach to ensure that the feather would be unlocked by 1.8 Mach.[94] Also, Scaled engineers were concerned about damaging the feather if it were locked before being fully retracted during the glide phase, so they programmed the MFD to provide pilots with an "OK TO LOCK" annunciation.

[93] AC 437.55-1 defined verification as "an evaluation to determine whether safety measures derived from a system safety process are effective and have been properly implemented. Verification provides measurable evidence that a safety measure reduces risk to acceptable levels."

[94] In addition, if the feather was not unlocked by 1.5 Mach, a light would illuminate on the caution annunciator panels in front of the pilot and copilot.

1.4.1.4.1 Design and Operational Considerations Analysis

For safety-critical systems of a commercial space vehicle, incorporating design considerations that account for the possibility that a flight crew could make an incorrect decision or take an incorrect action that would directly result in a catastrophic condition could mitigate the risks associated with these systems. Design considerations for the SS2 feather system could have included, but would not have been limited to, a mechanical lock for the handle or a "wait to unlock" or an "ok to unlock" annunciation during the boost phase. Scaled could also have considered a procedure to unlock the feather during a less critical flight phase and still mitigate the hazard resulting from an unfeathered reentry.

Valuable lessons for developing safe and efficient new systems and preventing future accidents can be learned when human error is considered early in the design of a system. For example, a review of mishaps from the US military's unmanned aerial vehicle (UAV) program (another emerging industry) found that 60% of these accidents and incidents (across all military branches) were the result of human factor issues, including human error and organizational policies and processes. A UAV study that assessed these data determined that many of the accidents could have been anticipated if a human factors analysis of the user interfaces had been employed (UAVs are operated from staffed control stations) and procedures had been implemented for using UAV systems (Williams 2004).

The identification of foreseeable human errors (omissions and commissions) that could make a commercial space operation vulnerable to a catastrophic failure is an essential first step in ensuring that the related vehicle interface and manual procedures are tolerant of such errors. Hazard analysis techniques beyond those traditionally used to analyze vehicle equipment system failures would best facilitate the identification of safety-significant errors that could occur during in-flight operations.[95] Safety-significant human errors that are documented as part of a comprehensive SSA process, along with the rationale for and decisions about the design and/or operational requirements that have been implemented, could mitigate the corresponding consequences of such errors.

If the rationale for and decisions about SS2's design and operational requirements had been more formally evaluated and documented during SS2's development, Scaled might have clearly recognized that the SS2 feather system design and operational procedures did not incorporate an error-tolerant mitigation to prevent the premature unlocking of the feather during the boost phase. Instead, Scaled relied solely on flight crew performance (through training and following the flight test data card procedures) to mitigate the catastrophic hazard associated with unlocking the feather early.

Critical evaluations of a commercial space system design should be performed as early as possible as part of a comprehensive SSA process—beginning with the concept development phase and continuing throughout the design and development phases—using a multifunctional team approach that includes human factors experts, test pilots, and design engineers. Existing government and industry guidance on human error, reliability, and risk assessment processes and

[95] Such techniques include a human factors process failure modes and effects analysis and probabilistic risk assessment. AC 437.55-1 states that, in a failure modes and effects analysis, "each potential failure in a system is analyzed to determine the effects on the system and to classify each potential failure according to its severity and likelihood." Probabilistic methods model and describe the random variations in systems.

techniques, such as the National Aeronautics and Space Administration's (NASA) human-rated spacecraft systems guidance and the Department of Defense's system safety guidance, can direct these safety-critical design activities (NASA 2007 and Department of Defense 2012). If such processes had been used in SS2's design and development, Scaled might have identified error-tolerant design strategies and incorporated error-tolerant features into the vehicle's design to more reliably mitigate the consequences of unlocking the feather early. The NTSB concludes that, by not considering human error as a potential cause of uncommanded feather extension on the SS2 vehicle, Scaled Composites missed opportunities to identify the design and/or operational requirements that could have mitigated the consequences of human error during a high workload phase of flight.

1.4.1.5 Analysis of Scaled Composites' Consideration of Human Factors in SpaceShipTwo's Design and Operation

Scaled is a research and development company that builds specialty composite vehicles that are primarily meant for use by highly trained and experienced test pilots. As a result, Scaled seemed to focus more on the reliability of the SS2 feather system than on designing the system with redundancies to minimize the possibility of human error and determining mitigations if such an error were to occur. Scaled's former chief aerodynamicist stated the feather system mitigations were "more for a failure of the feather system to unlock and not pilot error." However, because SS2 was being developed for eventual use by pilots who might not have test pilot experience, the SS2 design approach should have focused on both the reliability of the vehicle and the human factors involved.[96]

Scaled's accomplishments likely led to complacency regarding human factors. For example, Scaled's management, test pilots, and engineers did not fully consider the risk of human error because of the flawed assumption that test pilots would operate the vehicle correctly during every flight. Also, Scaled had not informed FAA/AST personnel that early unlocking of the feather could be catastrophic, which provided further evidence of Scaled's expectation that a pilot would perform as trained and not unlock the feather early. However, as researchers examining human error in aviation have stated, "we also must accept that some variability in skilled human performance is inevitable and put aside the myth that because skilled pilots normally perform a task without difficulty, they should be able to perform that task without error 100 percent of the time" (Berman and Dismukes 2006, 28-33). This accident demonstrated that even a highly experienced flight test pilot could make a mistake performing a task that he had successfully practiced during numerous simulator sessions before the flight.

Although Scaled recognized that the feather system had to remain locked during the transonic region of the boost phase of flight, Scaled did not consider, for its SS2 simulator training, pilot guidance, systems design, and FHA, the possibility that a pilot might unlock the feather during the transonic region. Also, the only documented discussions involving the

[96] In May 2015, Virgin Galactic indicated that all of its current pilots exceeded the following qualifications: "a long course graduate of a recognized test pilot school with a minimum of 2.5 years post-graduation experience in the flight test of high performance, military turbojet aircraft and/or spacecraft, a minimum of 1000 hours pilot in command of high performance, military turbojet aircraft, experience in multiengine non-centerline thrust aircraft, [and] experience in multi-place, crewed aircraft and/or spacecraft."

accident pilots about the loads on SS2's tail occurred more than 3 years before the accident. Further, these discussions assumed that a system failure, and not pilot error, could lead to early unlocking. The NTSB concludes that Scaled Composites did not ensure that the accident pilots and other SS2 test pilots adequately understood the risks of unlocking the feather early.

Humans are susceptible to making mistakes regardless of the type of vehicle being operated, and system designs that account for the possibility of human error can help ensure safer vehicle operations. However, Scaled did not consult with a human factors expert (who would have the training and education to understand the interactions between humans and systems) to determine whether SS2's design would minimize the possibility of human error. Several Scaled engineers and a Scaled test pilot stated that they had taken a college-level course or had professional experience in human factors, but Scaled did not have a human factors department or a dedicated human factors expert on the company's staff. Scaled's vice president/general manager stated that the company addressed human factors by relying on input from pilots to identify and resolve ergonomics and other human factors issues, and Scaled's former chief aerodynamicist stated that the company relied heavily on input from its pilots because they and the engineers "made a vehicle that worked really well."

Scaled's lack of emphasis on human factors was also apparent during the NTSB's review of SS2 simulator training. According to SS2 test pilots, pilots did not train in the simulator with flight suits, helmets, oxygen masks, parachutes, or gloves, which they would be expected to wear during actual flights in the SS2 vehicle. Because Scaled did not require test pilots to train in their flight gear, human factors limitations in the cockpit might not have been apparent until an actual flight. For example, during the accident flight, the pilot stated (before starting the L-10 checklist), "this headrest, [at] least the height I'm at, when I press up against it I kinda lose the bottom half of the [PFD] screen." The copilot responded, "I remember doing that on, on [PF01], I took my head, consciously took my head off the headrest." The information displayed on the lower portion of the PFD might not be needed during the boost phase of flight, but a pilot should not be surprised by this or similar conditions during an actual flight.

Also, even though Scaled's SS2 simulator replicated the SS2 cockpit, some aspects of the SS2 operating environment were difficult to model in the fixed-base (no motion) simulator, including the high G forces and vibration during flight.[97] As a result of the lack of motion in the SS2 simulator, pilots were unfamiliar with the vibration and loads to be expected during powered flight. Further, according to a Scaled project engineer, the force required to unlock the feather in the simulator was less than the force required to accomplish that action in the SS2 vehicle. (The forces were not quantified.) Thus, test pilots did not have a realistic expectation of the actual force needed to move the feather lock handle or the mechanics of operating the handle with the vibration and loads that would be occurring. If Scaled had a designated human factors expert on its staff, that person's expertise could possibly have been used to address this and other human factor limitations in simulator training, resulting in a training environment that would better prepare pilots for an actual flight.

[97] The use of motion-based simulators in the aerospace industry is not uncommon. An FAA/AST evaluator, who was a former space shuttle instructor for NASA, stated in a postaccident interview that the motion in the shuttle mission simulator "did an excellent job of simulating" a shuttle flight. After the accident, Virgin Galactic added vibration to its fixed-base simulator, but the simulator still cannot model G loads.

The civilian and military aviation and government aerospace industries have guidance for developing new systems that is based on decades of research, application in real-world environments, analysis, and lessons learned. Such guidance includes FAA ACs, military standards documents, SAE International technical standards documents, and NASA publications. (During postaccident interviews, Scaled engineers mentioned the use of some of these references in designing the SS2 cockpit displays but did not mention whether these documents were used in designing the feather system.) However, because the commercial space flight industry is relatively new, no such guidance exists that is specific to this emerging industry.[98] Such guidance could help ensure that human factor considerations are fully addressed not only during a commercial space vehicle's design but also during its operation by acknowledging human factors limitations in written guidance and simulator training.

The NTSB concludes that human factors should be emphasized in the design, operational procedures, hazard analysis, and flight crew simulator training for a commercial space vehicle to reduce the possibility that human error during operations could lead to a catastrophic event. Therefore, the NTSB recommends that the FAA, in collaboration with the Commercial Spaceflight Federation, develop and issue human factors guidance for operators to use throughout the design and operation of a crewed vehicle. The guidance should address, but not be limited to, the human factors issues identified during the SS2 accident investigation. Specifically, the guidance should include, but not be limited to, information on obtaining human factors expertise, considering human error in hazard analyses, ensuring that hazard analyses avoid or adequately mitigate single-point failures, performing simulator training in actual flight gear for full mission profiles, using existing human factors guidance from other related industries, and providing awareness and documentation to flight crews of known catastrophic hazards that could result from human error. The NTSB also recommends that the Commercial Spaceflight Federation work with the FAA to develop and issue this guidance.

1.4.2 Federal Aviation Administration

The Office of Commercial Space Transportation was initially established as part of the Office of the Secretary of Transportation within the Department of Transportation and was transferred to the FAA in November 1995. Among other things, the FAA/AST regulates the US commercial space transportation industry; protects public health and safety, safety of property, and US national security and foreign policy interests during commercial launch and reentry activities; and encourages, facilitates, and promotes commercial space transportation.[99]

[98] The NTSB notes that the FAA/AST issued guidance on August 27, 2014, titled "Recommended Practices for Human Space Flight Occupant Safety." The recommended practices in this document covered the safety of the flight crew and space flight participants only; the document did not address public safety and mission assurance. The document stated that the FAA/AST issued the guidance because "there are a number of industry and government standards that address the subject areas covered in this document, but some subject areas may not have standards that are appropriate for the commercial human space flight industry." The document also stated that "the development of industry consensus standards in these subject areas could have significant benefits for the safety of future commercial operations." Similar guidance addressing human factors in the design and operation of a commercial space vehicle could also have significant benefits for the safety of future commercial operations.

[99] According to the FAA, other agencies that regulate commercial space-related activities include the Federal Communications Commission; National Oceanic and Atmospheric Administration; Department of State, which manages the *International Traffic in Arms Regulations* (22 CFR Parts 120 through 130); and Department of Commerce, which manages the *Export Administration Regulations* (15 CFR Parts 730 through 774).

As part of these responsibilities, the FAA/AST issues licenses and experimental permits for commercial launches and reentries of orbital and suborbital rockets. AST comprises the Office of the Associate Administrator along with five divisions: the Space Transportation Development Division, Licensing and Evaluation Division, Regulations and Analysis Division, Safety Inspection Division, and Operations Integration Division.[100]

The FAA/AST received quarterly briefings from Scaled and Virgin Galactic about the SS2 and WK2 programs. The quarterly briefings included topics such as program milestones since the time of the previous meeting, rocket motor and systems updates, experimental permit progress, and future scheduled activities. The first quarterly briefing occurred on January 20, 2011, and the last quarterly briefing before PF04 occurred on August 13, 2014.

1.4.2.1 Experimental Permit Evaluation Process

1.4.2.1.1 Experimental Permit Background Information

The Commercial Space Launch Amendments Act of 2004 (Public Law 108-492), which was enacted to "promote the development of the emerging commercial human space flight industry," established the experimental permit regime (as an alternative to licensing) for manned and unmanned developmental reusable suborbital rockets. This act made it easier for the commercial space industry to test experimental reusable suborbital rockets because experimental permits could be granted more quickly and with fewer requirements than licenses. As stated in 14 CFR 413.15, the FAA's review period for an experimental permit application is 120 days; the review period for a reusable launch vehicle mission license is 180 days.[101]

In an April 6, 2007, final rule titled "Experimental Permits for Reusable Suborbital Rockets" (*Federal Register* 2007, 17001), the FAA stated that it was amending its commercial space transportation regulations under the Commercial Space Launch Amendments Act of 2004 to establish "application requirements for an operator of a manned or unmanned reusable suborbital rocket to obtain an experimental permit" and "operating requirements and restrictions on launch and reentry of reusable suborbital rockets operated under a permit." These amendments became effective on June 5, 2007.

The final rule enacted 14 CFR Part 437, "Experimental Permits," which provides information on the requirements to obtain and operate under an experimental permit. Section 437.5, "Eligibility for an Experimental Permit," stated that the FAA would issue an experimental permit to launch or reenter a reusable suborbital rocket only for—

> (a) Research and development to test new design concepts, new equipment, or new operating techniques;
>
> (b) A showing of compliance with requirements for obtaining a license under [14 CFR Parts 413 through 460]; or

[100] The FAA/AST's Licensing and Evaluation Division is responsible for approving experimental permit applications and developing experimental permit terms and conditions.

[101] In addition, the FAA prohibits carrying any property or human being for compensation or hire under an experimental permit but allows revenue-generating launches under a license. Title 14 CFR Part 415, "Launch License," provides regulatory information regarding launch licenses.

(c) Crew training before obtaining a license for a launch or reentry using the design of the rocket for which the permit would be issued.

The Commercial Space Launch Amendments Act of 2004 also included a provision indicating that, after an 8-year period, new regulations regarding commercial human space flight for crews and space flight participants could be proposed. The act stated that "any such regulations shall take into consideration the evolving standards of safety in the commercial space flight industry." The 8-year period was subsequently extended to October 1, 2015, but current working legislation was expected to further extend this date until at least 2020.

1.4.2.1.2 SpaceShipTwo Experimental Permit History

In March 2010, the FAA/AST began meeting with Scaled as part of the preapplication consultation process for obtaining an experimental permit for SS2.[102] During this process, the FAA/AST's main point of contact with Scaled was a member of the FAA/AST's west coast field operations office in Palmdale, California (which became a part of the FAA/AST's Operations Integration Division after its creation in 2012). The responsibilities of the FAA/AST main point of contact were to directly interact with Scaled and build a relationship and facilitate communication between Scaled and the FAA/AST. As part of the preapplication consultation process, Scaled submitted two draft versions of the SS2 experimental permit and supporting material to the FAA/AST main point of contact, who forwarded the information to the appropriate FAA/AST staff members for review. The FAA/AST main point of contact compiled the staff members' comments and provided them to Scaled. In addition, a Scaled project engineer stated that the SS2 hazard analysis was discussed with the FAA/AST during preapplication consultation meetings, and he did not recall any of the FAA/AST meeting participants disagreeing with Scaled's approach to system safety.

On January 24, 2012, Scaled submitted its Experimental Permit Application for the Tier 1B Reusable Suborbital System to the FAA/AST to obtain an experimental permit under 14 CFR Part 437 to conduct rocket-powered flight tests for SS2. In the application, Scaled stated that the SS2 vehicle would be flown to "test the design, equipment, and operating concepts of the vehicle, train crew in the operation of the vehicle, [and] obtain data necessary for [Virgin] Galactic to obtain a launch license."

The experimental permit evaluation process begins after the FAA/AST determines that an application is "complete enough."[103] For an application to be considered complete enough, the FAA/AST must determine that the application contains material that directly addresses each applicable regulation and that the material is clear and well supported with no obvious

[102] Title 14 CFR 413.5, "Pre-application Consultation," stated that "a prospective applicant must consult with the FAA before submitting an application to discuss the application process and possible issues relevant to the FAA's licensing or permitting decision." The regulation also stated, "early consultation helps an applicant to identify possible regulatory issues at the planning stage when changes to an application or to proposed licensed or permitted activities are less likely to result in significant delay or costs to the applicant." The preapplication consultation process is further discussed in section 1.4.2.1.5.

[103] Title 14 CFR 413.11, "Acceptance of an Application," states, "the FAA will initially screen an application to determine if it is complete enough for the FAA to start its review."

inconsistencies among the responses to the requirements of different regulations.[104] In a February 7, 2012, letter, the FAA/AST informed Scaled that its SS2 experimental permit application met the "complete enough" criteria.

Experimental permit evaluation teams perform more comprehensive reviews than those performed during the preapplication consultation process. The permit evaluation teams generally include (1) a permit team lead from the FAA/AST's Licensing and Evaluation Division, (2) multiple analysts from the FAA/AST's Regulations and Analysis Division who specialize in operating area analysis, hazard analysis, and maximum probable loss analysis, and (3) multiple engineers from the Licensing and Evaluation Division who specialize in safety-critical vehicle systems, such as propulsion, avionics, and flight controls. The permit team lead assigns each team member the responsibility for evaluating specific elements of the application, which includes checking the applicant's material to ensure that it demonstrates compliance with applicable regulations. The team meets regularly to discuss the status of the evaluation and review its findings. When the permit evaluation is completed, the team provides FAA/AST management with a summary of the application and supporting material and the team's recommendation regarding whether to grant the permit, and FAA/AST management decides the matter.

On May 23, 2012, the FAA/AST issued Commercial Space Transportation Experimental Permit Number EP 12-007 to Scaled. The permit, which the manager of the FAA/AST's Licensing and Evaluation Division signed, authorized Scaled to conduct "(1) an unlimited number of launches of SpaceShipTwo utilizing WhiteKnightTwo within the operating area identified by permit order A; and (2) pre-flight and post-flight ground operations at Mojave Air and Space Port associated with permitted flights of SpaceShipTwo utilizing WhiteKnightTwo."[105] Permit order A also included a condition (referred to as permit condition 8) that required Scaled to submit an updated hazard analysis showing that all identified hazards had been mitigated.[106] The FAA/AST had to approve this analysis before any SS2 permitted flight.

Experimental permits are valid for 1 year and can be renewed.[107] On March 6, 2013, Scaled submitted an application to renew its experimental permit. In accordance with 14 CFR 437.85, "Allowable Design Changes; Modification of an Experimental Permit," Scaled requested that its permit be modified because of the changes that had been made to SS2 since the time that the original permit was issued. As part of the application, Scaled provided an update to

[104] The FAA/AST's policy was to notify the applicant in writing, within 14 days from the date that an application was received, regarding whether the application was considered complete enough. During this time, the FAA/AST and the applicant might discuss ways to clarify statements in the application, identify any missing material, and determine how the applicant would provide that material.

[105] Permit order A stated that the operating area was the restricted airspace referred to as R-2508 (as discussed in section 1.1.4).

[106] According to the FAA/AST, this information would typically be included in an experimental permit application, but, in this case, Scaled had not completed this work.

[107] Title 14 CFR 413.23, "License or Permit Renewal," states that a permittee can apply to renew a permit by submitting a written application for renewal to the FAA at least 60 days before the permit expires.

its original hazard analysis, as required by condition 8 of the permit.[108] In an April 23, 2013, letter, the FAA/AST notified Scaled that it had met the requirements of condition 8.

The FAA/AST granted Scaled's request to renew the SS2 experimental permit and issued revision 1 of the permit on May 22, 2013. The renewed permit was subject to the terms, conditions, and limitations detailed in the original permit (except for the requirement for Scaled to submit an updated hazard analysis, which was no longer included as a condition of the permit.)

After the FAA/AST granted the first renewal of the SS2 experimental permit, the FAA/AST formed a team to conduct another review of Scaled's hazard analysis because of questions that an FAA/AST system safety engineer raised. (The review team included the analyst who evaluated the original permit application and other analysts with system safety experience). The review determined that the hazard analysis did not meet the minimum regulatory requirements. As a result, on July 9, 2013, the FAA/AST issued a waiver for the software and human error hazard analysis requirements of sections 437.29 and 437.55(a) for the first renewal of Scaled's experimental permit.[109] The FAA's notice of waiver (*Federal Register* 2013, 42994) stated that, although Scaled's experimental permit application did not identify software or human errors, the mitigations that Scaled had in place—aircraft and spacecraft design redundancy, flight and maintenance procedures, and ground and flight training—would prevent hazards resulting from such errors. Scaled did not request the waiver or have an opportunity to comment on the waiver before it was issued (except to identify proprietary information that should not be disclosed).[110]

The notice of waiver further stated that the FAA/AST was granting the waiver because it "is in the public interest and will not jeopardize public health and safety, safety of property, and national security and foreign policy interests of the United States." The FAA/AST determined that the operation of the SS2 vehicle and Scaled's activities would not jeopardize public health and safety or safety of property based on 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." The FAA/AST also determined that the waiver would not impact any US national security or foreign policy interest because Scaled's launch operations would occur within a specifically defined area in the United States used for military operations. In addition, the FAA/AST

[108] The update included two documents: "Clarification of Hazard Analyses Mitigations," dated April 4, 2013, and "Additional Information About Hazards," dated April 18, 2013.

[109] The FAA/AST can decide to waive an experimental permit requirement if the waiver (1) will not jeopardize public health and safety or safety of property, (2) will not jeopardize US national security and foreign policy interests, and (3) will be in the public interest. Title 14 CFR 417.3, "Definitions and Acronyms," states that a waiver "allows a launch operator to continue with a launch despite not satisfying a specific safety requirement and where the launch operator is not able to demonstrate an equivalent level of safety." The FAA/AST's Licensing and Evaluation Division led the evaluation of the waiver for Scaled with assistance from other FAA/AST divisions. The draft waiver was reviewed by other FAA/AST divisions, FAA/AST management, and the FAA general counsel before the manager of the Licensing and Evaluation Division signed the finalized waiver.

[110] In a March 4, 2015, document, Scaled stated, "in May 2013, AST unconditionally renewed Scaled's permit. Under these circumstances, Scaled understood it was in full compliance with FAA requirements." (The NTSB requested this document to determine Scaled's understanding of the issues related to the waiver.) The document also stated that Scaled "became aware of [the] FAA's intent to issue a waiver towards the end of June 2013."

determined that granting the waiver would be in the public interest because the SS2 test flights would stimulate economic growth, encourage technological developments, and create aerospace business opportunities.[111]

The FAA/AST received Scaled's second request for renewal of the SS2 experimental permit on March 17, 2014. The FAA/AST granted Scaled's request and issued revision 2 of the permit on May 21, 2014. Revision 2 of the permit was subject to the terms, conditions, and limitations detailed in revision 1 of the permit.

Also in its May 21, 2014, letter to Scaled, the FAA/AST stated that the experimental permit application included information about additional modifications to SS2 but did not include an updated hazard analysis. The letter notified Scaled that the FAA/AST had waived the hazard analysis requirements of sections 437.29 and 437.55(a) for revision 2 of the experimental permit. For the same reasons as those used to justify the initial waiver, the FAA/AST found that this waiver would not jeopardize public health and safety or safety of property, would not impact US national security or foreign policy interests, and would be in the public interest. (In April 2015, the FAA/AST clarified that the waiver pertained only to the software and human error hazard analysis requirements of the regulations.)

On July 16, 2014, Scaled submitted an application to modify revision 2 of the SS2 experimental permit to reflect material changes made to the vehicle (none of which involved the feather system). In an October 14, 2014, letter to Scaled, the FAA/AST approved the modifications and waived the requirements of 14 CFR 437.29 and 437.55(a) for the same reasons stated in its May 21, 2014, letter. According to the FAA/AST, this waiver pertained only to the software and human error hazard analysis requirements of the regulations and superseded the May 2014 waiver.

1.4.2.1.3 Analysis of Experimental Permit Evaluation Process

An FAA/AST analyst was required to perform a thorough evaluation of Scaled's hazard analysis to ensure that it clearly documented how compliance was shown for each of the hazard analysis requirements of 14 CFR 437.55(a). During a postaccident interview, the analyst who evaluated Scaled's applications for the SS2 original permit and first renewal of the permit stated that Scaled's analysis had addressed human error. He recalled that software and human errors were represented in the fault trees. However, the analyst did not document his rationale for accepting Scaled's method for addressing the section 437.55(a) human error requirements. If this information had been documented in the analyst's evaluation report, FAA/AST management and system safety analysts (who would later evaluate the hazard analysis for subsequent permit renewals) would have better understood the reasons for the FAA/AST's acceptance of the method that Scaled used to comply with the human error hazard analysis requirements.

Because the FAA/AST granted the original permit and the first renewal of the permit without any conditional requirements for Scaled to further address human error in its hazard analysis, Scaled believed that it had fully complied with 14 CFR 437.55(a). However, the

[111] According to the FAA, the Commercial Space Launch Act of 1984 (Public Law 98-575) was established to encourage private sector launches, reentries, and associated services, and the SS2 test flights supported the goals of 51 *United States Code* 509, "Commercial Space Launch Activities" (formerly known as the Commercial Space Launch Act).

FAA/AST's review of Scaled's hazard analysis (after the first renewal of Scaled's permit had been issued) determined that the hazard analysis did not meet the requirements of section 437.55(a) addressing software and human errors. Specifically, Scaled's hazard analysis did not clearly establish the relationship between each of the requirements of the regulation, the assumptions made, the resulting method used to show compliance, and any mitigations used.

On the basis of its evaluation, the review team recommended that FAA/AST management direct Scaled to either request a waiver or develop additional information showing how its hazard analysis met the requirements of the regulation. However, FAA/AST management decided to issue the waiver relieving Scaled from the software and human error requirements of 14 CFR 437.55(a) without giving Scaled an opportunity to comment on or correct the areas of noncompliance before the waiver was issued. In addition, the FAA/AST did not consult with Scaled technical staff as part of the waiver evaluation process.

According to an April 2015 FAA memo in response to an NTSB request for information as part of this accident investigation, the FAA/AST did not ask Scaled to modify its hazard analysis because the areas of noncompliance raised no public safety issues. The memo indicated that the FAA/AST's original evaluation determined that Scaled's approach for demonstrating compliance with the hazard analysis requirements of 14 CFR 437.55 was "sufficiently rigorous" to ensure public safety. The memo also indicated that, after reassessing Scaled's hazard analysis, the FAA/AST recognized that a waiver was "procedurally" necessary because Scaled's approach did not meet all of the requirements in the regulation.

The NTSB concludes that the FAA/AST's evaluations of Scaled Composites' initial and first renewal of the SS2 experimental permit application were deficient because the evaluations failed to recognize that Scaled Composites' hazard analysis did not meet regulatory requirements to identify hazards caused by human error. Therefore, the NTSB recommends that the FAA implement steps in its evaluation of experimental permit applications to ensure that applicants have (1) identified single flight crew tasks that, if performed incorrectly or at the wrong time, could result in a catastrophic hazard, (2) assessed the reasonableness, including human factor considerations, of the proposed mitigations to prevent errors that could result from performing those tasks, and (3) fully documented the rationale used to justify related assumptions in the hazard analysis required by 14 CFR 437.55.

The NTSB believes that the FAA/AST should only waive regulatory requirements for identifying hazards caused by human error under very limited circumstances and should ensure that an applicant seeking a waiver has sufficiently justified the basis for the waiver. If the FAA/AST decides to waive a requirement to comply with a regulation, provisions should exist, independent from the requirement being waived, to adequately address safety. In this case, the FAA/AST waived the need to include human errors in the SS2 hazard analysis but then depended in part on human error-related mitigations (including Scaled's pilot training) as a basis for the waiver. Therefore, the NTSB also recommends that the FAA develop a process to determine whether an experimental permit applicant has demonstrated the adequacy of existing mitigations to ensure public health and safety as well as safety of property before granting a waiver from the human error hazard analysis requirements of 14 CFR 437.55.

1.4.2.1.4 Waiver Mitigations

The FAA's April 2015 memo stated that the FAA/AST granted the waiver for compliance with the software and human error requirements of 14 CFR 437.29 and 437.55(a) based on mitigation measures that were "extracted" from Scaled's experimental permit application. The memo also stated that Scaled was required to comply with these mitigations because 14 CFR 437.83, "Compliance With Experimental Permit," required a permittee to conduct its operations according to the representations made in its permit application.

In its July 2013 notice of waiver, the FAA stated that flight crew training, which included the use of the SS2 simulator, was among the mitigations that Scaled had in place to protect against human errors. For example, the waiver stated that "Scaled runs its simulator 1.4 times faster than actual flight in order to ensure that pilots and ground crew are trained to respond quickly to various flight conditions and anomalies." However, Scaled's director of flight operations could not remember the last time that the simulator was operated at 1.4 times the normal speed but thought that it had been "a while." He did not think that the simulator had been operated at 1.4 times the normal speed as part of PF04 preparation. The NTSB's review of data from the PF04 integrated simulator sessions showed that all recorded sessions were run at the normal speed during the boost phase. In addition, Scaled test pilots indicated that the simulator was sometimes (but not often) operated at 1.4 times the normal speed during the SS2 program, and no FAA/AST inspectors recalled observing simulations at 1.4 times the normal speed.

The notice of waiver also stated that the FAA/AST determined that SS2's operation would not jeopardize public health and safety or safety of property based on, among other things, Scaled's use of chase planes. Specifically, the waiver stated that Scaled's use of "two chase planes" for SS2 flights "allows Scaled to identify problems when the system itself fails to disclose them, and provides redundancy." The waiver also stated that "the chase planes are able to monitor the WhiteKnightTwo and the SS2, so that if there is a computer failure and the pilot would not otherwise know of an external failure . . . the chase planes are able to provide that information." However, the use of chase planes was not addressed in Scaled's experimental permit application, and, for PF04, Scaled used only one chase plane (the Extra EA-300L). In addition, the waiver stated that, upon reentry of SS2, Scaled would use WK2 as an "additional chase plane"; the FAA/AST did not consider WK2 to be a second chase plane during the air launch, boost, and apogee phases of flight.[112]

It was unclear, from postaccident interviews with FAA/AST and Scaled personnel, who was responsible for ensuring that Scaled complied with the mitigations identified in the waiver. According to most FAA/AST inspectors interviewed, the inspector was responsible for ensuring that Scaled complied with regulations (as discussed in section 1.4.2.2), but Scaled was responsible for informing the FAA/AST of any changes to the mitigations in the waiver. However, an SS2 project engineer stated that Scaled "did not see the waiver as regulatory in any way, but rather as a way to relieve responsibilities."

It is important for FAA/AST inspectors to verify that an operator is performing the mitigations identified in a safety-related waiver of specific federal regulations so that the

[112] The Extra EA-300L POH stated that the airplane has a normal cruise speed of 170 knots, a maximum speed of 220 knots, and a service ceiling of 16,000 ft.

FAA/AST can fulfill its mandate to ensure public safety during commercial space operations. The NTSB is concerned about the FAA/AST's lack of awareness regarding whether Scaled was in compliance with the mitigations discussed in the waiver from the software and human error hazard analysis requirements of 14 CFR 437.55(a). Some of the inspectors who were interviewed were unfamiliar with the details of the waiver, and all of the interviewed inspectors thought that Scaled complied with the waiver for each powered flight. The NTSB concludes that the FAA/AST did not ensure that Scaled Composites was in compliance with the mitigations cited in the waiver from regulatory requirements or determine whether those mitigations would adequately address human errors with catastrophic consequences. Therefore, the NTSB recommends that the FAA develop and implement procedures and guidance for confirming that commercial space operators are implementing the mitigations identified in a safety-related waiver of federal regulations and work with the operators to determine the effectiveness of those mitigations that correspond to hazards contributing to catastrophic outcomes.

1.4.2.1.5 Preapplication Consultation Process

Scaled had fully complied with the preapplication consultation requirements of 14 CFR 413.5 by consulting with the FAA/AST before formally submitting the SS2 experimental permit application. During the SS2 preapplication consultation process, which began in March 2010 and ended in January 2012 (when Scaled formally submitted its application), Scaled and the FAA/AST met to discuss the SS2 project, including each of the vehicle's major systems, and resolved issues that could have impeded the permit evaluation process.

The NTSB notes that the SS2 preapplication consultation process began 3 months before the FAA issued the first special airworthiness certificate for SS2. Thus, when the preapplication process began, SS2 had been designed and manufactured, and the SSA was well underway. At that point, it could have been difficult and costly for Scaled to make changes to SS2 if the FAA/AST had found inadequacies in Scaled's hazard analysis, especially if those inadequacies could only be effectively addressed by changes to the vehicle's design.

AC 413-1, "License Application Procedures," dated August 16, 1999, stated that the preapplication consultation was an informal structure that "need not be accomplished within a set timetable." However, applicants could benefit from starting regular communication with the FAA/AST before a commercial space vehicle has been designed and/or manufactured. For example, starting the preapplication consultation process early would allow the applicant to discuss a vehicle's proposed design and development with the FAA/AST to identify potential issues and resolve any concerns at the planning stage, when changes to an applicant's program would be less likely to result in significant delays or costs. Such early communication would also provide an opportunity for the applicant and the FAA/AST to work together to agree on the methods to be used for complying with all pertinent regulations (including 14 CFR 437.55), as well as the level of detail that the FAA/AST would expect the applicant's hazard analysis to include, before the applicant accomplishes most of the work on a commercial space vehicle. The NTSB notes that the preapplication consultation process would also be an ideal time for the FAA/AST and the applicant to determine whether human error could result in a catastrophic hazard of a safety-critical vehicle system.

The NTSB concludes that the experimental permit preapplication consultation process would be more effective if it were to begin during a commercial space vehicle's design phase so that concerns can be resolved before a commercial space vehicle is developed and manufactured and potential catastrophic hazards resulting from human error can be identified early. In addition, the NTSB notes that AC 413-1 was issued before the experimental permit regime was established (by the Commercial Space Launch Amendments Act of 2004) and that similar guidance has not been established to indicate that the information in the AC also applies to experimental permit applicants.[113] Therefore, the NTSB recommends that the FAA develop and issue guidance for experimental permit applicants that (1) includes the information in AC 413-1 and (2) encourages commercial space vehicle manufacturers to begin the consultation process with AST during a vehicle's design phase.

1.4.2.2 Safety Inspections

A safety inspector and an assistant safety inspector from the FAA/AST's Safety Inspection Division were assigned to PF04. The inspectors were assigned to the individual launch operation and not specifically to Scaled. Although inspections for experimental permit operations were not required by federal regulations, the FAA/AST had an internal policy to conduct launch inspections (as staffing and resources permitted) using an internally generated safety inspection plan (SIP).[114] The primary focus of the SIP was to ensure compliance with federal regulations and the terms and conditions of the experimental permit and verify that the representations made in the operator's experimental permit application were still accurate. Inspectors could not cancel a launch for noncompliance and could only inform an operator about any areas of noncompliance.

SIPs were created from a general template and then were subsequently tailored for a particular launch operation. According to an FAA/AST inspector, a SIP was generally accomplished several days before a launch, and inspectors were occasionally unable to accomplish all of the checklist items on the SIP because of time constraints. For PF04, inspections of Scaled's operations, including a review of pilot and maintenance records, occurred on October 29, 2014, and an inspection of the launch operation occurred 2 days later (on the day of the accident).[115]

1.4.2.2.1 Analysis of Safety Inspections

The FAA/AST's surveillance of commercial space operators' launch operations was limited to completion of the SIP given the FAA/AST's mandate to ensure public safety during commercial space launches. This limitation precluded inspectors from conducting a comprehensive review of the operator and its commercial space vehicle. For example, although the inspectors for PF04 stated that they reviewed the PF04 flight test data card, neither of the inspectors recognized that the 0.8 Mach callout procedure and the trim callout procedure on the test card did not also appear in the SS2 normal procedures manual, even though the manual had

[113] For example, the AC states that it provides guidance to "launch applicants" and that the procedures within the AC apply "to any application for a license" for a launch or reentry vehicle.

[114] Even though the FAA was not required to conduct any inspection of a permittee, 14 CFR 437.93, "Compliance Monitoring," required Scaled to be available for inspections.

[115] The FAA/AST's inspection of Scaled's integrated simulation sessions occurred on October 17 and 27, 2014.

been updated 2 weeks before the accident.[116] Flight test data cards reflect the knowledge gained from previous test flights and the analysis of data from those flights, so it is important that FAA/AST inspectors review the POH to ensure that the procedures in both documents are consistent.[117] It is also important for FAA/AST inspectors to ensure that the POH has been updated with the most current procedures so that they can be formalized for current and future SS2 pilots.

POH revisions during an experimental flight test program are common as the program continues to mature, and the SIP included a note to inspectors that advised them that flight crew procedures would be frequently updated. However, the FAA/AST lead inspector for PF04 stated that he was not that familiar with the SS2 POH. Inspectors need to be aware of the revisions to the POH so that they can understand operational changes as they relate to the FAA/AST's mandate to protect the public during commercial space operations. Inspectors also need to be aware of POH revisions because both the POH and the flight test data card are used during SS2 simulations and operations.

As part of the SIP, the lead FAA/AST inspector for PF04 toured the simulator to check its fidelity. However, the SIP did not include a thorough review of the simulator, so that portion of the inspection was effectively just an observation. During the simulator inspection, the lead inspector was not informed of, and did not notice, that the MFD software had been upgraded to show pitch and roll trim values below the airspeed indicator on each pilot's PFD. As a result, the inspector was not familiar with the information that would be displayed on the PFDs during the flight.

The FAA/AST's limited surveillance of commercial space operators' launch operations is hampered by the fact that FAA/AST inspectors are assigned to an individual commercial space launch operation rather than the commercial space operator itself. As a result, FAA/AST inspectors have limited time (even with a preinspection meeting to prepare for a launch inspection) to understand a permittee's or licensee's training, procedures, and operations before conducting the SIP. Because the PF04 inspectors did not have any significant experience with Scaled, they lacked ongoing knowledge of Scaled's operations and procedures and missed the change to the simulator software and the inconsistencies between the PF04 flight test data card and the SS2 POH. In addition, even though SIPs were designed to ensure compliance with federal regulations and the representations made in an experimental permit application, none of the FAA/AST inspectors for PF02, PF03, and PF04 verified whether Scaled was performing the

[116] The 0.8 Mach callout originated after PF01 as a way for the pilot monitoring to prepare the pilot flying for the transonic bobble. The callout did not appear on the flight test data cards for PF02 and PF03 because, at the time, the callout was being used as a technique rather than a formal procedure. Many FAA/AST personnel and inspectors were either unaware or could not remember that, for PF02 and PF03, SS2 pilots used the technique of calling 0.8 Mach before the transonic bobble. The 0.8 Mach callout was formalized as a procedure after PF03 and was included in the flight test data card more than 3 months before PF04 occurred.

[117] The final report for the PF04 SIP indicated that the inspectors received the flight test data card for PF04, but the report did not indicate whether the inspectors had the most current SS2 POH or whether they had compared the flight test data card procedures with those in the SS2 POH.

mitigations involving the simulator and chase planes that were identified in the FAA/AST's waiver of two federal regulations.[118]

In the aviation sector, the FAA assigns flight test engineers and pilots to specific manufacturer certification programs. These flight test engineers and pilots, because of their continuing involvement with an individual manufacturer, are able to acquire comprehensive knowledge of the specific vehicle and the manufacturer's training, procedures, and organizational culture, which helps them understand ongoing changes to a certification program. The NTSB recognizes that commercial space vehicles are not certified in the same manner as aircraft are; however, the FAA's philosophy for aircraft programs would benefit commercial space manufacturers. For example, an FAA/AST inspector with surveillance responsibilities for a specific permittee or licensee would bring continuity and consistency to the inspection process. Also, an FAA/AST inspector who is assigned to a specific permittee or licensee could develop a foundation of knowledge and experience related to that operator and its vehicle, which could improve surveillance by better preparing the inspector to conduct the SIP.

The NTSB concludes that the effectiveness of the FAA/AST's inspection process would be improved if inspectors were assigned to commercial space operators rather than individual commercial space launch operations because the inspectors could become more familiar with the operators' training and procedures and could identify ways to enhance safety. Therefore, the NTSB recommends that the FAA develop and implement a program for AST inspectors that aligns them with individual operators applying for an experimental permit or a launch license to ensure that the inspectors have adequate time to become familiar with the technical, operational, training, and management controls that they will inspect.

1.4.2.3 Analysis of Office of Commercial Space Transportation's Organizational Information

According to the FAA, a safety management system (SMS) is the "formal, top-down business approach to managing safety risk, which includes a systemic approach to managing safety, including the necessary organizational structures, accountabilities, policies and procedures."[119] FAA Order 8000.369A, "Safety Management System," dated May 8, 2013, required FAA organizations, including AST, to "establish guidance for their own SMS activities and their industry segment on implementing SMS." AST did not have an SMS in place during the SS2 preapplication consultation and permit evaluation processes. AST released its "FAA Office of Commercial Space Transportation Safety Management System (SMS) Manual" in

[118] The NTSB reviewed the results of the SIPs conducted before each powered flight. The final reports for the PF02 and PF03 SIPs both stated that the waiver of 14 CFR 437.29 and 437.55(a) was among the "pre-approved non-compliances (waivers, equivalent levels of safety) . . . associated with this safety inspection." (PF01 occurred in April 2013, and the FAA/AST issued the initial waiver in July 2013.) The final report for the PF04 SIP did not indicate whether the waiver of sections 437.29 and 437.55(a) was associated with the PF04 inspection. An FAA/AST inspector stated that this oversight might have been a result of the computer entry process to create the final SIP report.

[119] This and other SMS information can be found on the FAA's website (www.faa.gov/about/initiatives/sms/, accessed June 15, 2015).

September 2014, which was revised in April 2015, to integrate SMS safety processes with existing AST processes, procedures, and policies.[120]

The four main components of an SMS are safety policy, safety risk management, safety assurance, and safety promotion. SMS basic principles include, but are not limited to, management commitment to improving safety; defined methods, processes, and organizational structure to meet safety goals; training, communication, and other actions to create a positive safety culture; risk controls through structured safety assurance processes; and effective knowledge sharing between the regulator and certificate holder. Although the FAA/AST was not required, during the SS2 preapplication consultation and experimental permit evaluation processes, to follow basic SMS principles, doing so would have improved these processes. For example, on the basis of information learned during postaccident interviews, the FAA/AST was not practicing effective knowledge sharing given the barriers to communication between FAA/AST analysts, evaluators, and engineers and experimental permit applicants, which impeded FAA/AST staff's ability to develop a complete understanding of the applications that Scaled submitted for evaluation.

As previously stated, one FAA/AST employee was the main point of contact for Scaled throughout the SS2 project. The deputy manager of the FAA/AST's Regulations and Analysis Division indicated that a single point of contact would "reduce the burden" on Scaled of having to interact with multiple individuals from the FAA/AST during the SS2 project.[121] As a result, the main point of contact (in the FAA/AST's Operations Integration Division) would provide information, such as a draft experimental permit application, a draft hazard analysis, or questions from Scaled, to the permit team lead (in the FAA/AST's Licensing and Evaluation Division), who would provide the information to the other permit evaluation team members. Likewise, when permit evaluation team members had questions for Scaled, the questions would be vetted by management and submitted through the permit team lead to the FAA/AST main point of contact, who would provide the questions to Scaled.

As a part of the review of SS2's experimental permit application, FAA/AST analysts and evaluators reviewed the assumptions in Scaled's hazard analysis that related to crew interactions with the vehicle and developed questions related to SS2's design and operation. Many of the questions that FAA/AST technical staff posed to Scaled technical staff were necessary to understand the hazards that could be present in the operation and the design, operational, and management controls that would be necessary to comply with existing FAA regulations to ensure public safety. However, FAA/AST technical staff members stated that, during the permit evaluation process, their questions to Scaled that did not directly relate to public safety were "filtered" or "scrubbed." One FAA/AST evaluator noted that, because these questions were

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[120] In addition, the FAA's Commercial Space Transportation Fiscal Year 2015 Business Plan, (www.faa.gov/about/plans_reports/media/2015/ast_business_plan, accessed June 15, 2015) which was dated January 21, 2015, stated the following core activities regarding SMS: "support FAA's SMS Executive Council and FAA SMS Committee on SMS concerns affecting multiple lines of business" and "modify AST's Safety Management System (SMS) as required to conform with FAA-wide policy, in order and to address industry's safety risk management issues more effectively." Modifications to AST's SMS were expected to be completed by September 30, 2015.

[121] Similarly, an external consultant who worked with the FAA/AST on Scaled's experimental permit application described AST as a "culture of not wanting to over-burden the applicant."

filtered, the technical information received in response was "so washed out, it's not even what we asked for in the beginning." Further, FAA/AST engineers with significant expertise in space operations (from their previous experience at NASA with the space shuttle and International Space Station programs) expressed frustration that their questions to experimental permit applicants were reviewed and significantly edited by FAA/AST management and Operations Integration Division staff members who had limited knowledge about space flight.

In addition, there was a push by FAA/AST management to approve experimental permit applications within the 120-day review period. Although FAA/AST had a process to delay the review period (referred to as "tolling"), that process was not used often and was not used for Scaled's initial or renewal permit applications.[122] An FAA/AST engineer stated, "what really exacerbates the pressure on us, or the time constraints, is the fact that . . . the technical data that we need to really do the evaluation isn't always there . . . [but] we had to press forward in the majority of the cases." An FAA/AST evaluator added that there was "a lot of pressure, political pressure" to issue experimental permits, even when FAA/AST evaluators were uncomfortable with an application, which diminished AST's safety culture.

The NTSB is encouraged by the FAA/AST's progress in implementing SMS and believes that, if SMS principles are followed, they will be an effective means for enhancing the regulatory oversight of the commercial space industry. However, at the time of the evaluation of Scaled's experimental permit applications, FAA/AST management underutilized FAA/AST evaluators' expertise, even though they understood the risks associated with commercial space flight, because FAA/AST management appeared to be more concerned about ensuring that the FAA's authority in this emerging industry was not being exceeded beyond defined limits and maintaining the timeframe in which to approve experimental permit applications. Further, the filtering of questions and the lack of direct communication between FAA/AST technical staff and Scaled technical staff impeded Scaled's ability to take advantage of the FAA/AST's safety expertise.

The dividing line between the questions that the FAA/AST needs to ask to determine the risk to the public and those to assess mission objectives is not always apparent because certain aspects of a vehicle's design and operation could impact both public safety and mission safety assurance. Thus, extensive technical interactions between FAA/AST staff and prospective experimental permit applicants would help perform future permit evaluations more effectively and efficiently. The FAA/AST's broader understanding of the vehicle design will especially be critical to maintaining public safety in the licensing and permitting processes because each vehicle's design safety provisions will be unique until enough knowledge is available to implement performance-based regulatory standards.[123] Until that time, FAA/AST technical staff will need to rely solely on written and verbal communications with an applicant's technical staff to fully understand the factors that might be critical to public safety, such as system failure

[122] Paragraph (b) of 14 CFR 413.15, "Review Period," stated that a review period would be tolled if an application did not provide sufficient information to complete the evaluations required for a licensing or permitting determination or an issue existed that would affect a determination. If a review period were tolled, the FAA/AST would inform the applicant, in writing, of any information required to complete the application.

[123] The systems on each commercial space vehicle are different. As a result, an understanding of the systems on one commercial space vehicle does not necessarily transfer to another such vehicle.

modes and their effects, the potential for human errors that could contribute to a divergence from operating area containment boundaries, and hazard causes and controls.

The NTSB concludes that the lack of direct communications between FAA/AST technical staff and Scaled Composites technical staff, the pressure to approve experimental permit applications within a 120-day review period, and the lack of a defined line between public safety and mission safety assurance interfered with the FAA's ability to thoroughly evaluate the SS2 experimental permit applications. Therefore, the NTSB recommends that the FAA direct AST management to work with AST technical staff to (1) develop clearer policies, practices, and procedures that allow direct communications between staff and applicants, (2) provide clearer guidance on evaluating commercial space transportation permits, waivers, and licenses, and (3) better define the line between the information needed to ensure public safety and the information pertaining more broadly to ensuring mission success. The NTSB notes that government, academia, and/or other impartial sources with space transportation expertise could help the FAA/AST in developing balanced guidance that ensures both public safety and mission success.

1.4.2.4 Commercial Space Flight Lessons Learned Database

During 2010, the FAA/AST began efforts to create a mishap lessons learned database, the Commercial Space Transportation Lessons Learned System.[124] According to the FAA, this database was designed to facilitate "the sharing of lessons learned resulting from positive and negative experiences" and allow "members of the commercial space transportation industry and the interested public to access and submit lessons learned pertaining to commercial space transportation activities and operations." However, the database currently contains only three entries, all of which were from August 2010, and the website containing this information still needs to be fully developed.[125]

The aviation industry has databases documenting accident and incident findings, which have been highly beneficial in preventing accidents and reducing fatal accident rates because the databases contain information about previously unrecognized hazards, their causes, and corresponding corrective actions.[126] This information is available to safety stakeholders, including air carriers and manufacturers, which has allowed the entire aviation industry to benefit from the safety lessons learned from each event. A favorable safety record instills public confidence, which can be an important driver of government and business investment in transportation infrastructure to support increased public use and overall growth of a

[124] Title 14 CFR 401.5 states that a mishap is "a launch or reentry accident, launch or reentry incident, launch site accident, failure to complete a launch or reentry as planned, or an unplanned event or series of events resulting in a fatality or serious injury (as defined in 49 CFR 830.2), or resulting in greater than $25,000 worth of damage to a payload, a launch or reentry vehicle, a launch or reentry support facility or government property located on the launch or reentry site."

[125] For more information, see the FAA's Commercial Space Transportation Lessons Learned System (www.faa.gov/about/office_org/headquarters_offices/ast/programs/cstlls/, accessed June 15, 2015).

[126] These databases include the FAA's Aviation Safety Information Analysis and Sharing system (www.asias.faa.gov/, accessed June 15, 2015), which the FAA promotes as "an open exchange of safety information in order to continuously improve aviation safety," and the FAA's Lessons Learned From Transport Airplane Accidents library (http://lessonslearned.faa.gov/, accessed June 15, 2015).

transportation industry. Thus, a transparent mishap database could not only benefit safety (by disseminating lessons learned) but could also promote growth while the commercial space industry is in its current formative stage.

The NTSB notes that manufacturers or other safety stakeholders in the commercial space industry might have concerns about providing proprietary and confidential commercial information pertaining to mishaps, incidents, and accidents, which could impede sharing important safety lessons learned. In the aviation industry, the FAA has secured needed protections to prevent the public release of certain types of voluntarily provided, confidential safety information (which might otherwise not be available without such protections) for use solely by safety stakeholders to more quickly and readily implement effective safety improvements. Such protections could also be useful for a database of safety lessons learned from commercial space mishap investigations, especially as the industry continues to mature.

The NTSB concludes that a database of lessons learned from commercial space mishap investigations would provide mutual benefits to public safety and industry promotion and would thus be consistent with the FAA's mission and authority. Therefore, the NTSB recommends that the FAA, in collaboration with the commercial space flight industry, continue work to implement a database of lessons learned from commercial space mishap investigations and encourage commercial space industry members to voluntarily submit lessons learned.

1.5 Parachute and Emergency Oxygen System

As part of their flight gear on the day of the accident, the pilot and copilot wore high-altitude parachute systems manufactured by Butler Parachute Systems.[127] The high-altitude parachute system consisted of four major subassemblies: the harness and container, parachute canopy, emergency oxygen system, and automatic activation device. According to Butler, the parachute system was designed to slow the descent of a crewmember after an emergency egress at altitude. The parachute had a standard ripcord handle that was designed to initiate parachute deployment when pulled. The parachute system was also equipped with a static lanyard that attached to a crewmember's seat. If a crewmember were to evacuate or become separated from his or her seat, the lanyard would pull a pin that activated the automatic activation device, which was designed to deploy the parachute after a set of predetermined criteria were met.[128]

Data from the automatic activation device from the pilot's parachute system indicated that that the device activated at 11,590 ft and that the device's cutters, which allowed the parachute to release, activated at 10,870 ft. The pilot reported that he was brought back to consciousness by the opening of the parachute and the accompanying deceleration. Thus, the

[127] The cockpit seat backs were hollowed out to allow room for the pilot's and copilot's parachutes. According to the pilot, he and the copilot were using Virgin Galactic's parachutes instead of Scaled's parachutes (which were Butler parachutes with the same part number) because the WK2 and SS2 preflight operations would be occurring in Virgin Galactic's hangar.

[128] Among these criteria were an altitude below 13,000 ft (as measured by an internal pressure sensor) and a vertical speed in excess of about 6,500 ft/min.

presence and activation of the automatic activation device was likely instrumental in saving the pilot's life.[129]

The parachute system's emergency oxygen system was designed to be activated inside the vehicle when needed regardless of whether egress was required. The oxygen flow was activated by (1) unstowing the oxygen handle from a pocket with 1-inch Velcro tape on the upper right front parachute harness strap and (2) pulling the handle, which broke a brass nipple inside the valve at the top of the emergency oxygen bottle, allowing oxygen to flow through the oxygen hose and the CRU-60 fitting and into the pilot's oxygen mask.[130]

1.5.1 Forces Needed to Activate Oxygen System

As indicated in section 1.1.2, during a postaccident interview, the pilot recalled attempting to activate his oxygen, stating that he tried to activate it "many times" during his descent. He reported that he "got the feeling" that it was not working because he did not get any oxygen flow and that he used only his left hand when trying to activate the oxygen system. The oxygen handle on the pilot's parachute was found stowed in its Velcro pocket, and the oxygen bottle was found full.

Scaled had previously expressed concerns about the amount of force needed to activate the emergency oxygen system. Specifically, in November 2013, two Scaled employees, who were attempting to discharge an oxygen bottle before shipping a parachute system, discovered that it was extremely hard to pull the oxygen handle. The Scaled employees later tested the system and determined that about 50 lbs of force was needed to activate oxygen flow. Scaled's director of quality assurance then sent an e-mail to Butler Parachute Systems, stating that the pull force required to activate the oxygen bottle was too high. At the time, Butler's parachute system user's guide stated that the oxygen handle could be pulled "with either hand."[131]

Subsequent tests that Butler Parachute Systems conducted showed that the average pull force required for activation of the oxygen bottle was about 37 lbs. The tests also showed that none of the test subjects could activate the oxygen bottle with only one hand but that all of the subjects could activate the bottle with two hands. Butler made no change to the parachute system's design, but the company revised the wording in the parachute system user's guide to indicate that the oxygen handle should be pulled "with both hands" and that a pilot should "apply sustained force" until receiving oxygen.[132] In May 2014, Butler delivered its report on the results

[129] During his postaccident interview, the pilot mentioned that, as Scaled's director of flight operations, he worked directly with Butler Parachute Systems and was responsible for the inclusion of the automatic activation device on the latest parachute configuration.

[130] The CRU-60 fitting, which was attached to the right side of the parachute harness, enabled oxygen flow to a crewmember. The two oxygen inputs into the CRU-60 fitting were normal spacecraft oxygen from SS2's regulator and emergency bottle oxygen from the parachute system.

[131] Butler Parachute System's *High Altitude Emergency Parachute System User's Guide*, dated November 2012, stated the following regarding the activation of the emergency oxygen system: "grab the green handle on the right side of the harness with either hand and make a fist" and "pull the handle forcefully downward."

[132] Butler's revised parachute system user's guide, dated March 2014, stated the following: "grab the green handle on the right side of the harness with both hands and make a fist. Pull the handle forcefully downward and apply sustained force on the cable until you receive oxygen" and "keep applying sustained force until you receive oxygen."

of the oxygen bottle activation testing to Scaled's director of quality assurance. The report indicated that the oxygen system would not be modified but that the system could be easily activated when using two hands. Postaccident interviews with Scaled pilots indicated that the information in Butler's report was either not appropriately disseminated to and/or understood by all Scaled pilots using Butler parachute systems. These interviews demonstrated the pilots' lack of clarity regarding whether the activation of the emergency oxygen required a one- or two-hand pull.

In January 2015, the NTSB led tests on the oxygen system from the accident pilot's parachute system and found, among other things, that 57.8 lbs of force was needed to break the brass nipple on the oxygen bottle and discharge the oxygen. Another NTSB-led test found that 55.3 lbs of force was needed to activate a different oxygen bottle.

In a February 11, 2015, e-mail to the NTSB, Scaled indicated that it was working with Butler Parachute Systems to resolve the difficulties with activating the oxygen bottle, with the goal to "rework of all of [Scaled's] parachutes to a common configuration." Specifically, Scaled wanted "a suitable, coordinated redesign of the emergency oxygen activation [to] allow an either hand, single-handed activation, whether in the seat, free falling, or in chute." The NTSB is encouraged that Scaled and Butler have been working together to resolve the difficulties with activating the emergency oxygen bottle but notes that continued work is still needed to fully resolve this issue.[133]

1.5.2 Parachute Training

According to a Scaled test pilot, before the accident, the company's director of quality assurance briefed Scaled crewmembers about the use of the company's parachutes. The date of the briefing and the list of attendees could not be found in company records. The test pilot stated that the briefing included information about the fit, preflight, and operation of the mask and helmet; a description of how the parachute works and the various components; a demonstration of the proper fitting of the parachute; information about the clothing (flight suit, gloves, and boots) to be worn during flights; and a description of basic skills, such as the free-fall position and landing procedures.[134] The test pilot also stated that manuals for the types of parachutes that Scaled owned were available for crewmembers' self-study. The test pilot further stated that "the pilot in command of each flight was responsible for knowing [that] all who flew were familiar with use of the parachutes."

[133] Scaled stated that, in the interim, it removed the emergency oxygen handle from the company's Butler parachute systems and replaced the handle with an emergency oxygen "loop" that allowed a "strong one-handed pull with a thumb through the loop" to activate the systems' oxygen bottles. Virgin Galactic indicated that, while Butler was working on a permanent fix, Virgin Galactic pilots would use an ad-hoc procedure involving "cocking the [oxygen handle] by partially removing it from the Velcro."

[134] If an emergency necessitated an egress from SS2 while it was airborne, the pilots would follow the "Bailout" procedure defined in the SS2 emergency procedures manual. This procedure included raising the feather, activating the emergency oxygen bottle, depressurizing the cabin, opening the SS2 side door, and diving away from the vehicle.

1.5.3 Analysis of Parachute System Training and Procedures

During the investigation of this accident, the NTSB documented training and procedural deficiencies related to the parachute system. For example, Scaled did not have a formal training program in place at the time of the accident that would have provided pilots with regular hands-on experience with the parachutes that they would use during actual flights, including training on how to use the parachute's emergency oxygen system. It is unrealistic to expect pilots to reliably use all features of an emergency system for the first time while involved in a life-threatening situation.

Also, after the accident, the pilot's oxygen hose was found disconnected from the CRU-60 fitting; thus, the pilot would not have received oxygen even if he had successfully extracted the oxygen handle and activated the emergency oxygen bottle. During a postaccident interview, the pilot stated that he did not check any of the hoses (including the connection between the oxygen hose and the CRU-60 fitting) during his preflight examination of his parachute and that no specific written checklist existed for doing so.[135] The parachute system's oxygen hose was likely not connected to the CRU-60 fitting before the flight given that the interconnect fittings that fastened the hose into the CRU-60 were found undamaged. Further, the lack of a specific preflight checklist for the parachute system likely prevented this problem from being discovered. As a result, even if the pilot had been able to activate the oxygen system, the oxygen would have vented directly into the atmosphere instead of into his mask.

The NTSB concludes that additional parachute training and procedures would have better prepared Scaled Composites' test pilots for emergency situations. The NTSB notes that, in June 2015, Scaled provided documentation to the NTSB indicating that Scaled had significantly improved the scope of the company's training program and had created checklists for preflight inspections of the parachute systems. The training covered the parachute's construction, operation, and egress procedures, including how to (1) fall, (2) steer the canopy to a safe landing spot, (3) land, and (4) get safely out of the parachute on all types of terrain. The training also included actual hands-on activation of the emergency oxygen handle and ripcord handle. Scaled stated that, as of July 2015, all of its test pilots had received this training.[136] In addition, Scaled had also finalized a contract to provide egress and parachute recurrent training on an annual basis.

1.6 Postaccident Actions to Prevent Early Unlocking of Feather System

After the accident, Virgin Galactic assumed full responsibility for the completion of the SS2 flight test program and, along with The Spaceship Company, undertook a "comprehensive internal and external program review of the SpaceShipTwo design and operations." Virgin Galactic stated that it had implemented a change to SS2's design to prevent a pilot from

[135] On October 30, 2014, the pilot and the copilot preflighted their parachutes. The pilot stated that they found nothing abnormal during their examinations. The parachutes were left in SS2 overnight and were donned before takeoff the next morning.

[136] In a February 24, 2015, e-mail to the NTSB, Virgin Galactic indicated that all of its pilots received annual egress training in January 2015.

inadvertently unlocking or locking the feather locks during critical phases of flight. Specifically, Virgin Galactic/The Spaceship Company's systems safety review process recommended, and Virgin Galactic/The Spaceship Company's change control board authorized, the development of an electromechanical inhibit device to prevent inadvertent pilot actuation of the feather locks.[137] The second SS2 vehicle, which has been under construction since before the accident, has already been modified with this device.

Virgin Galactic reported that it added, to the SS2 normal procedures checklist and POH, a warning about the consequences of prematurely unlocking the feather locks. Virgin Galactic also reported that it was implementing a "comprehensive" crew resource management approach for all future SS2 operations, including a "challenge/response protocol for all safety-critical aircrew actions, to include feather lock handle movement." In addition, Virgin Galactic stated that it was conducting "a comprehensive internal safety review of all SpaceShipTwo systems to identify and eliminate any single-point human performance actions that could result in a catastrophic event."

[137] According to Virgin Galactic, the inhibit device fails to the uninhibited position and incorporates an electrical and independent mechanical override that requires flight crew actions that are "distinct and separate" from normal activation of the control.

2. Conclusions

2.1 Findings

1. Although the copilot made the required 0.8 Mach callout at the correct point in the flight, he incorrectly unlocked the feather immediately afterward instead of waiting until SpaceShipTwo reached the required speed of 1.4 Mach.

2. The unlocking of the feather during the transonic region resulted in uncommanded feather operation because the external aerodynamic loads on the feather flap assembly were greater than the capability of the feather actuators to hold the assembly in the unfeathered position with the locks disengaged.

3. The copilot was experiencing high workload as a result of recalling tasks from memory while performing under time pressure and with vibration and loads that he had not recently experienced, which increased the opportunity for errors.

4. The pilot and copilot were properly certificated and qualified. Fatigue and medical and pathological issues were not factors in this accident. The recovered vehicle components showed no evidence of any structural, system, or rocket motor failures before the in-flight breakup.

5. SpaceShipTwo's instantaneous impact point on the day of the accident was consistent with the requirements of 14 *Code of Federal Regulations* 437.57, "Operating Area Containment."

6. Although Scaled Composites' systems safety analysis (SSA) correctly identified that uncommanded feather operation would be catastrophic during the boost phase of flight and that multiple independent system failures had to occur to result in this hazard, the SSA process was inadequate because it resulted in an analysis that failed to (1) identify that a single human error could lead to unintended feather operation during the boost phase and (2) consider the need to more rigorously verify and validate the effectiveness of the planned mitigation measures.

7. By not considering human error as a potential cause of uncommanded feather extension on the SpaceShipTwo vehicle, Scaled Composites missed opportunities to identify the design and/or operational requirements that could have mitigated the consequences of human error during a high workload phase of flight.

8. Scaled Composites did not ensure that the accident pilots and other SpaceShipTwo test pilots adequately understood the risks of unlocking the feather early.

9. Human factors should be emphasized in the design, operational procedures, hazard analysis, and flight crew simulator training for a commercial space vehicle to reduce the possibility that human error during operations could lead to a catastrophic event.

10. The Federal Aviation Administration Office of Commercial Space Transportation's evaluations of Scaled Composites' initial and first renewal of the SpaceShipTwo experimental permit application were deficient because the evaluations failed to recognize that Scaled Composites' hazard analysis did not meet regulatory requirements to identify hazards caused by human error.

11. The lack of direct communications between Federal Aviation Administration (FAA) Office of Commercial Space Transportation technical staff and Scaled Composites technical staff, the pressure to approve experimental permit applications within a 120-day review period, and the lack of a defined line between public safety and mission safety assurance interfered with the FAA's ability to thoroughly evaluate the SpaceShipTwo experimental permit applications.

12. The Federal Aviation Administration Office of Commercial Space Transportation did not ensure that Scaled Composites was in compliance with the mitigations cited in the waiver from regulatory requirements or determine whether those mitigations would adequately address human errors with catastrophic consequences.

13. The experimental permit preapplication consultation process would be more effective if it were to begin during a commercial space vehicle's design phase so that concerns can be resolved before a commercial space vehicle is developed and manufactured and potential catastrophic hazards resulting from human error can be identified early.

14. The effectiveness of the Federal Aviation Administration Office of Commercial Space Transportation's inspection process would be improved if inspectors were assigned to commercial space operators rather than individual commercial space launch operations because the inspectors could become more familiar with the operators' training and procedures and could identify ways to enhance safety.

15. A database of lessons learned from commercial space mishap investigations would provide mutual benefits to public safety and industry promotion and would thus be consistent with the Federal Aviation Administration's mission and authority.

16. Scaled Composites and local emergency response officials could improve their emergency readiness for future test flights by making better use of available helicopter assets.

17. Additional parachute training and procedures would have better prepared Scaled Composites' test pilots for emergency situations.

2.2 Probable Cause

The National Transportation Safety Board determines that the probable cause of this accident was Scaled Composites' failure to consider and protect against the possibility that a single human error could result in a catastrophic hazard to the SpaceShipTwo vehicle. This failure set the stage for the copilot's premature unlocking of the feather system as a result of time pressure and vibration and loads that he had not recently experienced, which led to uncommanded feather extension and the subsequent aerodynamic overload and in-flight breakup of the vehicle.

3. Recommendations

As a result of this investigation, the National Transportation Safety Board makes the following safety recommendations:

To the Federal Aviation Administration:

In collaboration with the Commercial Spaceflight Federation, develop and issue human factors guidance for operators to use throughout the design and operation of a crewed vehicle. The guidance should address, but not be limited to, the human factors issues identified during the SpaceShipTwo accident investigation. (A-15-19)

Implement steps in your evaluation of experimental permit applications to ensure that applicants have (1) identified single flight crew tasks that, if performed incorrectly or at the wrong time, could result in a catastrophic hazard, (2) assessed the reasonableness, including human factor considerations, of the proposed mitigations to prevent errors that could result from performing those tasks, and (3) fully documented the rationale used to justify related assumptions in the hazard analysis required by 14 *Code of Federal Regulations* 437.55. (A-15-20)

Develop a process to determine whether an experimental permit applicant has demonstrated the adequacy of existing mitigations to ensure public health and safety as well as safety of property before granting a waiver from the human error hazard analysis requirements of 14 *Code of Federal Regulations* 437.55. (A-15-21)

Develop and implement procedures and guidance for confirming that commercial space operators are implementing the mitigations identified in a safety-related waiver of federal regulations and work with the operators to determine the effectiveness of those mitigations that correspond to hazards contributing to catastrophic outcomes. (A-15-22)

Develop and issue guidance for experimental permit applicants that (1) includes the information in Advisory Circular 413-1, "License Application Procedures," and (2) encourages commercial space vehicle manufacturers to begin the consultation process with the Office of Commercial Space Transportation during a vehicle's design phase. (A-15-23)

Develop and implement a program for Office of Commercial Space Transportation inspectors that aligns them with individual operators applying for an experimental permit or a launch license to ensure that the inspectors have adequate time to become familiar with the technical, operational, training, and management controls that they will inspect. (A-15-24)

Direct Office of Commercial Space Transportation (AST) management to work with AST technical staff to (1) develop clearer policies, practices, and procedures that allow direct communications between staff and applicants, (2) provide clearer guidance on evaluating commercial space transportation permits, waivers, and licenses, and (3) better define the line between the information needed to ensure public safety and the information pertaining more broadly to ensuring mission success. (A-15-25)

In collaboration with the commercial space flight industry, continue work to implement a database of lessons learned from commercial space mishap investigations and encourage commercial space industry members to voluntarily submit lessons learned. (A-15-26)

To the Commercial Spaceflight Federation:

Advise commercial space operators to work with local emergency response partners to revise emergency response procedures and planning to ensure that helicopter and other resources are appropriately deployed during flights. (A-15-27)

Work with the Federal Aviation Administration to develop and issue human factors guidance for operators to use throughout the design and operation of a crewed vehicle. The guidance should address, but not be limited to, the human factors issues identified during the SpaceShipTwo accident investigation. (A-15-28)

BY THE NATIONAL TRANSPORTATION SAFETY BOARD

CHRISTOPHER A. HART
Chairman

ROBERT L. SUMWALT
Member

T. BELLA DINH-ZARR
Vice Chairman

EARL F. WEENER
Member

Adopted: July 28, 2015

Appendixes

Appendix A: The National Transportation Safety Board's Authority to Investigate Commercial Space Launch Accidents

Immediately after the accident, senior National Transportation Safety Board (NTSB) and Federal Aviation Administration (FAA) leaders discussed the known circumstances of the accident, and the NTSB informed the FAA that the NTSB would conduct an investigation pursuant to the agency's authority (as described in the memorandum that follows). A full go-team arrived on scene the following morning. NTSB Chairman Christopher Hart (then the NTSB Acting Chairman) accompanied the team. The following investigative groups were formed: data, human performance, operations, propulsion, structures, survival factors, system safety, systems, vehicle performance, and vehicle recovery. Also, specialists were assigned to the investigation to assess the meteorological information surrounding the time of the accident and conduct nondestructive examinations of the internal configuration of feather system components.

National Transportation Safety Board

Office of General Counsel

490 L'Enfant Plaza East, S.W.
Washington, D.C. 20594-2001

202/314-6080
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SUBJECT: THE NATIONAL TRANSPORTATION SAFETY BOARD'S AUTHORITY TO INVESTIGATE COMMERCIAL SPACE LAUNCH ACCIDENTS

D. Tochen

FROM: David K. Tochen
General Counsel

DATE: JULY 1, 2015

This memorandum describes the basis for the National Transportation Safety Board's (NTSB) authority to investigate commercial space launch accidents.

I. Relevant Statutory Provision

Section 1131(a)(1)(F) states:

> (a) General.—(1) The National Transportation Safety Board shall investigate or have investigated (in detail the Board prescribes) and establish the facts, circumstances, and cause or probable cause of—
>
> * * * * * *
>
> (F) any other accident related to the transportation of individuals or property when the Board decides—
>
> (i) the accident is catastrophic;
> (ii) the accident involves problems of a recurring character; or
> (iii) the investigation of the accident would carry out this chapter.

II. Executive Summary

In Chevron U.S.A. Inc. v. National Resources Defense Council, Inc., 467 U.S. 837 (1984), the Supreme Court established the standard of review regarding a government agency's reading of a statute that Congress has charged the agency with administering. Applying the reasoning from Chevron, the NTSB interprets 49 U.S.C. § 1131(a)(1)(F) (hereinafter, "section F") to provide the agency the authority to investigate commercial space accidents. This section's language clearly affords the agency discretion in determining the types of accidents related to transportation of individuals or property that the agency believes warrant investigation. In exercising this discretion as it applies to commercial space accidents, the agency considered the definition of the term "accident" in 49 U.S.C. § 1101, the plain meaning of the phrase "related to

... transportation" in section F, Congress's statement of the importance of space transportation to the United States transportation system, and the Federal Aviation Administration's (FAA) regulatory definitions of "launch and reentry accident." Reliance on these factors shows that NTSB's interpretation is reasonable, and therefore due the deference the Chevron Court contemplated.

III. Chevron Analysis: Step One

The Chevron opinion is best known for its two-step analysis for determining the appropriate level of deference to an agency's interpretation of the statutes it administers. The Chevron Court held, "[f]irst, always, is the question whether Congress has directly spoken to the precise question at issue. If the intent of Congress is clear, that is the end of the matter; for the court, as well as the agency, must give effect to the unambiguously expressed intent of Congress." Id. at 842. Courts interpreting Chevron consistently cite this step as an important component of the Chevron analysis. See, e.g., Utility Air Regulatory Group v. Environmental Protection Agency, 134 S. Ct. 2427, 2445 (2014) (quoting National Assn. of Home Builders v. Defenders of Wildlife, 551 U.S. 644, 665 (2007)).

A. The plain language of the NTSB statute grants the agency broad discretion.

While application of some terms from section F may benefit from further explanation, the plain language[1] of the section shows that Congress granted the NTSB broad discretion to determine which accidents the agency would investigate. The phrase "***when the Board decides***" supports this position. Hence, NTSB maintains the authority to determine whether an accident related to transportation is catastrophic, involves problems of a recurring character, or the investigation of the accident would carry out the provisions of 49 U.S.C. §§ 1101-1155. In addition, the phrase "***related to the transportation*** of individuals or property..." modifies the term "accident." In lieu of simply using the term "transportation accident," Congress specifically chose the term, "related to ... transportation." This careful selection of words demonstrates Congress's intent to ensure NTSB maintains abundant discretion in fulfilling its ultimate purpose of improving transportation safety.[2]

---

[1] See Zuni Pub. Sch. Dist. No. 89 v. Dep't of Educ., 550 U.S. 81, 93-94 (2007) (holding the Secretary of Education's interpretation fell within the plain meaning of the statute); Triton Marine Fuels Ltd., S.A., v. M/V Pacific Chukotka, 575 F.3d 409, 416 (4th Cir. 2009) ("[a]s with any question of statutory interpretation, our analysis begins with the plain language of the statute.") (quoting Jimenez v. Quarterman, 555 U.S. 113, 118 (2009)).

[2] Section 1131(a)(1)(F) was subject to the title 49 recodification in Pub. L. 103-272. Prior to recodification, subparagraph (F) read:

> other accident which occurs in connection with the transportation of people or property which, in the judgment of the Board, is catastrophic, involves problems of a recurring character, or would otherwise carry out the policy of this title.

Independent Safety Board Act of 1974, Pub. L. 93-633, section 304(a)(1).

Since recodification made *nonsubstantive* changes to the statute, the changes to subparagraph (F) (*i.e.*, "any other accident related to the transportation of" vs. "other accident which occurs in connection with the transportation of;" "when the Board decides," vs. "in the judgment of the Board;" "the investigation of the accident would carry out this

IV. Chevron Analysis: Step Two

The Chevron Court stated, "if the statute is silent or ambiguous with respect to the specific issue, the question for the court is whether the agency's answer is based on a permissible construction of the statute." Id. at 843. In this regard, the Court applied its well-settled precedent, which holds that the executive department's construction of a statutory scheme is due considerable weight. The Court also introduced the principle of *deference* to administrative interpretations. Id. at 844. For this reason, Chevron is best known for the concept that executive agencies are entitled to deference in interpreting their authorizing legislation and their regulations based on such legislation. The rationale for the necessity of such deference is based on the concept that understanding "the force of the statutory policy in the given situation has depended upon more than ordinary knowledge respecting the matters subjected to agency regulations." Id. As a result, courts defer to agencies' expertise on their areas of authorized responsibility. See, e.g., City of Arlington, Texas v. Federal Communications Commission, 133 S. Ct. 1863, 1869 (2013). Similarly, the Supreme Court has consistently afforded Chevron deference to agencies' construction of the scope of their own jurisdiction. See Commodity Futures Trading Commission v. Schor, 478 U.S. 833, 843 (1986).

The NTSB recognizes that the breadth of the statutory language in section F raises the question of which commercial space accidents are covered by this provision. As explained above, Congress expressly included in the agency's authorizing legislation the discretion for the NTSB to determine the scope of the agency's purview with regard to a discrete, specific category of transportation accidents—those that are "catastrophic," of a recurring nature, or the investigation of which would aid in the NTSB's achievement of its objective as defined in the agency's statute. In this analysis, the NTSB considers the statutory definition of "accident" under 49 U.S.C. § 1101[3] and the Commercial Space Launch Act of 1984 and amendments thereto,[4] as well as FAA regulations.

A. The meaning of the phrase "any other accident related to transportation"

When the NTSB determined that commercial launch accidents as a general matter qualify as "other accident[s]," it considered the definition of accident in 49 U.S.C. § 1101. Section 1101 defines "accident" as an event that "*includes* damage to or destruction of vehicles." The use of the word "includes" indicates Congress did not intend the listing of types of "accidents" to be exhaustive; rather, "accidents" could include more than events causing damage to or destruction of vehicles in surface or air transportation or pipelines.

chapter" vs. ""would otherwise carry out the policy of this title"), our analysis of the current language would apply equally to the original 1974 formulation.

[3] Section 1101 provides, in part, as follows: "In this chapter, the term "accident" includes damage to or destruction of vehicles in surface or air transportation or pipelines, regardless of whether the initiating event is accidental or otherwise."

[4] The Commercial Space Launch Act of 1984 and amendments thereto, formerly codified at 49 U.S.C. §§ 70101-19, were renumbered and transferred to 51 U.S.C. §§ 50901-23, Pub. L. 111–314, Dec. 18, 2010, 124 Stat. 3440.

The plain meaning of the phrase "related to transportation," requires that accidents covered by section F have a rational relationship to transportation. Congress explicitly has addressed whether commercial space activity should be considered transportation when it determined that "space *transportation* ... is an important element of the transportation system of the United States ...." 51 U.S.C. § 50901(a)(8) (emphasis added). The NTSB also notes that the FAA Office of Commercial Space Transportation (AST), established by 51 U.S.C. § 50921, has promulgated regulations governing commercial space launches. These regulations set forth definitions of accidents, incidents, and mishaps, with regard to launch and reentry vehicles, as well as a set of definitions specifically governing the regulation of such vehicles. 14 C.F.R. § 401.5. The involvement of the FAA in commercial space launch activities signifies that vehicles used in commercial space launches fall within the purview of the FAA's authority during specified periods of time, either because those activities are "transportation" or because they are so closely related to transportation that FAA oversight is necessary. In this regard, the involvement of the FAA's AST is both logical and reasonable: vehicles involved in commercial space launches *must* travel through the national airspace, wherein launches would need to be coordinated with air transportation systems to avoid interference with air traffic control as well as other aircraft.

B. "Of individuals and property"

The NTSB recognizes that individuals who travel on a commercial space flight are considered "participants," not passengers. This distinction, however, does not deprive the NTSB of jurisdiction under section F because its plain language authorizes the NTSB's investigation of accidents "related to transportation of *individuals* and property." In the commercial space context, "person" is defined broadly, to include individuals and organizations formed under the laws of any State or country.[5] Crews are the employees of a licensee who perform activities directly related to operation of a vehicle.[6] Individuals carried within a vehicle other than crew are designated "space flight participants."[7] "Third parties" are "persons" other than, among others, crew and space flight participants.[8] Therefore, the word "individuals" covers individuals who could be affected by a commercial space accident: crew, participants and third parties.

C. "Catastrophic" events under § 1131(a)(1)(F)(i)

Because the word "catastrophic" is not defined in 49 U.S.C. Chapter 11, in determining whether a commercial space accident is catastrophic, the NTSB first considers the plain meaning of the word. Merriam-Webster dictionary defines "catastrophic" as "a terrible disaster."[9] In engineering terms, a catastrophic failure is commonly viewed as a "sudden and drastic change in the operating characteristics of a material, product, or system resulting in total loss of useful performance."[10] The FAA has defined "catastrophic" in Advisory Circular 23.1309-1E, *System*

[5] 51 U.S.C. § 50902(12).
[6] Id. § 50902(2).
[7] Id. § 50902(17).
[8] Id. § 50902(21) (the U.S. Government and its contractors, licenses and transferees, and customers of launch or reentry services are also excluded from the definition of a "third party.")
[9] *Catastrophic*, MERRIAM-WEBSTER, http://www.merriam-webster.com/dictionary/catastrophic (last visited Jun. 11, 2015).
[10] See, e.g., *Catastrophic Failure*, BUSINESSDICTIONARY.COM, http://www.businessdictionary.com/definition/catastrophic-failure.html (last visited Jun. 11, 2015).

Safety Analysis and Assessment for Part 23 Airplanes (2011) as "[f]ailure conditions that are expected to result in multiple fatalities of the occupants, or incapacitation or fatal injury to a flight crewmember normally with the loss of the airplane... ." While this Advisory Circular is directed at aviation applications, its definition of catastrophic failure is consistent with common engineering understanding. For example, the Columbia Accident Investigation Board referred to Columbia's "catastrophically damaged left wing"[11] and described the "rapid catastrophic sequential structural breakdown."[12] Finally, the NTSB also considered the FAA's definition of launch and re-entry accidents and incidents at 14 C.F.R. § 401.5, in defining catastrophic.[13]

The NTSB found the SpaceShipTwo accident to be catastrophic because it resulted in breakup and total loss of the vehicle, the debris landed outside the designated landing site, and it involved a fatality.[14] The vehicle broke up at approximately 50,000 feet altitude.[15] The main debris field was spread over a distance of almost five miles.[16] The breakup of the vehicle resulted in the death of the co-pilot and serious injury to the pilot. Thus, the accident resulted in death or serious injury to both occupants of the SpaceShipTwo flight.

V. The NTSB has experience both leading and supporting commercial space launch investigations.

The NTSB's has exercised its authority to investigate commercial space accidents for more than 20 years. In 1993, the NTSB led the investigation of a procedural anomaly associated with the launch of an Orbital Sciences Corporation Pegasus expendable launch vehicle (ELV). This accident raised the concern that a similar anomaly might result in debris falling outside the protected safety area for the launch. *See* NTSB/SIR-93-02. In this event, a National Aeronautics and Space Administration (NASA) Wallops Range Safety Officer identified a mandatory abort

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[11] NAT'L AERONAUTICS & SPACE ADMIN., REPORT VOL. 1, COLUMBIA ACCIDENT INVESTIGATION BOARD6 (2003) *available at* http://www.nasa.gov/columbia/home/CAIB_Vol1.html.

[12] Id. at 77.

[13] *Launch accident* means: (1) An event that causes a fatality or serious injury (as defined in 49 CFR § 830.2) to any person who is not associated with the flight; (2) An event that causes damage estimated to exceed $25,000 to property not associated with the flight that is not located at the launch site or designated recovery area; (3) An unplanned event occurring during the flight of a launch vehicle resulting in the impact of a launch vehicle, its payload or any component thereof: (i) For an expendable launch vehicle, outside designated impact limit lines; and (ii) For a reusable launch vehicle, outside a designated landing site. (4) For a launch that takes place with a person on board, a fatality or serious injury to a space flight participant or crew member.
Reentry accidents, means: (1) Any unplanned event occurring during the reentry of a reentry vehicle resulting in the impact of the reentry vehicle, its payload, or any component thereof, outside a designated reentry site; (2) An event that causes a fatality or serious injury (as defined in 49 C.F.R. § 830.2) to any person who is not associated with the reentry; and (3) For a reentry that takes place with a person on board, a fatality or serious injury to a space flight participant or crew member. *Launch incidents*, defined as, any unplanned event during the launch, involving a malfunction of a flight safety system or safety-critical system. Reentry incidents, defined as. any unplanned event occurring during the reentry of a reentry vehicle, involving a malfunction of a reentry safety-critical system or failure of the licensees.

[14] See, e.g., NTSBgov, *B-Roll of the SpaceShipTwo Crash Scene in Mojave, Calif.*, YOUTUBE (Nov. 1, 2014), https://youtu.be/cZnQcMpzunM; *PHOTOS: Virgin Galactic SpaceShipTwo Accident*, ABC7 (Oct. 31, 2014), http://abc7.com/news/photos-virgin-galactic-spaceship-two-accident-/375109/.

[15] See, e.g., *Our Vehicles*, VIRGIN GALACTIC, http://www.virgingalactic.com/human-spaceflight/our-vehicles/ (last visited June 11, 2015).

[16] See NTSBgov, *Acting Chairman Christopher A. Hart's Second Media Briefing on Crash of SpaceShipTwo, Mojave, Calif.*, YOUTUBE (Nov. 1, 2014), https://youtube/OYFVbQ4YCP0?t=4m50s.

condition. The NASA Wallops Test Director called for an abort, and the Orbital Sciences Test Coordinator also called for an abort. The Test Coordinator later, however, reinitiated the launch sequence and launched the ELV, which successfully deployed two satellites.

Successful execution of launch abort procedures is critical to ensuring public safety by preventing launch vehicles or debris from landing outside the safety zone defined by the impact limit lines defined for a commercial launch. As a result, the NTSB investigated the incident and issued safety recommendations to the Department of Transportation, NASA, and Orbital Sciences.

On February 1, 2003, the Space Shuttle Columbia broke up while reentering the earth's atmosphere on shuttle mission STS- 107. All seven astronauts onboard perished, and debris from the vehicle fell over a large section of Texas, and a smaller section of Louisiana. Soon after the shuttle was destroyed, the NTSB, at the request of NASA, launched six people to Texas and Louisiana to assist NASA in debris recovery and to help initiate the investigation, including two investigators with extensive experience with in-flight break ups, a forensic pathologist, and structures, systems and aircraft performance experts. In Washington, NTSB technical staff examined radar and weather data to help locate wreckage. In the weeks that followed, six NTSB investigators were assigned to the Kennedy Space Center in Florida helping NASA engineers reassemble portions of the shuttle. The NTSB also assigned several radar interpretation experts to assist their NASA counterparts at the Johnson Space Center in Houston. Several NTSB supervisory personnel and public affairs personnel assisted members of the independent Columbia Accident Investigation Board, also operating out of the Johnson Space Center. In all, more than 50 NTSB employees supported the investigation.

On September 8, 2004, the NASA Genesis sample-return capsule crashed into the desert floor of the Dugway Proving Ground, Tooele, Utah. An NTSB investigator launched to the accident scene with NASA mishap investigation board (MIB) members to document the site and recover the wreckage. The NTSB assisted the MIB in setting up the investigation and developing the investigation plan. NTSB Systems and Materials Laboratory investigators participated in the investigation by helping to examine and document the vehicles' wiring harness for evidence of micrometeorite impact damage. The NTSB also assisted in developing and reviewing portions of the final report.

These examples demonstrate the NTSB has been involved in space launch accident investigations for more than 20 years. The NTSB's investigative process has applied equally well in leading investigations of accidents and incidents, and in supporting other agencies with their investigations.

VI. Conclusion

Section F provides the basis for NTSB's authority to determine what type of accidents, other than those specified in 49 U.S.C. § 1131(a)(1)((A)-(E)), it will investigate. Congress has found commercial space transportation is an important part of the United States transportation system. To the extent NTSB's authorizing statute contains undefined terms, such as "catastrophic," the agency views the plain language of the term and FAA's regulations, among other factors, as instructive. The SpaceShipTwo accident was catastrophic because it resulted in vehicle debris landing outside of the designated landing site and in a fatality and a serious injury.

Applying these constructions, NTSB determined it was authorized to investigate the SpaceShipTwo launch accident by 49 U.S.C. 1131(a)(1)(F)(i). In all cases, the NTSB's goal is adherence to Congress's purpose for the agency: to conduct transportation accident and incident investigations for the purpose of improving transportation safety for the public.

National Transportation Safety Board
Washington, D.C. 20594

Office of the Chairman

July 2, 2015

The Honorable Lamar S. Smith
Chairman
Committee on Science, Space, and Technology
U.S. House of Representatives
2321 Rayburn House Office Building
Washington, DC 20515

The Honorable Eddie Bernice Johnson
Ranking Member
Committee on Science, Space, and Technology
U.S. House of Representatives
394 Ford House Office Building.
Washington, DC 20515

Dear Chairman Smith and Congresswoman Johnson:

The National Transportation Safety Board (NTSB) is an independent agency of the United States Government charged with investigating transportation accidents and incidents and making recommendations aimed at improving transportation safety and preventing future accidents. The NTSB appreciates the opportunity to respond to inquiries from Committee staff staff concerning the NTSB's role in conducting investigations of commercial space launch accidents.

In particular, Committee staff requested an analysis of the agency's authority to conduct the SpaceShipTwo accident investigation, which arose from an accident that occurred on October 31, 2014 in Mojave, California. The NTSB is pleased to provide this legal analysis, which I am enclosing with this correspondence. In addition, my staff and I are available to discuss the enclosed analysis and our ongoing investigation of the SpaceShipTwo accident should you seek further information.

We greatly appreciate your Committee's interest in the NTSB's investigations.

An identical letter has been send to Chairman Shuster and Ranking Member DeFazio, Committee on Transportation and Infrastructure.

Sincerely,

Christopher A. Hart
Chairman

Enclosure

Office of the Chairman

National Transportation Safety Board
Washington, D.C. 20594

July 2, 2015

The Honorable Bill Shuster
Chairman
Committee on Transportation and Infrastructure
U.S. House of Representatives
2251 Rayburn House Office Building
Washington, DC 20515

The Honorable Peter A. DeFazio
Ranking Member
Committee on Transportation and Infrastructure
U.S. House of Representatives
2164 Rayburn House Office Building
Washington, DC 20515

Dear Chairman Shuster and Congressman DeFazio:

The National Transportation Safety Board (NTSB) is an independent agency of the United States Government charged with investigating transportation accidents and incidents and making recommendations aimed at improving transportation safety and preventing future accidents. The NTSB appreciates the opportunity to respond to inquiries from Committee on Science, Space, and Technology staff concerning NTSB's role in conducting investigations of commercial space launch accidents.

In particular, Committee staff requested an analysis of the agency's authority to conduct the SpaceShipTwo accident investigation, which arose from an accident that occurred on October 31, 2014 in Mojave, California. The NTSB is pleased to provide this legal analysis, which I am enclosing with this correspondence. In addition, my staff and I are available to discuss the enclosed analysis and our ongoing investigation of the SpaceShipTwo accident should you seek further information.

We greatly appreciate your Committee's interest in the NTSB's investigations.

An identical letter has been send to Chairman Smith and Ranking Member Johnson, Committee on Science, Space, and Technology.

Sincerely,

Christopher A. Hart
Chairman

Enclosure

National Transportation Safety Board
Washington, D.C. 20594

Office of the Chairman

July 2, 2015

The Honorable John Thune
Chairman
Committee on Commerce, Science, and Transportation
United States Senate
512 Dirksen Senate Office Building
Washington, DC 20510

The Honorable Bill Nelson
Ranking Member
Committee on Commerce, Science, and Transportation
United States Senate
425 Hart Senate Office Building
Washington, DC 20515

Dear Chairman Thune and Senator Nelson:

The National Transportation Safety Board (NTSB) is an independent agency of the United States Government charged with investigating transportation accidents and incidents and making recommendations aimed at improving transportation safety and preventing future accidents. Recently, staff from the Committee on Transportation and Infrastructure and the Committee on Science, Space, and Technology, U.S. House of Representatives, inquired about the NTSB's role in conducting investigations of commercial space launch accidents.

In particular, staff from both Committees requested an analysis of the agency's authority to conduct the SpaceShipTwo accident investigation, which arose from an accident that occurred on October 31, 2014 in Mojave, California. The NTSB has provided our legal analysis to the Chairmen and Ranking Members of the two Committees and I am pleased to provide the enclosed copy to the Committee on Commerce, Science, and Transportation.

My staff and I are available to discuss the enclosed analysis and our ongoing investigation of the SpaceShipTwo accident should you seek further information.

We greatly appreciate your Committee's interest in the NTSB's investigations.

Sincerely,

Christopher A. Hart
Chairman

Enclosure

Appendix B: SpaceShipTwo Flight Information

Date	Flight	Flight crew			
		SS2		WK2	
		Accident pilot	Accident copilot	Accident pilot	Accident copilot
October 10, 2010	Glide flight 01	✓	✓		
October 28, 2010	Glide flight 02		✓	✓	
November 17, 2010	Glide flight 03	✓			✓
January 13, 2011	Glide flight 04			✓	✓
April 22, 2011	Glide flight 05	✓			
April 27, 2011	Glide flight 06		✓	✓	
May 4, 2011	Glide flight 07	✓			
May 10, 2011	Glide flight 08			✓	
May 19, 2011	Glide flight 09	✓			
May 25, 2011	Glide flight 10			✓	
June 14, 2011	Glide flight 11	✓			
June 15, 2011	Glide flight 12			✓	
June 21, 2011	Glide flight 13	✓			
June 23, 2011	Glide flight 14			✓	
June 27, 2011	Glide flight 15	✓			✓
September 29, 2011	Glide flight 16			✓	
June 26, 2012	Glide flight 17	✓	✓		
June 29, 2012	Glide flight 18			✓	
July 18, 2012	Glide flight 19	✓			
August 2, 2012	Glide flight 20			✓	
August 7, 2012	Glide flight 21	✓			
August 11, 2012	Glide flight 22			✓	
December 19, 2012	Glide flight 23		✓		
April 3, 2013	Glide flight 24				✓
April 12, 2013	Cold flow flight 01		✓		
April 29, 2013	Powered flight 01		✓		
July 25, 2013	Glide flight 25				
August 8, 2013	Glide flight 26				✓
September 5, 2013	Powered flight 02				✓
December 11, 2013	Glide flight 27				
January 10, 2014	Powered flight 03				✓
January 17, 2014	Glide flight 28	✓			
July 29, 2014	Glide flight 29	✓			
August 28, 2014	Cold flow flight 02	✓	✓		
October 7, 2014	Glide flight 30	✓			✓
October 31, 2014	Powered flight 04	✓	✓		

Note: For glide flights 29 and 30, the accident pilot was the instructor pilot.

Appendix C: Data Source Information

Device name	Data type	Device location	Data recovery status
SS2 Strap On Data Acquisition System (SODAS)	Telemetry data	Mission control	Full
SS2 forward-facing cockpit camera (cockpit image recorder)	Telemetry data	Mission control	Full
SS2 left tailboom camera	Telemetry data	Mission control	Full
SODAS compact flash card	Flight data	SS2	Full
High-definition left tailboom camera	External video	SS2	Full
Aitech rocket motor controller	Rocket motor data	SS2	Full
High-definition release pylon camera	External video	WK2	Full
High-definition right tailboom camera	External video	WK2	Full
High-definition forward-facing cockpit camera	Onboard video	WK2	Full
Pressurization system controller data logger	Pressurization system data	SS2	Partial
Avionics compact flash cards 1 and 2	Firmware load data	SS2	Failed
Apple iPhone (copilot)	Personal electronic device	SS2	Failed
High-definition aft tailcone camera	External video	SS2	Failed
High-definition cockpit image recorder	Onboard video	SS2	Not located
High-definition cabin cameras	Onboard video	SS2	Not located
High-definition aft-facing cockpit camera	Onboard video	SS2	Not located
Scaled Composites employee 5K-resolution camera	Ground-based video	8 nautical miles (nm) NE of MHV	N/A (not involved in accident)
MARS Epic 5K-resolution camera	Ground-based video	12 nm NE of MHV	N/A
MARS near-field infrared camera	Ground-based photography	12 nm NE of MHV	N/A
MARS short-wave infrared camera	Ground-based photography	12 nm NE of MHV	N/A
NASA Dryden/Edwards AFB long-range optics camera	Ground-based video	16 nm SE of MHV	N/A
NASA Dryden/Edwards AFB RDR-34 camera	Ground-based video	13 nm SE of MHV	N/A
Spectator Canon EOS 50D camera	Ground-based photography	16 nm NE of MHV	N/A
Virgin Galactic contract photographer GoPro Hero 3+ camera	Head-mounted video	Extra EA-300L	N/A
Virgin Galactic contract photographer Canon EOS 5D MK III camera	Hand-held photography	Extra EA-300L	N/A
Virgin Galactic contract photographer Canon EOS 70D camera	Hand-held photography	Extra EA-300L	N/A
Scaled Composites employee Canon EOS T2i camera	Hand-held postaccident photography	Extra EA-300L	N/A

Appendix D: Cockpit Image Recorder Transcript

The following is a transcript from the cockpit image recorder installed on the SpaceShipTwo reusable suborbital rocket (N339SS), which broke up into multiple pieces during a rocket-powered test flight and impacted terrain over a 5-mile area near Koehn Dry Lake, California, on October 31, 2014. The recording was obtained from a telemetry ground station located in the Scaled Composites control room at Mojave Airport, Mojave, California. The video was processed from an Imperx Bobcat camera.

LEGEND	
SS2	SpaceShipTwo
WK2	WhiteKnightTwo
RDO	Push to Talk Radio Transmission over VHF
HOT	Flight crew audio panel voice or sound source
BASE	Scaled Composites Mission Control Room radio transmissions
MHV-TWR	Radio transmission from Mojave (KMHV) Tower
Joshua-APP	Joshua Approach Control Facility
CHASE	Radio transmission from the Scaled Composites chase aircraft (Extra 300)
Pilot-1	Physical action by pilot
Pilot-2	Physical action by copilot
SS2 Cockpit	Observed action/status on instrument panel/ in general cockpit area
SCAT-21	Callsign for SS2
Galactic-01	Callsign for WK2
Galactic-03	Callsign for CHASE
EXTRA	Alternate callsign for CHASE
-1	Voice identified as the pilot of SS2
-2	Voice identified as the copilot of SS2
-3	Voice identified as the pilot of WK2
-4	Voice identified as the copilot of WK2
-5	Voice identified as the flight test engineer of WK2
-?	Voice unidentified
*****	Unintelligible word
#	Expletive
@	Non-pertinent word
( )	Questionable insertion
(( ))	Material Inserted from an alternate video/audio source
[ ]	Editorial insertion
Italics	Narrative of visible cockpit action or event

Note 1: Times are expressed in Universal Coordinated Time (UTC).

Note 2: Generally, only radio transmissions to and from the accident vehicle and carrier vehicle were transcribed.

Note 3: Words shown with excess vowels, letters, or drawn out syllables are a phonetic representation of the words as spoken.

Note 4: A non-pertinent word, where noted, refers to a word not directly related to the operation, control or condition of the aircraft.

Note 5: A acronym spoken phonetically is spelled phonetically and capitalized. An acronym spoken by individual letter is delineated by a hyphen between capitalized letters.

SS2		WK2	RDO	
HOT-1 16:28:20.08	how's the P-S-C doing?			
Pilot-1 16:28:20.40	*[Reaches for and touches Lower right outer knob of the center MFD, to select RKT master page. Uses inner knob to get to CTN sub page.]*			
SS2 Cockpit 16:28:29.70	*[Center MFD fades to black.]*			
HOT-1 16:28:29.92	[sigh] oohhhggg.			
HOT-2 16:28:31.09	ughhh.			
HOT-2 16:28:32.68	there ya go.			
SS2 Cockpit 16:28:32.93	*[Center MFD begins rebooting at splash screen]*			
HOT-2 16:28:34.25	base we just had a uh center M-F-D failure, with uhh @, moving the uhh, right lower small knob.			
			BASE 16:28:45.16	base copies and were, uh, seeing it rebooting on the, uh, big screen.
HOT-1 16:28:52.78	I think that's a first. at least in the airplane.			
HOT-2 16:29:08.83	I'm gunna go ahead and pull it up on my side.			

SS2	WK2	RDO
Pilot-2 16:29:10.90 *[Reaches toward own PFD and makes softkey input]*		
SS2 Cockpit 16:29:17.50 *[Center MFD finishes rebooting]*		
Pilot-1 16:29:19.93 *[Reaches toward and manipulates lower right center MFD knobs. Selects RKT master page.]*		
HOT-2 16:29:25.93 alright, uhh, I'm selecting P-F-D on my side again...and I'm punching out the lights.		
Pilot-2 16:29:29.20 *[Reaches toward softkey and selects PFD screen.]*		
Pilot-2 16:29:35.37 *[Punches out (deselects) annunciator lights.]*		
Pilot-1 16:29:44.20 *[Finishes manipulating Center MFD. Leaves screen at COM master page and COM subpage and puts hands in lap.]*		
HOT-2 16:29:49.75 alright thirty thousand foot checks. ready for that?		
HOT-1 16:29:51.90 ready.		
HOT-2 16:29:53.03 alright, cabin altitude is fifty-three hundred.		

SS2	WK2	RDO
Pilot-1 16:29:56.80 *[Removes oxygen mask from helmet.]*		
HOT-1 16:29:56.90 [Sound similar to the ambient noise of free air flowing around the pilot's facemask mounted microphone.]		
HOT-2 16:29:58.60 and delta P is seven point niner.		
Pilot-1 16:30:00.03 *[Switches O2 regulator OFF.]*		
HOT-2 16:30:04.22 oxygen mask(s) can come down.		
HOT-1 16:30:05.63 off left and the regulator off left.		
Pilot-2 16:30:05.77 *[Removes mask from right side of helmet.]*		
Pilot-2 16:30:06.23 *[Reaches for unseen control on right side of instrument panel.]*		
Pilot-2 16:30:14.03 *[Closes isolation valve on the center console.]*		
Pilot-2 16:30:16.53 *[Touches soft key on right PFD, likely the timer.]*		
HOT-2 16:30:18.41 alright, isolation valve is closed, starting the timer.		
Pilot-1 16:30:21.00 *[Takes drink of water.]*		
HOT-2 16:30:49.03 thirty seconds to go.		

SS2		WK2	RDO
HOT-1 16:30:52.75	alright, thin layer here at uh thirty-two thousand looks like tops probably thirty-five or so, maybe thirty-eight.		
HOT-1 16:31:10.44	call it just, uh, thin cirrus		
HOT-2 16:31:16.87	alright there's, uhh, one minute, rates, uh, less than a hundred feet per minute.		
Pilot-2 16:31:29.20	*[Opens isolation valve on the center console.]*		
Pilot-2 16:31:31.70	*[Reaches toward right hand side of instrument panel and manipulates a control. [primary air on]]*		
HOT-2 16:31:37.88	‘kay, can put your, uh, mask and regulator back on.		
Pilot-2 16:31:40.13	*[Starts putting O2 mask back on.]*		
Pilot-1 16:31:41.10	*[Starts putting O2 mask back on.]*		
HOT-2 16:31:44.95	and WhiteKnight, Spaceship's ready for the climb.		
Pilot-1 16:31:51.23	*[Reaches toward oxygen regulator with left hand and manipulates a control(s).]*		

SS2		WK2		RDO	
HOT-1 16:32:00.35	alright oxygen to a hundred percent for pre-breathe. let's see if we can get some heat soak in here as well.				
HOT-2 16:32:03.57	copy.				
Pilot-2 16:32:07.23	*[Reaches and looks toward right side of instrument panel and manipulates control(s).]*				
HOT-1 16:32:07.52	full hot on the…				
HOT-2 16:32:09.10	gunna sweat me out, huh?				
HOT-1 16:32:11.23	well if it gets too hot we can turn it down.				
HOT-1 16:32:15.26	are you hot right now?				
HOT-2 16:32:16.44	naw.				
HOT-2 16:32:19.72	alright full hot is selected, uh, thirty thousand foot checks are complete.				
Pilot-2 16:32:20.77	*[Removes hand from right portion of instrument panel.]*				
				BASE 16:32:30.62	galactic one, base is green for climb.
		RDO-4 16:32:35.60	base, galactic one copies.		

SS2		WK2	RDO	
Pilot-2 16:32:46.60	*[Reaches behind pilot seat.]*			
Pilot-2 16:33:10.60	*[Finishes reaching behind pilot seat.]*			
Pilot-1&2 16:33:12.20	*[A movement of the co-pilot's head momentarily exposed the oxygen regulator panel to the camera's view. The Oxygen Regulator Panel Diluter Lever (white) on the co-pilot side appears in the up (100%) position. The position of the Emergency Lever (red) appears to be at "Normal" detent. The position of the Supply Lever (green) is indiscernible. The pilot's oxygen panel settings also appear nominal for this stage of flight.]*			
			BASE 16:33:28.24	scat two-one, base, we are ready for INTER O-V ((checks)) * *.
HOT-2 16:33:33.19	copy. alright rocket motor initialization checks.			
Pilot-2 16:33:38.97	*[Selects RKT master page on center MFD. Then selects VALVE subpage.]*			
HOT-2 16:33:45.65	alright. ready for INTER OV?			
HOT-1 16:33:47.35	ready.			

SS2	WK2	RDO
Pilot-2 16:33:48.03 *[Reaches toward INTER-OV switch.]*		
HOT-2 16:33:49.52 three. two. one. mark.		
Pilot-2 16:33:52.47 *[Manipulates INTER-OV switch. [Holds switch in EQUALIZE position].]*		
HOT-2 16:33:59.92 (right) pressure is stable.		
Pilot-2 16:34:01.83 *[reaches right hand toward soft key on the Left side of the PFD.]*		
		BASE 16:34:07.29 base has good ((Inter O-V)).
HOT-2 16:34:11.64 holding for twenty seconds, ten seconds to go.		
HOT-2 16:34:25.10 complete.		
Pilot-2 16:34:25.47 *[Removes left hand from INTER-OV switch.]*		
Pilot-2 16:34:26.17 *[reaches left hand toward soft key on left side of PFD. Presses soft key twice. [stop and clear timer]]*		
Pilot-2 16:34:28.40 *[Manipulates lower right knob(s) on center MFD to reach the CTN subpage of the RKT master page.]*		

SS2		WK2		RDO
HOT-1 16:34:29.91	alright we're at the top of the, uhh, cirrus layer here at thirty-six thousand.			
HOT-2 16:34:33.38	alright temperatures look good.			
Pilot-2 16:34:39.77	*[Manipulates center MFD to display VALVE sub page.]*			
		HOT-3 16:34:46.92	@?	
		HOT-4 16:34:48.23	yes sir	
		HOT-3 16:34:50.68	just coming up to the turn towards DEATH [user defined fix].	
		HOT-3 16:34:55.58	you have control.	
		HOT-4 16:34:56.52	‘kay, I have the controls, watching the speed and the mach.	
		HOT-3 16:34:59.08	I'll take the radio.	
		HOT-4 16:35:03.06	start(ing) the turn.	
HOT-2 16:35:03.90	alright INTER OV pressures greater for… stable for greater than thirty seconds, L minus ten checks are next.			

SS2		WK2		RDO	
				BASE 16:35:11.27	((scat)) two-one, base ((copies and if you've got time we'd like to do a couple more directional antenna checks.))
HOT-1 16:35:16.89	alright base you're starting to come in scratchy around that last call. it's probably a good place to do it.				
		HOT-3 16:35:25.60	have you got your I-C-S switch (flipped)?		
		HOT-4 16:35:32.22	what's that?		
		HOT-3 16:35:39.72	((like you)) have NAV to (DEATH)?		
		HOT-4 16:35:41.70	okay, direct DEATH.		
		HOT-4 16:35:44.49	okay.		
HOT-2 16:36:21.99	and base we've heard no further transmissions on comm since your last.				
				BASE 16:36:26.65	yeah copy that, we're switching antennas right now.
HOT-2 16:36:30.34	copy.				

SS2	WK2	RDO
	HOT-3 16:37:50.19 bottle pressure's good.	
HOT-1 16:37:56.91 you have any, uh, geographic features...out that window?		
	HOT-4 16:38:02.83 nothing here.	
	HOT-3 16:38:03.34 no, not yet.	
HOT-2 16:38:03.68 yeah I can, I can kinda make out some of the hills and stuff, saw the river a minute ago… but it's definitely difficult with the sun shining through it.		
		BASE 16:38:31.34 ((scat two-one, scaled base, how do you read?))
HOT-2 16:38:36.07 loud and clear.		
		BASE 16:38:38.69 * * *.
	RDO-3 16:38:47.15 galactic zero-three from zero-one, you're loud and clear.	
Pilot-2 16:38:59.13 *[Manipulates center MFD to display COM master page, COM sub page.]*		
HOT-1 16:39:01.15 I didn't hear Zer… I didn't hear him check in.		

SS2	WK2	RDO
	HOT-3 16:39:01.65 I thought I was on mission.	
HOT-2 16:39:04.69 yeah he wasn't, he wasn't on mission.		
HOT-1 16:39:06.05 oh, ok.		
HOT-2 16:39:14.47 Uh, @, was the extra wasn't on mission frequency was he?		
	HOT-3 16:39:17.26 No I don't think he was, it was my mistake.	
HOT-2 16:39:20.66 yeah we just wanted to check cause we didn't hear him.		
		CHASE 16:39:32.19 scaled base, extra is airborne.
		BASE 16:39:35.53 copy all.
	RDO-3 16:39:40.27 ((extra, from galactic zero-one, you are loud and clear))	
		CHASE 16:39:41.83 ((got you loud and clear galactic zero-one. scaled base, extra is airborne.))
RDO-2 16:39:47.26 extra from scat two-one, (loud and clear).		

SS2	WK2	RDO
		CHASE 16:39:50.73 loud and clear scat two-one.
	HOT-4 16:39:53.04 alright, we have fuel cooler.	
	HOT-3 16:39:55.93 yup, so fuel coolers closed.	
	HOT-3 16:40:01.26 yes, so @ have you got fuel cooler indications on your kneepad?	
	HOT-5 16:40:05.23 I've only got one.	
	HOT-3 16:40:06.25 okay, okay, they're going to close.	
	HOT-5 16:40:12.69 yeah I show it movin'. oh, maybe they're all four there? never mind, I've got 'em all.	
	HOT-3 16:40:16.35 uh huh.	
	HOT-5 16:40:17.05 they're all movin'	
		BASE 16:40:25.09 ((galactic one,)) scaled base, ((we)) are good for the climb past forty.

SS2	WK2	RDO
	RDO-3 16:40:29.46 ((scaled base, for galactic)) zero-one copied.	
	HOT-5 16:40:33.05 alright, all four are closed.	
	HOT-3 16:40:34.77 excellent, thank you.	
	HOT-3 16:40:50.68 the next is the L minus ten.	
	HOT-5 16:40:53.81 like we're gunna be good on pylon bottle temp.	
	HOT-3 16:40:58.61 good.	
	HOT-5 16:41:00.60 and press[ure]?	
	HOT-3 16:41:03.30 yup.	
HOT-2 16:41:12.81 Uhh, @, we're just getting an intermittent caution on the T Pad for DAS battery current and it’s just showing a negative, uh, point zero one.		
HOT-1 16:41:26.09 I think uh until pylon power turns off it's not going through that. base is that correct?		
HOT-2 16:41:42.57 that makes sense. it’s a higher		

SS2		WK2	RDO	
	potential so it just uses the pylon current.			
			JOSHUA APP 16:41:58.39	galactic zero-three traffic west and two miles ((maneuvering D-C three, one zero thousand.))
			CHASE 16:42:05.08	galactic zero-three's looking… ((galactic zero-three's visual.))
			JOSHUA APP 16:42:09.86	((galactic zero-three)) roger.
HOT-1 16:42:26.81	I have visa, visibility's startin' to improve a little bit on the left side.			
HOT-2 16:42:31.54	yup. same on the right.			
HOT-1 16:42:39.66	(uh) I got pretty good S-A out the right, see the... hills now, to the north, it's, uh, ...not great.			
HOT-2 16:42:52.25	[cough]			
Pilot-2 16:43:00.40	*[Manipulates center MFD to scroll through pages to briefly reach the ECS master page PRESS sub page, then scans ECS master TEMPS subpage, returns to display COM master page, COM sub page.]*			

SS2	WK2	RDO
HOT-1 16:43:44.87 amazing how much, uh, rate of climb you lose at the very end.		
	HOT-4 16:44:11.20 we need to work on, uh, card six point twelve.	
	HOT-3 16:44:14.97 yup.	
HOT-2 16:44:20.39 showin', uh, three degrees beta on the FADS.		
	HOT-3 16:44:29.45 ((it says at a hundred and forty KEAS [Knots Equivalent Airspeed]))	
	HOT-4 16:44:32.88 ((oh… at…)) max beta is ten at one forty.	
	HOT-3 16:44:36.42 uh, yeah, okay.	
	HOT-4 16:44:38.85 @, what do you show for beta?	
	HOT-5 16:44:41.17 stand-by	
	HOT-5 16:44:43.67 uhh, one point five.	
	HOT-3 16:44:46.21 plus one point five, yeah, I think the ball is slightly out to the right, isn't it?	
	HOT-4 16:44:52.44 yeah, let me step on that.	

SS2	WK2	RDO
	HOT-4 16:44:56.80 alright, how's that?	
	HOT-5 16:44:58.07 one point three, one point five.	
HOT-2 16:45:02.66 we're showin', uh, two degrees.		
	HOT-5 16:45:07.38 one. two.	
	HOT-5 16:45:12.26 point three.	
	HOT-4 16:45:17.72 all I did was start an oscillation.	
	HOT-5 16:45:19.57 yup.	
	WK2-3 16:45:20.01 [light chuckling]	
	HOT-3 16:45:33.91 goin' to smack in a little bit of trim there, @.	
	HOT-4 16:45:36.54 yea, just a little bit of right.	
	HOT-4 16:45:42.98 okay.	
	HOT-3 16:45:52.18 Spaceship, from, uh, T-TOP, how's your sideslip?	
HOT-2 16:45:55.55 we're oscillating between two and two point five degrees.		

SS2	WK2	RDO
	HOT-3 16:45:58.92 (roger.)	
	HOT-3 16:46:00.80 I think that’s, that’s gonna req… require a bit more. @ are you happy with me just, uhh…	
	HOT-4 16:46:04.95 okay, go ahead and flip it.	
	HOT-3 16:46:06.20 good.	
	HOT-3 16:46:10.03 settle down at that for a bit and…	
	HOT-4 16:46:11.58 alright.	
	HOT-4 16:46:14.24 the ball moved.	
	HOT-5 16:46:15.55 yup, showin' about zero now.	
HOT-2 16:46:20.19 and we're showin', uh, one point five.		
	HOT-4 16:46:22.98 * * *	
	HOT-3 16:46:22.98 * one point five.	
	HOT-4 16:46:24.75 puttin' in some left roll trim to counter that.	
	HOT-3 16:46:39.33 Spaceship, from T-TOP,	

SS2		WK2		RDO
			confirm you're still at one point five.	
HOT-2 16:46:41.99	(right now) it's coming down now, it's, uhh, oscillating we're at one degree currently.			
		HOT-5 16:46:56.63	good visibility now.	
		HOT-4 16:46:58.70	oh yeah.	
		HOT-3 16:46:59.65	yeah, look at that.	
		HOT-3 16:47:02.70	* * Spaceship you were stepped on there, say again your sideslip.	
HOT-2 16:47:05.82	point five.			
		HOT-3 16:47:07.84	uhh, you happy with that? do you want us to try and take that out as well?	
HOT-2 16:47:11.29	I think probably one more blip, uh, of trim for you guys will put it in close for us.			
		HOT-3 16:47:16.15	‘kay, here we go.	

SS2		WK2		RDO
Pilot-1 16:47:33.23	*[Reaches toward the SS2 Pilot Camera on the left side of the instrument panel and ensures it is attached securely.]*			
HOT-2 16:47:40.14	that's point, uh, (oh) point five it's oscillating a little bit @.			
HOT-2 16:47:46.15	point five, plus or minus point three.			
		HOT-4 16:47:50.28	there's a little right pedal.	
HOT-2 16:47:52.45	uh, now its negative, so we're oscillating around zero,			
		HOT-4 16:47:57.58	alright, starting the turn.	
		HOT-3 16:47:59.35	okay.	
HOT-1 16:48:02.10	uhh, seems good.			
HOT-2 16:48:04.00	looks good over here @.			
		HOT-3 16:48:05.68	great.	
HOT-1 16:48:09.24	good vis to the east and south.			
		HOT-3 16:48:11.88	it's looking much better now. out the right hand side.	

SS2	WK2	RDO
	HOT-3 16:48:50.61 two one zero at niner. [Switched to AWOS. Unheard on recording.]	
		BASE 16:49:06.19 scat two-one, base.
HOT-2 16:49:09.34 go 'head base.		
		BASE 16:49:11.07 yeah, can you just verify that your waypoints ((are sequencing properly?))
HOT-2 16:49:15.22 A-firm		
HOT-2 16:49:24.71 we'll have to get a little bit past that, right, before it'll sequence?		
Pilot-2 16:49:25.67 *[Points toward waypoint on PFD screen.]*		
HOT-1 16:49:27.62 yeah, we'll see.		
HOT-1 16:49:31.03 I've lost track of when it wor- doesn't. when it works, when it doesn't.		
HOT-2 16:49:40.07 I don't know that'll work on the next sequence though cause that's a discontinuity.		
HOT-2 16:49:48.50 after, uh, ERANG [user defined waypoint].		

SS2		WK2		RDO	
HOT-2 16:49:53.69	good sequence.				
		HOT-4 16:50:04.27	forty-five I-N-S altitude.		
		HOT-3 16:50:11.27	yup, that's good. well done @.		
		HOT-3 16:50:32.63	yeah, they're not sequencing are they?		
		HOT-4 16:50:34.66	yeah, okay.		
HOT-2 16:50:56.62	and base, can you just give us an update on, uhh, wind trends and nitrous temps?				
				BASE 16:51:06.66	((copy, uh, winds are holding right now)) one ((nine)) zero at eight knots. tre… trends are *. ((stand by for nitrous.))
HOT-2 16:51:13.50	copy all.				
HOT-1 16:51:15.00	what was that? two nine zero?				
HOT-2 16:51:18.23	no.				
				BASE 16:51:19.57	((‘kay and scat two-one, nitrous temps are)) confirmed good all ((around.))

SS2	WK2	RDO
HOT-2 16:51:22.38 copy. two one zero at eight.		
		BASE 16:51:25.87 ((negative.)) one ((niner)) zero *.
HOT-1 16:51:29.42 one nine.		
	HOT-3 16:51:39.57 @, do you mind if I just give ((you)) nav to DROP [user defined waypoint] here?	
	HOT-4 16:51:43.89 okay.	
	HOT-4 16:51:48.29 how come the line doesn't... come all the way?	
	HOT-3 16:51:53.73 I don't know actually. why've we got a gap? don't know.	
	HOT-3 16:52:08.29 (passing) sixteen minutes to DROP [user defined waypoint].	
	HOT-? 16:52:10.11 [light chuckling]	
	HOT-5 16:52:17.84 yeah, you never ask, uh, mission what the winds situation is.	

SS2		WK2		RDO	
Pilot-1 16:52:17.97	*[begins brushing/dusting pilot side Backup Panel glareshield with right finger.]*				
		HOT-3 16:52:21.48	[light chuckling]		
				BASE 16:52:30.14	scat two-one, did you ((call?))
Pilot-1 16:52:30.70	*[Finishes brushin/dusting pilot side Backup Panel glareshield with right finger.]*				
HOT-2 16:52:32.63	negative.				
HOT-1 16:52:35.98	alright, visibility looks great...or acceptable.				
		HOT-4 16:52:43.42	mach point five.		
HOT-1 16:52:59.14	so let's talk through a center M-F-D fail. you'll go P-F-D.				
HOT-2 16:53:03.11	yup.				
HOT-1 16:53:05.22	watch those CAS messages like a hawk, we won't have audio.				
HOT-2 16:53:10.72	yeah, so we'll uh…				
		HOT-3 16:53:11.87	is your I-C-S switch centered @?		

SS2		WK2		RDO
		HOT-4		
		16:53:16.67	yeah it's centered.	
		HOT-3		
		16:53:17.45	okay, thanks.	
HOT-1				
16:53:19.71	sorry, ours is engaged here, we like listening to you guys.			
		HOT-3		
		16:53:22.99	we really like listening to you too.	
HOT-1				
16:53:23.06	[background chuckling]			
		HOT-3		
		16:53:38.64	we're doing well on performance.	
		HOT-5		
		16:53:40.62	yeah, we are.	
		HOT-3		
		16:53:47.11	so, correct me if I'm wrong here, I think (the), uh…now we've achieved the minimum we can trade a little bit of altitude if we want to for speed, up to point five five.	
SS2 Cockpit				
16:53:47.57	*[Center MFD upper display auto sequences to display rocket information.]*			
HOT-2				
16:53:49.27	good sequence.			

SS2	WK2	RDO
	HOT-4 16:53:58.71 right, but..	
	HOT-3 16:53:59.94 there's plenty of, there's. there's time to do that but uh…	
	HOT-4 16:54:03.15 (yeah) try and get it high then dive down.	
	HOT-3 16:54:05.37 yeah.	
	HOT-4 16:54:06.78 so fourteen minutes.	
	HOT-3 16:54:08.26 yeah, I think we're we're plenty of time to do that, but, uh, preference was to go a little bit faster rather than, uh, higher and slower.	
	HOT-4 16:54:17.24 alright, but yeah we should go as high as we can and then, uh...	
Pilot-2 16:54:18.83 *[Briefly checks shoulder harness.]*		
	HOT-3 16:54:19.85 exactly, yeah, and then dive into it or something.	
	HOT-4 16:54:23.81 (oh).	
	HOT-5 16:54:24.83 we are, uh, conning	

SS2	WK2	RDO
	[creating contrails] for @'s S-A.	
	HOT-3 16:54:27.44 good.	
Pilot-2 16:54:34.20 *[Briefly checks shoulder harness again.]*		
Pilot-1 16:54:34.60 *[Brushes/dusts pilot side Backup Panel glareshield with hand briefly.]*		
Pilot-2 16:54:36.33 *[Reaches toward the rear of helmet, touches rear of helmet, touches headrest, moves head briefly back onto headrest.]*		
	RDO-3 16:54:36.59 [exhales] (sorry base, galactic one, go ahead.)	
Pilot-2 16:54:39.00 *[Raises visor and adjusts glasses, lowers visor.]*		
		BASE 16:54:41.06 ((yeah we concur)) with your discussion. climb ((at this speed and then you can)) trade and gain, uh, ((some altitude for,)) uhh, ((point five five mach.))
Pilot-1 16:54:46.67 *[Removes cover on visor and places in right thigh pocket of flight suit.]*		
Pilot-2 16:55:10.70 *[Briefly touches oxygen mask and*		

SS2		WK2		RDO	
	quickly taps left side of helmet.]				
		HOT-5 16:55:21.90	that the big, uhh, Vegas solar farm off to the left?		
		HOT-3 16:55:25.85	uhh yeah.		
		HOT-3 16:55:31.66	lot of those around now.		
		HOT-4 16:55:33.25	yeah.		
HOT-1 16:55:45.39	and base, uh, the P-S-C intermittent, uh, display do we anticipate any consequence of the, that fault during boost, any display anomalies that we should expect?				
				BASE 16:56:02.80	((scat two one, base. negative. uh,)) it has been solid ((since takeoff)) and ((uh)) we don't anticipate, uh, even if it goes ((intermittent display, we don't an-anticipate any issues.))
HOT-1 16:56:11.66	okay. copy. thanks.				
Pilot-1 16:56:34.20	*[Places head firmly against headrest, begins adjusting positon of head while placed firmly against headrest.]*				

SS2	WK2	RDO
	RDO-3 16:56:43.38 base from ((galactic zero-one, we're just coming up on eleven minutes thirty.))	
HOT-1 16:56:43.85 this headrest, least the height I'm at, when I press up against it I kinda lose the bottom half of the screen.		
Pilot-1 16:56:44.67 *[Briefly removes head from being placed firmly against headrest and turns head slightly toward copilot side of the crew cabin while again pressing head firmly against headrest.]*		
Pilot-2 16:56:47.07 *[Presses head firmly against headrest.]*		
Pilot-1 16:56:48.17 *[Looks forward and firmly places and adjusts head against headrest.]*		
Pilot-1 16:56:48.83 *[Motions with right hand toward lower portion of PFD.]*		
HOT-2 16:56:49.44 right.		
Pilot-2 16:56:51.53 *[Reaches both hands behind helmet and briefly touches headrest.]*		
Pilot-1 16:56:53.97 *[Adjusts head and reaches with both hands behind helmet to touch headrest.]*		

SS2		WK2		RDO	
HOT-2 16:56:54.83	I remember doing that on, on P-F oh one, I took my head, consciously took my head off the headrest.				
Pilot-2 16:56:58.00	*[Motions head briefly back and forth between normal seating position and holding head firmly against headrest.]*				
Pilot-1 16:57:01.50	*[Returns to a normal seated positon.]*				
Pilot-2 16:57:01.57	*[Returns to normal seated positon.]*				
Pilot-2 16:57:06.73	*[Presses head firmly against headrest.]*				
				MHV TWR 16:57:08.69	((galactic zero-one, tower,)) I ((had)) missed the last call. did you say ten minutes?
Pilot-2 16:57:10.17	*[Returns to normal seated position.]*				
		RDO-3 16:57:14.43	((uh, negative, uh, we're just, uh,)) (eleven minutes now,) we're showing eleven minutes now.		
				MHV TWR 16:57:18.84	((tower,)) eleven minutes.
Pilot-2 16:57:26.33	*[Reaches left hand around behind*				

SS2		WK2		RDO
	helmet, makes a fist shape with his left hand and places between his helmet and headrest. Firmly puts force on hand and subsequently the headrest also. Removes hand from behind helmet.]			
		HOT-3 16:57:31.22	@, shall I take it now and you get ready for the L minus ten?	
		HOT-4 16:57:34.14	okay, you have the controls.	
		HOT-3 16:57:34.93	thank you very much, I have.	
Pilot-2 16:57:37.23	*[Raises visor and adjusts glasses.]*			
Pilot-2 16:57:42.13	*[Lowers visor. touches mask. places hand back on paper checklist.]*			
Pilot-1 16:57:59.37	*[Removes oxygen mask from right side of helmet.]*			
HOT-1 16:57:59.84	*[Sound similar to the ambient noise of free air flowing around the pilot's facemask mounted microphone.]*			
Pilot-1 16:58:04.57	*[Takes sip from water bottle.]*			
		HOT-4 16:58:11.52	and @, can you find,	

SS2	WK2	RDO
	uhh, on the kneeboard, W-K two pylon arm heat?	
Pilot-1 16:58:15.93 *[Replaces oxygen mask strap to right side of helmet.]*		
	HOT-5 16:58:17.90 pylon arm heat, stand-by.	
HOT-2 16:58:19.22 I show L minus ten.		
HOT-1 16:58:22.77 yup.		
	HOT-5 16:58:23.24 yeah, I believe its six C.	
Pilot-1 16:58:24.07 *[Finishes replacing and adjusting mask.]*		
Pilot-2 16:58:25.07 *[Touches hand to oxygen mask briefly.]*		
	HOT-4 16:58:25.82 ok, it needs to be above minus five, so that's good.	
	HOT-5 16:58:28.43 yup and the pressure's up too.	
	RDO-3 16:58:30.82 [high frequency tone] ((galactic zero-one is at)) nine minutes thirty, nine minutes thirty.	

SS2	WK2	RDO
	HOT-4 16:58:37.33 alright.	
		BASE 16:58:37.82 scat two-one, base is ready for ((L minus ten checks.))
HOT-2 16:58:40.56 alright.		
HOT-1 16:58:40.95 roger, Spaceship commencing L minus ten.		
HOT-2 16:58:44.52 P-S-C enable. go to the page [unintelligible]		
Pilot-2 16:58:46.17 *[Manipulates center MFD to display RKT main page, VENT sub page.]*		
	HOT-4 16:58:46.94 now we have nav to DROP.	
	HOT-4 16:58:51.30 DROP [user defined waypoint] system *	
HOT-2 16:58:52.49 alright, here we go.		
Pilot-2 16:58:52.67 *[Reaches left hand toward PSC enable switch]*		
HOT-2 16:58:54.15 mark.		
Pilot-2 16:58:54.60 *[Removes left hand from area near PSC enable switch]*		

SS2	WK2	RDO
HOT-2 16:58:56.07 P-S-C active.		
	HOT-4 16:58:56.18 all green. hooks are locked.	
Pilot-2 16:58:56.83 *[Manipulates center MFD to display RKT main page, VALVE sub page]*		
HOT-1 16:58:58.80 good pressurization.		
	HOT-4 16:58:59.70 bottle pressure's good.	
	HOT-4 16:59:00.82 arm valve temperature is good.	
HOT-2 16:59:01.17 (b) (4) coming to auto.		
Pilot-2 16:59:03.20 *[Reaches left hand to* (b) (4) *RUN switch from "OFF" to "AUTO". Removes hand.]*		
HOT-2 16:59:04.18 mark. good indication.		
Pilot-2 16:59:06.10 *[Points to top of MFD screen.]*		
HOT-2 16:59:07.87 loose items?		
HOT-1 16:59:08.66 alright, secured left.		
HOT-2 16:59:10.23 and secured right.		
HOT-2 16:59:11.695 seatbelts and shoulder harnesses?		

SS2	WK2	RDO
HOT-1 16:59:13.87 I am snug in the left.		
SS2 Cockpit 16:59:14.93 *[Makes motion towards respective harness, both crew slightly wiggle in seat.]*		
HOT-2 16:59:15.05 snug on the right.		
HOT-2 16:59:16.25 flight plan set up?		
HOT-1 16:59:17.95 we've got, uh... DROP spaceship WIF-left, runway three zero. winds are still favoring three zero.		
Pilot-2 16:59:18.50 *[Reached toward but did not manipulate PFD.]*		
Pilot-1 16:59:20.37 *[Switches PFD to COM master page, COM sub page.]*		
Pilot-1 16:59:26.53 *[Switches PFD back to NAV master page.]*		
HOT-2 16:59:27.03 okay, and uh, C-D-I selected?		
HOT-1 16:59:29.47 alright, I've got selected left.		
Pilot-1 16:59:30.00 *[Briefly points to CDI select region on PFD screen.]*		
HOT-2 16:59:31.36 yeah, mine's selected right. batteries are coming on.		

SS2		WK2	RDO
Pilot-2 16:59:31.57	*[Places left hand near instrument panel and selects Left then Right battery switches to ON.]*		
HOT-2 16:59:35.80	pylon power is coming off.		
Pilot-2 16:59:37.23	*[Uses left hand to place PYLON POWER switch to OFF.]*		
HOT-2 16:59:39.07	electrical system?		
Pilot-2 16:59:39.67	*[Manipulates center MFD to display ELEC master page.]*		
Pilot-2 16:59:45.53	*[Points to center MFD with Left hand and makes a checking motion.]*		
HOT-1 16:59:46.73	all looks good.		
HOT-2 16:59:47.89	okay. pneumatics?		
Pilot-2 16:59:48.53	*[Manipulates center MFD to display PNEU page.]*		
HOT-1 16:59:50.43	greater than twenty-three, good regulator pressures.		
HOT-2 16:59:53.65	right, uh, feather locks. here comes the locks.		
Pilot-2 16:59:55.77	*[Places left hand on Feather Lock Handles. Favors Left side of the LT*		

SS2		WK2	RDO
	and RT Feather Lock Handles]		
Pilot-2 16:59:56.80	*[Moves Feather Lock Handles slightly right out of the detent and down to the UNLOCK position.]*		
SS2 Cockpit 16:59:58.03	*[FEATHER NOT LOCKED Light illuminates on the backup panel.]*		
Pilot-2 16:59:58.10	*[Reaches UNLOCK position with Feather Lock Handles.]*		
HOT-2 17:00:02.08	pressures...good indications... and locking.		
Pilot-2 17:00:04.20	*[Briefly removes hand from Feather Lock Handles and motions finger toward center MFD.]*		
Pilot-2 17:00:04.90	*[Places hand back on Feather Lock Handle and begins transiting handles toward the LOCK position.]*		
Pilot-1 17:00:06.70	*[Places hand to remove glare from Backup Panel, looks toward Backup Panel.]*		
SS2 Cockpit 17:00:08.10	*[FEATHER OK TO LOCK Light extinguishes on Backup Panel]*		

SS2	WK2	RDO
Pilot-2 17:00:09.07 *[Reaches handle LOCK position, moves handles slightly left into detent, ensures handles are seated in LOCK detent.]*		
Pilot-2 17:00:10.03 *[Motions with left fingers toward top of MFD/Backup Panel in a checking motion.]*		
HOT-2 17:00:10.07 and show locked.		
HOT-2 17:00:11.56 back-up indications look good.		
HOT-2 17:00:13.56 pri and alt air's coming off.		
Pilot-2 17:00:14.80 *[Reaches right hand toward right side of instrument panel.]*		
HOT-2 17:00:16.92 isolation valve…		
Pilot-2 17:00:17.87 *[Uses left hand to move Isolation Valve to the closed position.]*		
HOT-2 17:00:19.01 …it's closed.		
HOT-2 17:00:22.51 pri and emergency regulators are comin' to auto.		
Pilot-2 17:00:23.73 *[Uses left hand to move PRIMARY and EMERGENCY Regulator switches to AUTO position.]*		

SS2	WK2	RDO
HOT-2 17:00:26.86 radios?		
Pilot-2 17:00:28.43 *[Manipulates center MFD to COM main page, COM sub page.]*		
HOT-1 17:00:29.95 alright, we have mission set, one and two.		
HOT-2 17:00:32.67 okay, pitch and roll trim.		
HOT-1 17:00:36.38 alright goin' to pri and, uh, T Top we're, uhh, stirring the stick and we're gonna go off I-C-S.		
Pilot-1 17:00:37.27 *[Places right hand on STAB TRIM switches, after a pause, moves switches to the PRI position.]*		
	HOT-3 17:00:43.06 roger.	
HOT-2 17:00:49.22 alright. pitch and roll trim functionality?		
HOT-1 17:00:51.50 alright, trimming up...down.		
HOT-1 17:00:56.71 good pitch functionality, setting minus nine.		
HOT-1 17:01:10.04 alright, minus nine set...roll functionality…		

SS2		WK2	RDO
HOT-1 17:01:17.93	good roll and, uh, release trims are set.		
HOT-2 17:01:20.54	okay, tweak the pitch just a bit there.		
HOT-1 17:01:24.38	alright, tweaked.		
HOT-2 17:01:25.65	alright...roll boost?		
HOT-1 17:01:28.42	roll boost coming on.		
Pilot-1 17:01:29.17	*[Uses right hand to press ROLL BOOST pushbutton.]*		
HOT-2 17:01:30.08	and verify operation.		
Pilot-1 17:01:31.47	*[Moves stick laterally with both hands.]*		
HOT-1 17:01:34.73	good roll boost.		
HOT-2 17:01:36.30	okay, primary flight controls, dampers on?		
HOT-1 17:01:40.00	dampers coming on, good lights...rudders are locked...stick is free... dampers off... rudders free... stick free.		
Pilot-1 17:01:40.90	*[Uses right hand to move DAMPERS switch to ON, four white lights illuminate near DAMPERS switch.]*		

SS2		WK2		RDO
Pilot-1 17:01:43.53	*[Presses firmly with feet against rudder pedals.]*			
Pilot-1 17:01:44.60	*[Grabs sticks with both hands and begins moving control stick in a circular motion.]*			
Pilot-1 17:01:46.43	*[Completes moving stick in a circular motion, removes right hand and moves DAMPERS switch to OFF position. Four white lights near the DAMPERS switch extinguish.]*			
Pilot-1 17:01:49.83	*[Presses firmly against rudder pedals.]*			
Pilot-1 17:01:52.00	*[Uses both hands to move control stick in a circular motion.]*			
Pilot-1 17:01:53.13	*[Completes motion and removes both hands.]*			
HOT-2 17:01:53.94	'kay, cabin altitude's five thousand five hundred feet.			
Pilot-2 17:01:54.47	*[Uses left hand to point toward center MFD screen.]*			
HOT-2 17:02:00.09	(and) WhiteKnight, Spaceship's complete with L minus ten.			
		HOT-4 17:02:04.62	copy. complete. and, uh,	

SS2		WK2		RDO	
			we're going payload electrical power and payload E-C-S to off.		
HOT-2 17:02:14.65	alright, five minutes out. L minus four is next.				
				CHASE 17:03:00.19	extra's visual.
		RDO-3 17:03:03.62	roger extra.		
HOT-1 17:03:05.19	alright, comin' up on four minutes.				
HOT-1 17:03:19.16	four minutes.				
		RDO-4 17:03:22.68	and flight ((L minus four minutes.))		
HOT-2 17:03:26.41	alright. rocket burn timer?				
Pilot-1 17:03:28.93	*[Uses right hand to point toward center console, then quickly points toward center MFD.]*				
HOT-1 17:03:29.16	set and verified.				
HOT-2 17:03:30.44	alright, here comes the inter OV.				
Pilot-2 17:03:32.57	*[Places left hand near INTER-OV switch, makes an upward motion with hand near switch.]*				

SS2	WK2	RDO
HOT-2 17:03:35.551 alright, it's equalized.		
HOT-1 17:03:36.17 some light turbulence here.		
HOT-2 17:03:38.22 here comes the B-O-V.		
Pilot-2 17:03:38.67 *[Removes left hand from area near INTER-OV switch, places left hand near BOV switch. Removes left hand from area near BOV switch.]*		
HOT-1 17:03:42.42 light chop is, uh, maybe a better... better description.		
Pilot-2 17:03:45.70 *[RMC STATUS GO lights illuminate green]*		
HOT-2 17:03:47.29 R-M-C status?		
HOT-1 17:03:48.75 alright, we've got BOV open, two green lights.		
HOT-2 17:03:51.61 dampers?		
Pilot-1 17:03:53.67 *[Uses right hand to select CTRL master page on PFD.]*		
Pilot-1 17:04:00.87 *[Uses right hand to move DAMPERS switch to ON, four white lights illuminate near DAMPERS switch.]*		

SS2	WK2	RDO
HOT-1 17:04:01.38 dampers are symmetric, had to put in, uh, quite a bit of left force to get 'em there.		
HOT-2 17:04:07.19 okay...roll boost?		
Pilot-1 17:04:09.50 *[Uses right hand to select NAV master page, sub page indiscernible on PFD.]*		
HOT-1 17:04:09.74 roll boost is on.		
HOT-2 17:04:11.67 speed brake?		
HOT-1 17:04:13.27 it's disabled.		
Pilot-1 17:04:13.80 *[Uses right hand and points to area near SPEED BRAKE pushbutton.]*		
HOT-2 17:04:14.93 window heat's coming off.		
Pilot-2 17:04:16.17 *[Moves left hand to area near WINDOW HEAT switch, manipulates switch.]*		
HOT-2 17:04:18.74 M-F-D, uhh, A-D-C source auto.		
HOT-1 17:04:21.66 alright, source auto set left.		
HOT-2 17:04:23.34 and center and right. M-F-D CAS messages?		

SS2		WK2	RDO
HOT-1 17:04:25.96	they're all out.		
HOT-2 17:04:27.13	caution and warning lights?		
HOT-1 17:04:27.96	all... all out.		
HOT-2 17:04:30.05	transponder?		
Pilot-2 17:04:31.67	*[Manipulates center MFD to COM main page, XPDR sub page.]*		
Pilot-2 17:04:36.13	*[Manipulates soft keys on Left side of center MFD.]*		
Pilot-2 17:04:40.73	*[Manipulates center MFD to COM main page, COM sub page.]*		
HOT-2 17:04:43.81	alright.		
RDO-2 17:04:46.14	S-S Two is squawking.		
HOT-2 17:04:51.45	alright, release clearance…		
Pilot-1 17:04:53.83	*[Uses right hand to point toward right side of instrument panel.]*		
Pilot-2 17:04:55.00	*[Briefly points to lower section of center MFD in a checking motion.]*		
RDO-2 17:04:57.52	[high frequency tone] Mojave Tower, scat two-one request landing clearance runway three zero.		

SS2	WK2	RDO
		MHV TWR 17:05:10.34 ((scat two-one, this is)) Mojave ((tower.)) wind ((direction estimated two three)) zero ((at niner. approach end of)) runway three zero ((winds. runway three zero, cleared to land.))
RDO-2 17:05:19.80 cleared to land (three zero scat two-one.)		
	RDO-4 17:05:25.47 ((joshua, galactic zero-one is two minutes from)) release.	
HOT-2 17:05:27.31 L minus four checks are complete, @.		
HOT-1 17:05:29.51 alright.		
HOT-1 17:05:38.69 alright, you're clear to arm, uh, at pylon release, I'll call for fire, and uh...call the pitch up, pitch down, trim, feather unlock one point four.		
HOT-2 17:05:54.11 I'll uh, I'll try to keep a hack on that three-forty-five as well.		
HOT-1 17:05:57.54 okay.		
HOT-1 17:06:12.02 alright, then after, uh, shutdown, roll boost, uh, while we have some speed, roll boost will come off. primary (R-		

SS2		WK2	RDO	
	C-S) is uh, comin' on. set the, uh, attitudes...feather uh, up, at uh, apogee...reset trims for minus ten...you're cleared to feather at, uh, apogee, if I haven't called for it, and, uh, remind me on the uh trims, if I haven't gotten to 'em.			
HOT-1 17:06:43.84	alright, the visibility's goin' down a little bit here...I still have lakebed, and uh...			
HOT-2 17:06:52.68	L minus thirty.			
			BASE 17:06:54.438	((scat two-one, glide trims good)) green for release.
HOT-2 17:06:55.41	alright, stick?			
HOT-1 17:06:57.27	stick is forward.			
Pilot-1 17:06:57.37	*[Places both hands on control stick and moves it to a forward position.]*			
Pilot-2 17:06:58.40	*[Quickly moves left hand toward lower center console, then quickly moves left hand up to the LAUNCH CONTROL ARM switch.]*			
RDO-2 17:06:59.98	armed. yellow light.			
Pilot-2 17:07:00.40	*[Removes left hand from LAUNCH CONTROL ARM switch, an amber*			

SS2		WK2		RDO	
	colored arm pushbutton light below switch is illuminated.]				
SS2-Cockpit 17:07:01.23	*[Pilot places head firmly against headrest and slightly readjusts his seated position. Remains with head positioned on headrest until vehicle breakup. Co-pilot's head is slightly off headrest and moves toward instrument panel as he reaches for switches on panel. At no time during the boost portion does co-pilot's head touch the headrest. There is slight noticeable vibration to the pilot's helmet due to it being pushed against the structure of the seat and minimal vibration noticeable to the co-pilot's helmet during boost portion of flight.]*				
Pilot-2 17:07:03.30	*[Moves his left hand onto ROCKET MOTOR ARM AND FIRE panel and makes an upward motion in vicinity of a switch.]*				
Pilot-2 17:07:14.50	*[Moves left hand near ROCKET MOTOR ARM AND FIRE panel.]*				
		RDO-4 17:07:15.92	((five. four. three.)) two. one. release. release. ((release.))		

SS2		WK2	RDO
HOT-?			
17:07:19.01	clean release.		
SS2 Cockpit			
17:07:19.27	*[There is a visible jolt to cockpit and occupants.]*		
HOT-2			
17:07:19.27	[mechanical sound associated with the operation of the SS2/WK2 release mechanism.]		
HOT-1			
17:07:19.51	fire.		
SS2 Cockpit			
17:07:20.00	*[Shadow of WK2's wing can be seen quickly crossing inside of cabin of SS2]*		
Pilot-2			
17:07:20.13	*[moves left hand toward ROCKET MOTOR ARM switch.]*		
HOT-2			
17:07:20.69	arm.		
Pilot-2			
17:07:20.87	*[Makes quick motions with his left hand near ROCKET MOTOR ARM and FIRE switches.]*		
Pilot-1			
17:07:21.20	*[Relaxes forward pressure on stick.]*		
HOT-2			
17:07:21.29	fire.		
SS2 Cockpit			
17:07:22.73	*[Both PFDs auto sequence to BOOST phase and graphically change.]*		

SS2		WK2	RDO
HOT-1			
17:07:24.46	[strained voice] good light.		
Pilot-2			
17:07:25.30	*[Makes contact with left hand on left side of the control stick. Fingers and thumb of left hand appear to be around left horn of control stick.]*		
Pilot-1			
17:07:25.90	*[Uses both hands on stick to make minor lateral movements to make left and right roll corrections.]*		
HOT-1			
17:07:26.28	[strained voice] yeehaw.		
Pilot-2			
17:07:26.80	*[Begins moving left hand off of left horn of control stick. Begins left hand movement toward Feather Lock Handles.]*		
SS2 Cockpit			
17:07:26.83	*[PFD speed display on both PFD auto switches from ADC to INS by displaying the KEAS gauge from a black to a greyish white background.]*		
HOT-2			
17:07:26.91	[strained voice] point eight.		
Pilot-2			
17:07:27.37	*[Places left hand on Feather Lock Handles.]*		
Pilot-2			
17:07:27.47	*[Moves Feather Lock Handles slightly right out of lock detent.]*		

SS2	WK2	RDO
Pilot-2 17:07:27.57 *[LT and RT Feather Lock Handles appear wider than previously seen. Handles appear to slightly diverge.]*		
Pilot-2 17:07:27.90 *[Co-pilot appears to be leaning forward and into a downward unlocking motion with his left arm and shoulder.]*		
Pilot-1 17:07:27.99 *[Pilot's left thumb rapidly moved from right to left and back again in the immediate vicinity of the trim hat switch on the flight controls. The movement appeared consistent with a possible quick left lateral trim input.]*		
Pilot-2 17:07:28.10 *[Left hand is briefly removed from Feather Lock Handles and LT and RT portions appear to converge.]*		
Pilot-2 17:07:28.27 *[Left hand has shifted grip to LT side of LT and RT Feather Lock Handles.]*		
HOT-2 17:07:28.39 [straining] unlocking.		
Pilot-2 17:07:28.40 *[A slight right motion to move LT and RT Feather Lock Handles out of LOCK detents.]*		
Pilot-2 17:07:28.43 *[A downward motion of Feather Lock Handles begins, handles appear to be slightly twisted with LT Feather*		

SS2		WK2	RDO
	Lock handle lower than RT Feather Lock handle.]		
Pilot-2 17:07:28.60	*[Feather Lock Handles are in mid transit.]*		
Pilot-2 17:07:28.90	*[Feather Lock Handles appear to have reached UNLOCK position.]*		
Pilot-2 17:07:29.00	*[Relaxes Left hand grip on Feather Lock Handles while still touching mechanism.]*		
SS2 Cockpit 17:07:29.57	*[FEATHER NOT LOCKED Light illuminates on backup panel.]*		
Pilot-2 17:07:30.07	*[Moves left hand off of Feather Lock Handles.]*		
SS2 Cockpit 17:07:30.67	*[There is a slight but noticeable right roll indicated on ADI on both PFDs.]*		
SS2 Cockpit 17:07:30.97	*[FEATHER OK TO LOCK Light extinguishes, FEATHER NOT LOCKED Light remains illuminated.]*		
SS2 Cockpit 17:07:31.40	*[Both pilots' bodies appear to begin to be pushed downward into their seats.]*		
HOT-1 17:07:31.42	[strained voice] pitch up.		

SS2	WK2	RDO

HOT-2
17:07:31.76 [strained voice] pitch up.

Pilot-1
17:07:31.79 *[Pilot's left thumb rapidly moved to a position just above the trim hat switch on the flight controls and remains near the hat trim switch until the end of the recording. During this time, no forward, aft or lateral trim input movements were seen.]*

SS2 Cockpit
17:07:31.80 *[Backup FEATHER POSITION INDICATOR Light appears to have moved slightly upward on scale. ADI begins showing a pitch up trend on both PFDs.]*

Pilot-2
17:07:31.80 *[Co-pilot's head appears to move noticeably forward.]*

SS2 Cockpit
17:07:32.03 *[Right roll indication on ADI on both PFDs appears to become more level.]*

HOT-1&2
17:07:32.26 [Sound of grunting]

Pilot-2
17:07:32.33 *[Co-pilot's head continues to move forward toward his lap. There is some movement of left hand off of left knee.]*

Pilot-1
17:07:32.37 *[Pilot's head begins to move off headrest and slightly forward.]*

SS2	WK2	RDO
SS2 Cockpit 17:07:32.47 *[There is a noticeable vibration to the cockpit image.]*		
SS2 Cockpit 17:07:32.80 *[Both pilots' torsos appear to be slumped forward with their harnesses restraining their bodies. pilots' heads have been pushed forward toward control panel and almost into their laps.]*		
SS2 Cockpit 17:07:32.80 *[End of recording. End of Transcript]*		

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