Pilot/Race 177, *The Galloping Ghost*
North American P-51D, N79111
Reno, Nevada
September 16, 2011

Accident Brief

NTSB/AAB-12/01
PB2012-916203

National
Transportation
Safety Board

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Notation 8349C
Adopted August 27, 2012

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

National Transportation Safety Board. 2012. ***Pilot/Race 177, The Galloping Ghost, North American P-51D, N79111, Reno, Nevada, September 16, 2011*****. NTSB/AAB-12/01. Washington, DC.**

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Acronyms and Abbreviations

AC	advisory circular
ADI	anti-detonation injection
agl	above ground level
CAMI	Civil Aerospace Medical Institute
CFR	*Code of Federal Regulations*
CG	center of gravity
DCU	data collection unit
EFIS	electronic flight information system
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
FSDO	flight standards district office
G-LOC	G-induced loss of consciousness
GPS	global positioning system
NAG	National Air-racing Group
NCAR	National Championship Air Races
NTSB	National Transportation Safety Board
RARA	Reno Air Racing Association
REMSA	Reno Emergency Medical Services Authority
RF	radio-frequency transmitter
RTAA	Reno Tahoe Airport Authority
RTS	Reno/Stead Airport, Reno, Nevada
SD	secure digital

Executive Summary

On September 16, 2011, about 1625 Pacific daylight time, an experimental, single-seat North American P-51D, N79111, collided with the airport ramp in the spectator box seating area following a loss of control during the National Championship Air Races unlimited class gold race at the Reno/Stead Airport (RTS), Reno, Nevada. The airplane was registered to Aero-Trans Corp (dba Leeward Aeronautical Sales), Ocala, Florida, and operated by the commercial pilot as Race 177, *The Galloping Ghost*, under the provisions of 14 *Code of Federal Regulations* Part 91. The pilot and 10 people on the ground sustained fatal injuries, and at least 64 people on the ground were injured (at least 16 of whom were reported to have sustained serious injuries). The airplane sustained substantial damage, fragmenting upon collision with the ramp. Visual meteorological conditions prevailed, and no flight plan had been filed for the local air race flight, which departed RTS about 10 minutes before the accident.

The accident airplane was in third place during the third lap of the six-lap race and was traveling about 445 knots when it experienced a left roll upset and high-G pitch up. Subsequently, the airplane entered a right-rolling climb maneuver. During these events, the vertical acceleration peaked at 17.3 G, and, a few seconds later, a section of the left elevator trim tab separated in flight. The characteristics of the airplane's pitch changes during the upset were such that the pilot's time of useful consciousness was likely less than 1 second. As a result, the pilot soon became completely incapacitated, and the airplane's continued climb and helical descent occurred without his control.

The accident airplane had undergone many structural and flight control modifications that were undocumented and for which no flight testing or analysis had been performed to assess their effects on the airplane's structural strength, performance, or flight characteristics. The investigation determined that some of these modifications had undesirable effects. For example, the use of a single, controllable elevator trim tab (installed on the left elevator) increased the aerodynamic load on the left trim tab (compared to a stock airplane, which has a controllable tab on each elevator). Also, filler material on the elevator trim tabs (both the controllable left tab and the fixed right tab) increased the potential for flutter because it increased the weight of the tabs and moved their center of gravity aft, and modifications to the elevator counterweights and inertia weight made the airplane more sensitive in pitch control. It is likely that, had engineering evaluations and diligent flight testing for the modifications been performed, many of the airplane's undesirable structural and control characteristics could have been identified and corrected.

The investigation determined that the looseness of the elevator trim tab attachment screws (for both the controllable left tab and the fixed right tab) and a fatigue crack in one of the screws caused a decrease in the structural stiffness of the elevator trim system. At racing speeds, the decreased stiffness was sufficient to allow aerodynamic flutter of the elevator trim tabs. Excitation of the flutter resulted in dynamic compressive loads in the left elevator trim tab's link assembly that increased beyond its buckling strength, causing a bending fracture. The flutter and the failure of the left elevator trim tab's link assembly excited the flutter of the right elevator trim tab, increasing the dynamic compressive loads in the right elevator trim tab's fixed link assembly beyond its buckling strength, causing a bending fracture. The investigation found that the

condition of the trim tab attachment screws' locknut inserts, which showed evidence of age and reuse, rendered them ineffective at providing sufficient clamping pressure on the trim tab attachment screws to keep the hinge surfaces tight.

The National Transportation Safety Board (NTSB) determines that the probable cause of this accident was the reduced stiffness of the elevator trim tab system that allowed aerodynamic flutter to occur at racing speeds. The reduced stiffness was a result of deteriorated locknut inserts that allowed the trim tab attachment screws to become loose and to initiate fatigue cracking in one screw sometime before the accident flight. Aerodynamic flutter of the trim tabs resulted in a failure of the left trim tab link assembly, elevator movement, high flight loads, and a loss of control. Contributing to the accident were the undocumented and untested major modifications to the airplane and the pilot's operation of the airplane in the unique air racing environment without adequate flight testing.

As a result of this investigation and the NTSB's January 10, 2012, investigative hearing on air race and air show safety, on April 10, 2012, the NTSB issued 10 safety recommendations to the Reno Air Racing Association, the National Air-racing Group Unlimited Division, and the Federal Aviation Administration (FAA) with the intent of improving the safety of air race operations. These recommendations addressed requiring engineering evaluations for aircraft with major modifications, raising the level of safety for spectators and personnel near the race course, improving FAA guidance for air races and course design, providing race pilots with high-G training, evaluating the feasibility of G-suit requirements for race pilots, and tracking the resolution of race aircraft discrepancies identified during prerace technical inspections. Each safety recommendation recipient has initiated or completed positive action in response to these safety recommendations.

National Transportation Safety Board
Washington, D.C. 20594

Aircraft Accident Brief

Accident Number: WPR11MA454
Operator/Flight Number: Pilot/Race 177, "The Galloping Ghost"
Aircraft and Registration: North American P-51D, N79111
Location: Reno, Nevada
Date: September 16, 2011
Adopted:

1. FACTUAL INFORMATION

1.1 HISTORY OF FLIGHT

On September 16, 2011, about 1625 Pacific daylight time,[1] an experimental, single-seat North American P-51D, N79111, collided with the airport ramp in the spectator box seating area following a loss of control during the National Championship Air Races (NCAR) unlimited class[2] gold race at the Reno/Stead Airport (RTS), Reno, Nevada. The airplane was registered to Aero-Trans Corp (dba Leeward Aeronautical Sales), Ocala, Florida, and operated by the commercial pilot as Race 177,[3] *The Galloping Ghost*, under the provisions of 14 *Code of Federal Regulations* (CFR) Part 91. The pilot and 10 people on the ground sustained fatal injuries, and at least 64 people on the ground were injured (at least 16 of whom were reported to have sustained serious injuries).[4] The airplane sustained substantial damage, fragmenting upon collision with the ramp. Visual meteorological conditions prevailed, and no flight plan had been filed for the local air race flight, which departed RTS about 10 minutes before the accident.

The accident airplane was in third place during the third lap of the six-lap race, trailing the second-place airplane (*Voodoo*, another experimental P-51D) by about 4.5 seconds and the lead airplane (*Strega*, also an experimental P-51D) by about 8.8 seconds. The accident airplane was traveling about 445 knots as it passed pylon 8 (see figure 1) and experienced a left roll upset

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

[2] The unlimited class, which is one of six NCAR race classes, includes several types of modified propeller-driven, reciprocating-engine-equipped airplanes that have an empty weight greater than 4,500 pounds. The unlimited class airplanes may operate at ground speeds in excess of 435 knots.

[3] NCAR race control identifies each participating airplane using its assigned race number, which is painted on the fuselage and wings.

[4] The precise number of injured persons could not be determined. Although three hospitals provided information about the number of patients treated and the extent of their injuries, a fourth hospital provided only limited information. Also, limited information was available about patients who were either treated only at the scene or sought medical treatment at other facilities.

and high-G[5] pitch-up. During the upset, in less than 1 second, the airplane rolled from its established approximate 73°-left-bank turn to about 93° left bank, and vertical acceleration reached about 11 G.[6] After the left roll upset, the airplane entered a right-rolling climb maneuver. During these events, the vertical acceleration peaked at 17.3 G, and, a few seconds later, a section of the left elevator trim tab separated in flight. The airplane subsequently descended in a helical flightpath to the ground.

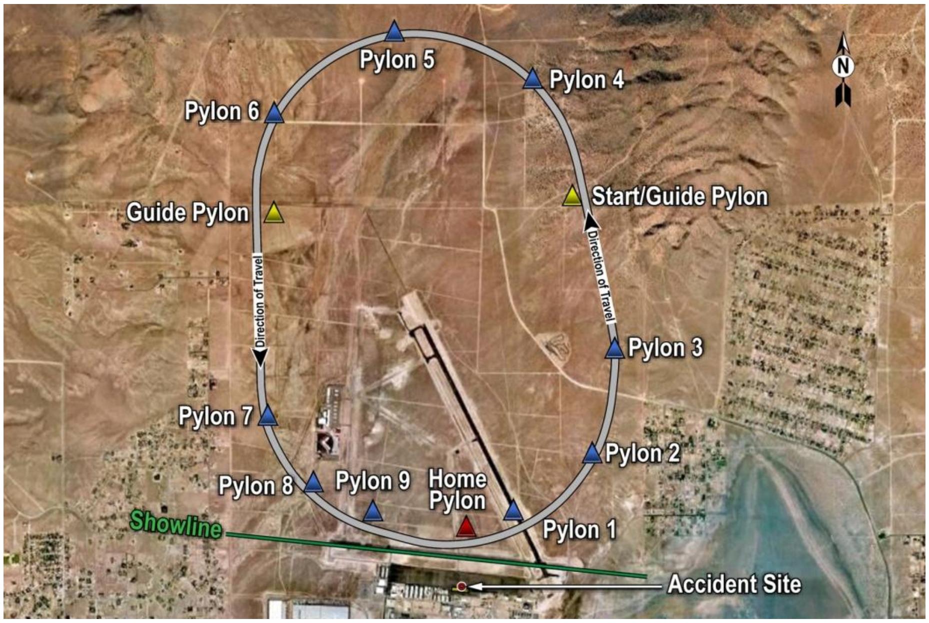

Figure 1. Diagram of the NCAR unlimited class race course at RTS, showing relative locations of pylons and the accident site.

1.2 PERSONNEL INFORMATION

The pilot, age 74, held a commercial pilot certificate for airplane single-engine land, single-engine sea, and multi-engine land; instrument airplane; rotorcraft-helicopter; and glider. He held type ratings for numerous airplanes and was authorized to fly numerous experimental aircraft. His most recent Federal Aviation Administration (FAA) second-class medical certificate

[5] The term G is used as a dimensionless measure of acceleration or force. The value can be determined by the ratio of a particular acceleration (a) to the acceleration due to gravity (g) at sea level (in which G = a/g and g = 32.2 feet per second^2), the ratio of a force on an object (F) to the weight (W) of the object being accelerated (in which G = F/W), or the ratio of the lift (L) of a wing to the weight (W) of an airplane (in which G = L/W). In accordance with common practice, this brief refers to accelerations or forces in terms of G. For example, it is customarily understood that “5 G” represents an acceleration of five times the acceleration of gravity at sea level (acceleration = 5 × 32.2 feet per second^2 or 5 g), or that lift is five times the weight of the aircraft ($L = 5 \times W_{aircraft}$), or that the restraint force holding an occupant in place is five times the weight of the occupant (seatbelt force = $5 \times W_{occupant}$).

[6] Information about the airplane’s vertical acceleration that is summarized throughout this brief was derived from the NTSB’s Video Study calculations (performed using video footage of the airplane provided by ground witnesses) and the airplane’s onboard accelerometer; for more information, see figure 11 in section 1.10.1.2 of this brief and the video study in the public docket for this accident. Information about the airplane’s bank angle, speed, and timing was derived from study calculations performed using photographs, video footage, and telemetry data for the airplane; for more information, see section 1.10.1 of this brief and the Image Study, Performance Study, and Data Recorders Report in the public docket for this accident.

was issued on March 2, 2010, with no limitations. The pilot's 2011 NCAR entry form that was submitted to the Reno Air Racing Association (RARA) listed the pilot's total flight time as "13,200±" hours, his time in the "entered race airplane" (the accident airplane) as "2,700±" hours, and his time in the airplane make and model as "2,700±" hours. There were some discrepancies between this information and the information provided on the pilot's 2009 and 2010 NCAR entry forms.[7]

A review of the pilot's FAA airman medical records revealed that his most recent application for an airman medical certificate indicated no history of medical, psychiatric, drug, or alcohol conditions. The aviation medical examiner noted on the application that the pilot used only one medication rarely and seemed to be in good health. A review of the pilot's personal medical records revealed diagnoses in 2007 of elevated homocysteine (an independent risk factor for heart disease) and hyperlipidemia (elevated cholesterol), for which he was prescribed medications. During a February 27, 2012, telephone interview with the NTSB medical officer, the pilot's physician described the accident pilot as being in good general health and fitness for his age. The physician stated that he found no evidence on physical examination or by electrocardiogram that the pilot had pulmonary hypertension (high blood pressure in lung vasculature) and that he saw no history of symptoms that might suggest that the pilot had pulmonary hypertension or chronic hypoxemia (low blood oxygen pressure).

1.3 AIRPLANE INFORMATION

The North American P-51D is an all-metal (with the exception of some control surfaces), low-wing, single-seat, single-engine, propeller-driven airplane with conventional landing gear. The first P-51 variant entered production in 1941 and was originally designed and built as a long-range military fighter airplane. The P-51D variant entered production in April 1944. The stock P-51D's empty weight was 7,635 pounds, and its maximum gross weight was 12,100 pounds. The accident airplane, serial number 44-15651, was delivered to the Army Air Forces on December 23, 1944, and, in July 1946, it was declared surplus and sold. The airplane was raced in the NCAR from 1969 through 1982 with various modifications for racing before being acquired by the accident pilot in July 1983.[8]

The accident pilot raced the airplane in the NCAR from 1983 through 1989 before placing it in storage until 2007.[9] Between 2007 and 2009, the airplane underwent overhaul and further modifications in Arizona, Texas, and Nevada. The configuration that the airplane had on the day of the accident was completed in the fall of 2009 in Minden, Nevada, where it remained when not being raced in the NCAR.

[7] The pilot's 2009 and 2010 entry forms listed the pilot's age as "59," but the 2011 entry form accurately listed his age. In 2009, the pilot's total flight time was listed as "13,700" hours, and, in 2010, it was listed as "13,000±" hours. On the 2009 and 2010 entry forms, the pilot's total time in the "entered race airplane" was listed as "2,500+" hours and "2,500 hrs ±", respectively.

[8] Before it was purchased by the accident pilot, the airplane had raced in the NCAR as Race 69, *Miss Candace*, and Race 69, *Jeannie*.

[9] The accident pilot previously raced the airplane as Race X, *Spectre*; Race 44, *Leeward Air Ranch Special*; and Race 9, *Leeward Air Ranch Special*.

1.3.1 Racing Modifications

The airplane was equipped with a Rolls-Royce Merlin V-1650-9A engine, which was modified for racing, and an unmodified Hamilton Standard 24D50 propeller. Solid aluminum engine mounts were installed (instead of stock elastic mounts) to prevent the engine from moving at high race-power settings. The airplane was equipped with a racing canopy that had a smaller frontal area than the stock canopy and was hinged to open upward (rather than slide aft). The upper fuselage structure was modified with an aerodynamic turtle deck[10] to accept the smaller racing canopy.

The airplane's boil-off engine cooling system (which a stock P-51D does not have) submerged the radiators in a water/methanol bath.[11] The boiler was installed aft of the pilot's seat in an area sealed off from the cockpit. The water/methanol mixture (which was used in both the boil-off cooling system and the engine's anti-detonation injection [ADI] system[12]) was contained in a 150-gallon tank in the left wing that had been converted from the original left wing fuel tank. A custom-built fuselage structure was installed in place of the stock lower air scoop (which normally houses the stock radiators, one for the engine coolant and aftercooler, and the other for the engine oil) to provide an aerodynamic shape on the underside of the fuselage aft of the wing. No information, such as skin gauge or other details, was available for the modified turtle deck or lower fuselage structure.

The outboard section of each wing was removed, and a new wingtip with an end plate was installed. The airplane's modified wingspan was about 28 feet 10 inches (compared to the stock wingspan of 37 feet 5/16 inch), which was the shortest wingspan of any modified P-51D racing in 2011. Each aileron was shortened to about 3 feet (from a stock length of about 7 feet) and had two hinges (a stock aileron has three). The right aileron trim tab was removed, and the trim for the left aileron was run by an electric trim motor installed at the wing root (as opposed to the stock manual trim system). The horizontal stabilizer and elevators were equipped with modified flat end caps that reduced the horizontal stabilizer span to about 12 feet 1 inch (from a stock span of 13 feet 2 1/8 inches). (See figure 2.)

[10] The turtle deck is the upper fuselage structure located immediately aft of the cockpit and forward of the empennage.

[11] During engine operation, as the water/methanol mixture absorbs heat, it boils off and vents overboard as vapor.

[12] The ADI system functioned by injecting the water/methanol mixture in the fuel/air charge upstream of the supercharger to cool the mixture and prevent auto detonation.

Figure 2. Illustration of the accident airplane with stock P-51D dimensions shown in red.

Modifications to the elevator counterweights, upper rudder counterweight, vertical stabilizer incidence, horizontal stabilizer incidence, and rudder were discovered during the postaccident wreckage examination. The horizontal stabilizer, elevators, and trim tabs were of all-metal construction but were modified with up to 1/8 inch of filler material on the upper and lower skins that smoothed the surfaces. The left elevator counterweight weighed 26 pounds, and the right elevator counterweight (with some of the elevator structure and outboard hinge assembly still attached) weighed 27.5 pounds. Available documentation for the stock elevator counterweight specified a maximum total weight of 13.75 pounds. The vertical stabilizer's leading edge was offset to the right of the airplane's longitudinal axis by means of a tapered shim installed between the vertical stabilizer rear spar and the empennage structure (the stock P-51D's vertical stabilizer is offset to the left of the airplane's longitudinal axis). The rudder was modified to remove the stock trim tab and its associated control cables and to cover the trim-tab cutout with fabric. The modified upper rudder counterweight weighed 25 pounds. Available documentation for the stock upper rudder counterweight specified a maximum total weight of 16.6 pounds. The horizontal stabilizer incidence was increased from the stock value of 0.5° leading edge up to 0.91° leading edge up through the installation of a shim between the forward attach points and the fuselage.

The right elevator trim tab was modified such that it was fixed in place and faired with the right elevator by means of a steel rod installed between the elevator rear spar and the link assembly; the stock trim actuator had been removed from the right horizontal stabilizer. The left elevator trim tab, link assembly, and trim actuator remained installed as designed but had been converted from manual control to electric control through the installation of an electric trim motor on the forward side of the horizontal stabilizer forward spar. The electric elevator (pitch) trim and aileron (roll) trim systems were controlled by the pilot via switches on the left side of the cockpit, and an indicator light provided a neutral elevator trim indication to the pilot. Members of the airplane's ground crew stated that they believed that the airplane was typically raced with neutral elevator trim (0° left tab deflection). They stated that full travel of the left elevator trim tab (from full up to full down deflection) would take about 20 seconds.

The reasons for many of the modifications could not be established. Neither the pilot's family members nor the airplane's ground crew were aware of any detailed drawings, engineering calculations, or other substantiating data for any of the modifications. A ground crewmember stated that the pilot had wanted the airplane to be set up like a former racing airplane, "Stiletto,"[13] which was also a modified P-51D (some of the parts for the accident airplane were previously installed on Stiletto). According to the ground crewmembers, the accident pilot was the only person to fly the airplane from 2009 to the date of the accident.

1.3.2 Maintenance Records

An airframe logbook entry dated September 16, 2009, stated that the airplane was assembled in accordance with the P-51D&K Erection and Maintenance Manual (AN 01-60JE-2). The entry also stated that a boil-off cooling system was installed and a condition inspection[14] was accomplished in accordance with 14 CFR Part 43, Appendix D. A logbook entry dated September 22, 2009, and signed by the accident pilot stated the following:

> The prescribed flight test hours have been completed, and the aircraft is controllable throughout its normal range of speeds and throughout all manevers [sic] to be executed, has no hazardous operating characteristics or design features, and is safe for operation.

The most recent airframe logbook entry was a condition inspection entry dated July 29, 2011, that listed an airframe total time of 1,447.2 hours.[15]

The engine logbook contained two entries dated September 8, 2009, documenting that the engine was repaired and assembled in accordance with the U.S. Army Manual AN 02-55AC-3 (Revision 07-15-1945) to the manufacturer tolerances listed in sections X-XI at an airframe total time of 1,428.9 hours. An engine condition inspection entry dated July 29, 2011, listed an

[13] Stiletto, which raced at the NCAR from 1984 to 1992, had shortened wings, horizontal stabilizers, and elevators (with dimensions similar to those of the accident airplane); a removed lower air scoop; and trim controls that used only the left elevator and left aileron trim tabs. An accomplished Lockheed Skunk Works test pilot who was involved in the Stiletto project published an article in 1985 that described a rigorous flight test program that was used to determine the flying qualities of the airplane, including flutter characteristics. See S. Holm, "How I Won Reno: Skip Holm Flies Stiletto," *Air Progress*, vol. 47, no. 1 (1985), pp. 52-56.

[14] A condition inspection is a required inspection for experimental airplanes, as specified in the airplane's operating limitations, that typically must be performed within the preceding 12 calendar months. It is similar in scope to an annual inspection that must be performed for certificated airplanes.

[15] The investigation determined that this airframe total time was off by 6.4 hours due to an error made in a September 16, 2009, entry that was carried forward. The correct airframe total time on July 29, 2011, was 1,453.6 hours, which was accurately reflected in an engine logbook entry that listed the total airframe time on that date.

airframe total time of 1,453.6 hours. The propeller logbook contained a propeller condition inspection entry dated July 29, 2011, that listed a propeller total time of 24.7 hours. An entry dated September 4, 2011, indicated that a propeller dynamic balance was performed.

According to an airplane weight and balance report dated September 14, 2009, the accident airplane's empty weight was 6,474 pounds with an empty-weight center of gravity (CG) of 135.38 inches aft of the reference datum. The report indicated that the CG limits for the airplane were from 135.77 to 143.8 inches, which are the same values for the stock P-51D. There was no record of any testing performed to establish the forward and aft CG limits of the modified airplane. Postaccident calculations using conservative fuel and ADI fluid consumption rates for telemetry-derived engine power settings for the flight determined that, at the time of the upset, the airplane weighed about 7,760 pounds with a CG located about 140.2 inches aft of datum.

According to one member of the airplane's ground crew, work was done on the airplane to tighten up some "free-play" in the airplane's trim control tabs before it arrived at the NCAR. The right elevator trim tab screws were also removed and reinstalled after the prerace technical inspection identified a discrepancy before the airplane flew on the course.[16]

1.4 METEOROLOGICAL INFORMATION

The automated weather observing system at RTS, elevation 5,050 feet, reported at 1620 that wind was from 240° at 15 knots with gusts to 21 knots, visibility 10 miles, clear sky conditions below 12,000 feet above ground level (agl), temperature 22°C, dew point 0°C, and altimeter setting 29.99 inches of mercury. At 1630, wind was from 240° at 15 knots with gusts to 20 knots, with the same visibility, sky conditions, temperature, dew point, and altimeter setting.

A Weather Research and Forecasting Model simulation[17] was run to simulate the weather conditions surrounding the accident site at the accident time. According to the simulation, at 1620, the wind over the accident site about 100 feet agl was from 275° at 20 knots, and, at 1630, it was from 275° at 21 knots. At 1630 at higher altitudes (about 400 feet and 1,100 feet agl), the wind was from 280° at 24 knots and from 275° at 23 knots, respectively. Although the simulation indicated signatures of rapid wind changes within small distances both north-northwest and south of the accident site, the wind conditions above the surface at RTS remained laminar.

1.5 AIRPORT AND RACE COURSE INFORMATION

RTS is at an elevation of 5,050 feet above mean sea level and has two runways: runway 14/32, which is 9,000 feet long, and runway 8/26, which is 7,608 feet long. The FAA issued a certificate of waiver or authorization on September 2, 2011, to enable the NCAR to be held at RTS. Provisions of the waiver stated that all flights conducted at altitudes less than

[16] More information can be found in section 1.11.2 of this brief.

[17] The simulation was the Weather Research and Forecasting Model (WRF) Advanced Research WRF core version 3.2.1.5. For more information, see the Meteorological Factual Report in the NTSB's public docket for this accident.

1,000 feet agl must remain north of the showline[18] located on the south edge of runway 8/26 and within 1,000 feet horizontally of the depicted course. It also stated that race flight operations may be no closer than 500 feet horizontally from the primary spectator areas for all aircraft.

The closed course design for the NCAR unlimited class race course at RTS featured 10 pylons (plus 2 guide pylons), and the course distance was about 8.4 miles. FAA guidance for air races and course design was provided in two documents: FAA Order 8900.1, *Flight Standards Information Management System* (volume 3, chapter 6, section 1, paragraph 3-151) and Advisory Circular (AC) 91-45C, "Waivers: Aviation Events" (chapter 4). These documents specified the required distance between the spectators and the showline, formulas for calculating the minimum turn radius in evaluating the suitability of a race course design, and information about constructing safety areas.

A comparison of the two FAA guidance documents revealed that FAA Order 8900.1 stated that all racing classes "require a distance of 500 feet between the primary spectator area and the showline," whereas AC 91-45C stated that the unlimited racing class (or other classes with "speeds in excess of 250 miles per hour") "requires a spacing of 1,000 feet between the spectator area and the showline." The order and the AC also differed in the specified formula for determining the minimum turn radius for race course designs. The two documents differed from RARA documents regarding aircraft operating speeds for the unlimited class and jet class, and AC 91-45C (which had not been revised since 1990) did not address the jet class. Further, the order's discussion of race course safety areas provided a figure that illustrated information related to aerobatic maneuvers, not race course design.

1.6 FLIGHT RECORDERS

The airplane was not equipped (and was not required to be equipped) with a flight data recorder or cockpit voice recorder.[19] However, the airplane had two onboard devices that, although not specifically designed for crashworthiness or accident investigation purposes, were capable of recording some flight data parameters. One of these devices was a Dynon electronic flight information system (EFIS) D10A, which integrates multiple flight instruments and can log certain EFIS and global positioning system (GPS) parameters to internal memory.[20] Multiple pieces of the EFIS-D10A were identified in the wreckage, but the memory device was not located.

The airplane was also equipped with an RCATS Systems telemetry system that included a data collection unit (DCU), radio-frequency (RF) transmitter, and sensor adapter board. The DCU is designed to collect data from various onboard sensors, an internal GPS receiver, and an

[18] FAA Advisory Circular 91-45C defines a showline as "a prominent, readily visible ground reference, such as a river, runway, taxiway…or any straight line that enhances pilot orientation during aerobatic routines…[that] also serves as the horizontal axis for the show."

[19] Title 14 CFR 91.609 specifies flight data recorder and cockpit voice recorder requirements for aircraft operated under Part 91.

[20] According to the manufacturer, firmware versions 5.0 and later contain the ability to log certain EFIS and GPS parameters to internal memory. The data logging must be configured by the operator to enable logging and set the data log interval. The internal memory can store at least 2 hours of cumulative data at a 1-second recording interval or at least 120 hours at a 60-second recording interval.

internal accelerometer and is capable of both recording the data on an onboard secure digital (SD) card and transmitting it via data link (using the RF transmitter) to a ground station equipped with a receiver. These data include time, true course, magnetic course, latitude, longitude, GPS-derived altitude, GPS-derived velocity, vertical acceleration, engine rpm, engine manifold pressure, oil temperature, oil pressure, boiler pressure, ADI pressure, coolant temperature, fuel pressure, and other parameters. The ground station operator can monitor and store various airplane parameters in real time using the system's virtual instrument panel software. The software can also be used to play back recorded data from the onboard SD card or from the ground station. The DCU, RF transmitter, and sensor adapter board were recovered damaged in the wreckage. Although attempts to recover data from the damaged SD card were unsuccessful, ground station telemetry data were available, including data from the accident flight and previous flights and ground runs dating back to September 21, 2009.[21]

1.7 WRECKAGE AND IMPACT INFORMATION

The airplane was fragmented by ground impact forces. Most of the empennage (with the vertical stabilizer and the inboard portions of the right horizontal stabilizer, right elevator, and left elevator attached) was recovered as one large piece of mangled wreckage. The elevator counterweights were located, but the elevator inertia weight (also commonly referred to as a bob weight) was not identified in the wreckage; preaccident photographs taken of the elevator inertia weight before its installation show that it appeared to be modified, such that the ends outboard of the attach brackets were removed. All of the airplane's control cable fractures examined exhibited a splayed appearance, consistent with tension overload. A piece of the left elevator trim tab (from the center hinge outboard) was still attached to the left elevator in the wreckage. The inboard piece of the left elevator trim tab (which separated in flight) was recovered on the ground near the race course's home pylon.

The pilot's portable oxygen bottle was not identified in the wreckage, but the valve was located.[22] X-ray examination of the valve revealed that the end of the threaded section attached to the handle was not seated against the bottom of the opening, which indicates that the valve was open at the time of impact.

1.8 MEDICAL AND PATHOLOGICAL INFORMATION

1.8.1 Autopsy and Toxicological Examination

The Washoe County Medical Examiner – Coroner's Office, Reno, Nevada, performed an autopsy on the pilot. The autopsy report listed the pilot's cause of death as "multiple blunt force injuries due to a single aircraft collision." A muscle sample was positive for ethanol and methanol, which the medical examiner interpreted as having resulted from "contamination by

[21] More information about the telemetry data can be found in section 1.10.1 of this brief. A detailed report about the data can be found in the Data Recorders Report in the NTSB's public docket for this accident.

[22] Members of the airplane's ground crew reported that the pilot used 100 percent oxygen from a portable oxygen bottle (in accordance with race rules) and that a filled bottle would last for several races. It was not determined when the bottle was last filled. Photographs show that the pilot was wearing his oxygen mask during the race.

aviation fuel."[23] The FAA's Civil Aerospace Medical Institute (CAMI), Oklahoma City, Oklahoma, performed forensic toxicology on muscle specimens from the pilot. Quantities of ethanol and methanol were detected; no other drugs or chemicals were detected.

1.8.2 Effects of High-G Levels on Pilots

Aeronautical publications have established that, when exposed to high-G levels, a pilot can experience a range of impairing effects, such as graying or complete loss of vision and loss of consciousness (commonly referred to as G-induced loss of consciousness, or G-LOC), because of decreased blood flow to the brain.[24] Individual G tolerance varies depending on the rate of onset, G levels experienced, and the duration of exposure, as well as a person's training and anthropometry.[25]

1.9 SURVIVAL ASPECTS

1.9.1 NCAR Ramp Area Layout

Ten people on the ground were fatally injured and dozens of others sustained minor to serious injuries when the airplane collided with the airport ramp in the spectator box seating area and scattered wreckage debris in the box seating area, ramp, and grandstands. The edge of the box seating area was 874 feet south of the showline, the edge of the pit area (where many other spectators were located) was 748 feet south of the showline, and a fuel truck was parked on the ramp near the pits (see figure 3). Racing airplanes were expected to fly parallel to the showline on the north side.

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[23] Although the medical examiner indicated that the airplane's fuel was the source of the contamination, the airplane's fuel did not contain any ethanol or methanol. The airplane's ADI fluid contained methanol, and beverages containing alcohol (ethanol) were present in the box seat area of the viewing stands where the airplane impacted the ground. Ethanol can also develop naturally within the body postmortem.

[24] For more information, see (a) *G Effects on the Pilot During Aerobatics*, FAA Report FAA-AM-72-28 (Washington, DC: Federal Aviation Administration, 1972); (b) AC 91-61, "A Hazard in Aeronautics: Effects of G-Forces on Pilots"; and (c) paragraph 8-1-7, "Aerobatic Flight," in the *Aeronautical Information Manual* (AIM). Issuance of AC 91-61 and the inclusion of this topic in the AIM occurred as a result of NTSB Safety Recommendation A-81-48, which asked the FAA to revise the AIM to briefly discuss the physiology of aerobatic *G* levels as explained in FAA-AM-72-28.

[25] Anthropometry is the science that deals with the measurement of the size, weight, and proportions of the human body. Germane to the discussion of G tolerance is the heart-to-brain hydrostatic column length.

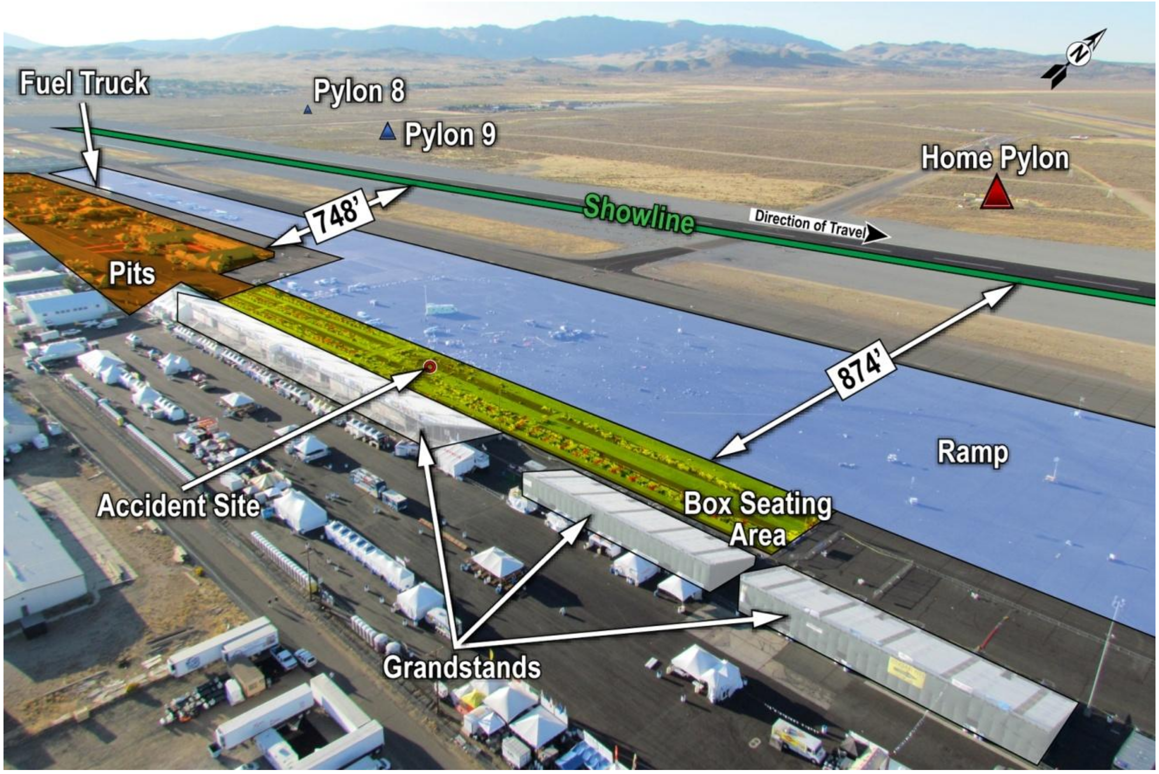

Figure 3. NCAR ramp area layout with accident site depicted.

Low-level metal fencing was installed at the edge of the pit area between the crew pits and the ramp and between the box seating area and the grandstand. Metal piping fitted with curtains was installed at the edge of the box seating area between the box seats and the ramp.

1.9.2 Emergency Response

The Regional Emergency Medical Services Authority (REMSA) declared a mass-casualty incident at 1626. First responder vehicles immediately arrived on scene and remained on the outer perimeter of the wreckage debris. Within 62 minutes of the incident declaration, all critical patients had been triaged and were en route to hospitals, and initial treatment was provided to others needing care at the scene. The NCAR announcing team, despite being in the immediate proximity of the accident site, remained calm and provided clear evacuation procedures guidance to the crowd, assisted first responders, and requested additional help from medical staff on scene.

During the initial response, cellular telephone communications were intermittent due to the extensive cellular telephone usage following the accident, with some loss of service for about 15 to 20 minutes. According to the Reno Fire Department Battalion Chief, who was the incident commander, the loss of cellular service had no impact on emergency operations because the mass-casualty incident declaration was made within seconds of the accident, and all communication to field units was handled via the radio system. The incident commander reported that there was also a dedicated land line in the tower that was used to make necessary calls. Trauma blankets were distributed from the Reno Tahoe Airport Authority (RTAA) vehicle, and spectators removed curtains from the box seating area and used them to assist the injured.[26]

As part of the RARA's emergency operations plan, a mass-casualty response tabletop exercise had been conducted on June 2, 2011, by representatives of the RARA, FAA, Washoe County fire agencies, Washoe County law enforcement agencies, Washoe County Medical Examiner – Coroner's Office, Washoe County Emergency Management, Nevada Air and Army National Guard units, REMSA, and Washoe County hospitals. The scenario for the exercise had been for 23 fatalities with an additional 46 injured. As a result of the tabletop exercise and at the request of the incident commander, the Nevada Highway Patrol had decided that, in the event of a mass-casualty accident during the NCAR, State Highway 395 would be shut down to allow better travel time for multiple ambulances; this decision was put into practice for the accident response. In addition, many of the same local agencies that participated in the tabletop exercise had attended and participated in the Reno/Tahoe International Airport triennial full-scale emergency exercise on May 25, 2011.

1.10 TESTS AND RESEARCH

1.10.1 Airplane Performance

An airplane performance study, video study, and image study were performed to gain insight into the accident airplane's performance and movement during the accident flight. These studies examined the left roll upset (in which the airplane rolled from about 73° left bank to about 93° left bank in less than 1 second) and compared the performance of the airplane during the upset with its performance at earlier times. These studies correlated telemetry data and other data to supplement or refine the accuracy of findings. The following subsections summarize some of the studies' findings.[27]

1.10.1.1 Elevator Trim Tab and Aileron Positions

Several high-resolution photographs[28] of the airplane provided information about the in-flight positions of the airplane's control surfaces and elevator trim tabs (both of which changed position during the upset sequence). The photographs also showed that the airplane was flown with little to no aileron trim input and that the left aileron always appeared slightly trailing

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[26] The trauma blankets were yellow, and the curtains used by spectators were blue and red. The investigation found that the RARA's plan for responding to a mass-casualty event (which followed the established Washoe County Multi-Casualty Incident Plan) included the use of the SMART Triage System, which incorporated the use of color-coded tags or tarps to ensure that patients are transported to hospitals appropriate for their medical needs. Red indicated that immediate response is required within 30 minutes, yellow denoted that care is needed in 30 minutes to several hours, green indicated that care may be delayed for several hours or days, and black indicated that the patient is fatally injured. The incident commander from the Reno Fire Department stated that the SMART Triage System's color-coded tarps were very effective for rapidly categorizing the injured and that there was no indication that any responders were confused by the use of yellow trauma blankets in conjunction with the color-coded tarps. An RTAA representative reported that, within the months following the accident, the RTAA response vehicle was restocked with neutral-colored trauma blankets.

[27] Each study is available in the NTSB's public docket for this accident.

[28] Compressed resolution copies are used in the figures in this brief. Full-resolution copies are available in the public docket for this accident.

edge down when the right aileron was faired with the wing. Photographs of the airplane during flights on the race course 3 days before the accident showed that the airplane's left elevator trim tab was deflected trailing edge up; image study calculations determined that, in one photograph, the deflection was 5° trailing edge up, and in another photograph, it was 8° trailing edge up. Available telemetry data showed that, at the time that the photograph showing 8° trailing edge up was taken, the airplane was in a section of the race course between pylons 6 and 7 and had a ground speed of about 360 to 380 knots (see figure 4).

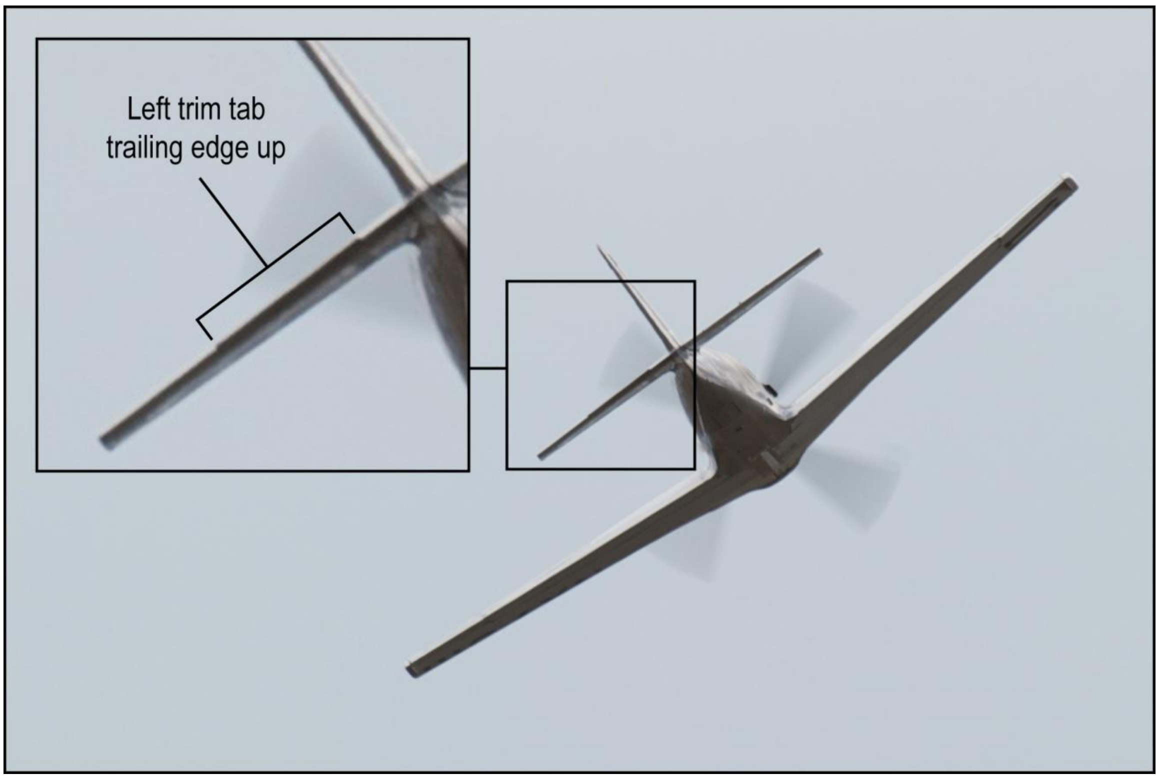

Figure 4. Left trim tab deflection of 8° trailing edge up during a previous flight.

Photograph courtesy of Bruce Croft.

Trailing-edge-up left elevator trim tab deflection was also evident in photographs of the airplane during the accident race. One photograph showed that, as the airplane began to round pylon 8 at 1624:28.65[29] during the accident lap, the left elevator trim tab was trailing edge up, consistent with the position observed during previous laps (see figure 5).

[29] Photographs and video times were correlated using available embedded timing data in the photographs, video image matching, and the airplane's telemetry data. Timing precision differed among cameras.

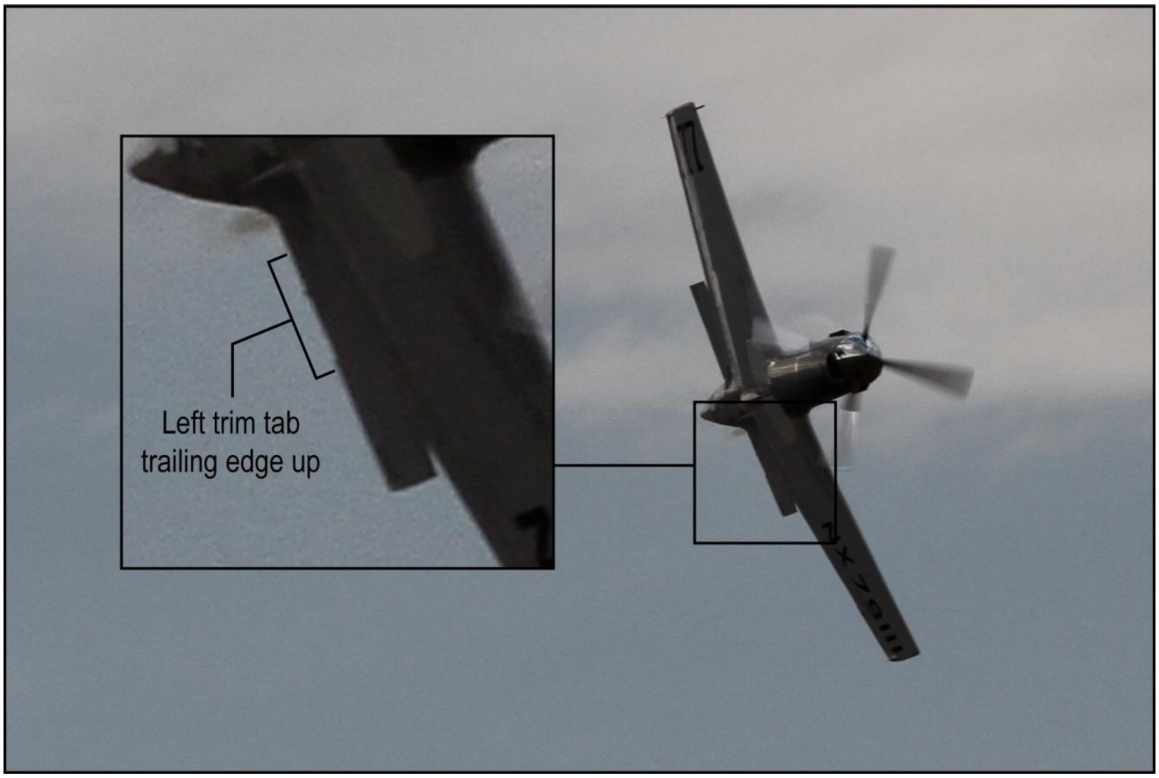

Figure 5. Airplane rounding pylon 8 during accident lap before the left roll upset at 1624:28.65.

Photograph courtesy of Jonathan Apfelbaum.

The video and image studies established that the left roll upset began at 1624:28.9, and the performance study found evidence that the change in rolling moment began less than 1 second earlier. Based on the available photographs that showed the airplane before the left roll upset, there was no evidence that any pilot control input initiated the left roll. According to the image study, right-wing-down aileron input to counter the left roll was first visible at 1624:29.17, and the vertical load factor on the airplane at that time was about 3 G (which is comparable to the load sustained during a normal turn around the pylon).

A subsequent photograph showed the airplane at 1624:29.46, before it reached its maximum left bank angle. In the photograph, the left elevator trim tab was out of view of the camera and the cutout in the elevator for the link assembly was visible (see figure 6). Calculations performed using this photograph determined that, based on the camera angle, for the trim tab to be out of view, it would have to be deflected a minimum of 21° trailing edge up.[30] The trim tab system on the accident airplane would typically allow a maximum of 13° trailing-edge-up deflection.[31] Tab deflection greater than 13° indicates a discontinuity in the left

[30] These values were determined by scaling the photographs based on known dimensions, measuring angles and deflections, and correcting them based on the airplane's attitude with respect to the camera.

[31] According to available documentation, the stock P-51D elevator trim tab travel is limited to 10° trailing edge up. However, examination of the accident airplane found that the maximum trailing-edge-up travel was about 13° (due to variances in the system).

elevator trim tab control system, which the investigation determined to be a broken link assembly.[32]

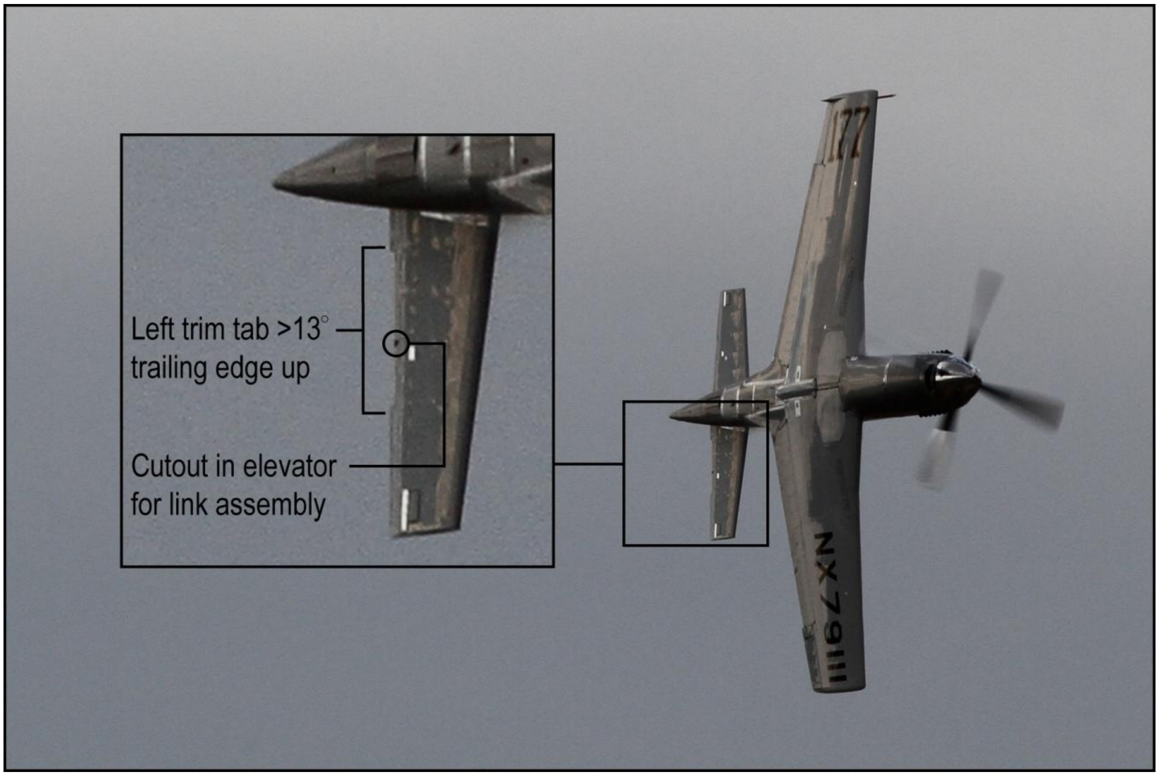

Figure 6. Airplane during left roll upset at 1624:29.46, before it reached maximum left bank angle. Inset shows detail of left elevator trim tab and the cutout in the elevator for the trim tab link assembly.

Photograph courtesy of Jonathan Apfelbaum.

A subsequent photograph showed the airplane at 1624:30.20 as it rolled back to the right and pitched up. Examination of the photograph showed that the left elevator trim tab was faired with the elevator, and the right elevator trim tab was trailing edge down (see figure 7). The deflection of the right trim tab from its fixed, faired position indicates that the right elevator trim tab link assembly had also broken by this time in the flight. This image, which was captured about the time that the airplane sustained its maximum vertical load factor of 17.3 G, also showed that the tailwheel had begun to extend from its housing.

[32] For more information, see section 1.10.2 of this brief.

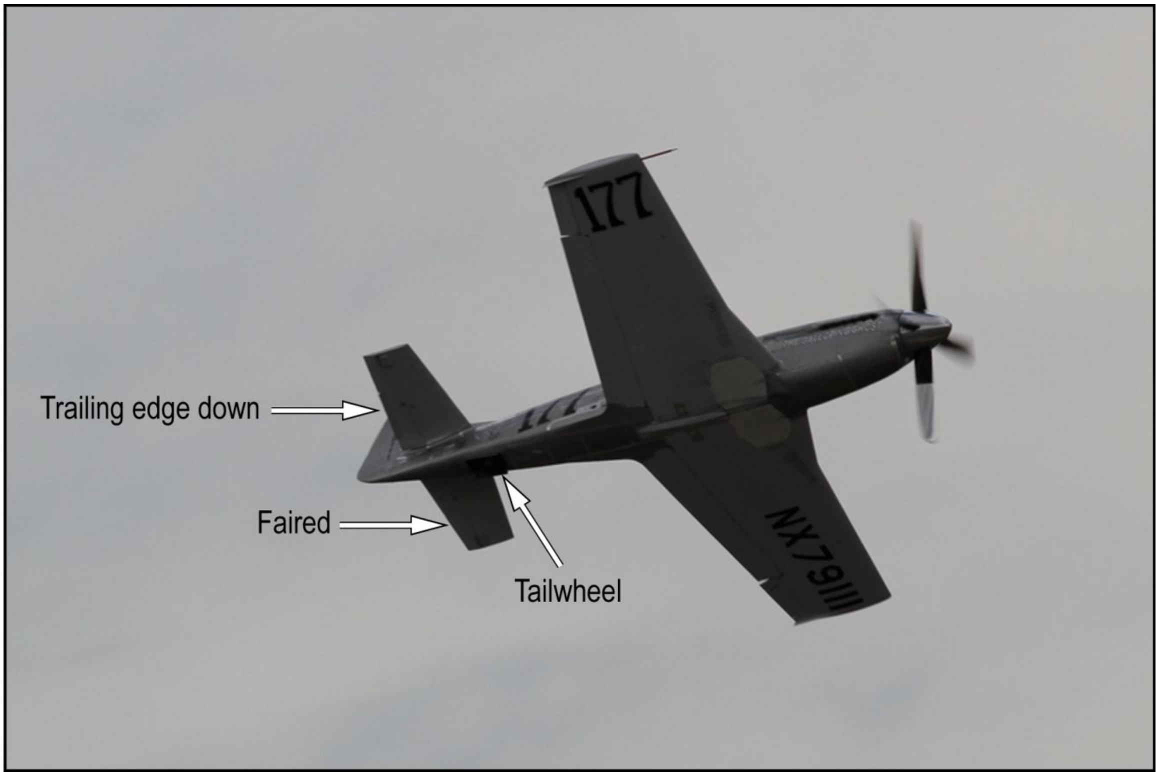

Figure 7. Airplane rolling right and pitching up at 1624:30.20, about the time it sustained its maximum vertical load factor.

Photograph courtesy of Jonathan Apfelbaum.

A photograph captured about 0.14 second later, at 1624:30.34, showed that the left elevator trim tab was trailing edge down, and the right elevator trim tab was trailing edge up. Nearly full right-wing-down aileron deflection (right aileron trailing edge up, left aileron trailing edge down) was also evident (see figure 8).

Figure 8. Airplane pitching up with left elevator trim tab trailing edge down at 1624:30.34, right elevator trim tab trailing edge up, and nearly full right-wing-down aileron deflection.

Photograph courtesy of Jonathan Apfelbaum.

A photograph taken about 1624:32 showed that, as the airplane reached the apex of the climb, the left elevator trim tab was detached from its inboard hinge (see figure 9). Another photograph showed that, about 1624:33.5 (about 4.6 seconds after the left roll upset began), the inboard piece of the left elevator trim tab was separated from the airplane (see figure 10).

Figure 9. Inboard piece of left elevator trim tab detached from inboard hinge.

Photograph courtesy of Frank Ranney.

Figure 10. Inboard piece of left elevator trim tab separated.

Photograph courtesy of Julia Kirchenbauer.

In figures 9 and 10 and other photographs showing the airplane's climb, the pilot appeared to be slumped down, forward, and to the right in the cockpit (rather than seated in his typical racing posture). In subsequent photographs that showed side views of the airplane during its final descent, the pilot was no longer visible in the cockpit. The table below summarizes events in the sequence using video study, image study, and airplane performance study findings.

Table. Summary of events.

Time[33]	Elapsed Time (seconds)	Event
1624:28.9	0	Airplane rounds pylon 8, begins to roll through 73° left bank
1624:29.17	0.27	Left elevator trim tab trailing edge up, right elevator trim tab faired with elevator, first right-wing-down aileron deflection visible to counter the left roll
1624:29.46	0.56	Left elevator trim tab trailing-edge-up deflection at least 21°
1624:29.73	0.83	Airplane reaches maximum left roll of about 93°
1624:30.20	1.3	Airplane reaches maximum vertical acceleration, tailwheel extends, right elevator trim tab trailing edge down, left tab faired with elevator
1624:30.34	1.44	Right elevator trim tab trailing edge up, left elevator trim tab trailing edge down, ailerons at or near full right-wing-down deflection
1624:32	~3.1	Airplane reaching apex of climb, piece of left elevator trim tab detached from inboard hinge
1624:33.5	4.6	Inboard piece of left elevator trim tab is separated
1624:38	~9.1	Airplane impacts ground

1.10.1.2 Airplane Motion and Vertical Load Factors

Telemetry data were time-correlated with the results of the video study calculations that determined the airplane's roll, pitch, and heading angles and vertical load factors throughout the upset event. During the roll upset and the onset of the pitch-up maneuver, the airplane's onboard accelerometer recorded a greater than 5-G jump in vertical acceleration within about 0.3 second. The video study established that, during the pitch-up maneuver, the maximum vertical load factor reached about 17.3 G about 0.47 second after the airplane reached its maximum left bank angle. Figure 11 shows the vertical acceleration leading up to, during, and after the roll upset as

[33] The time precision for some events varies due to differences in timestamp precision of the various source cameras.

determined through the video study calculations and the telemetry data (the telemetry data were subject to the accelerometer's limitations).[34]

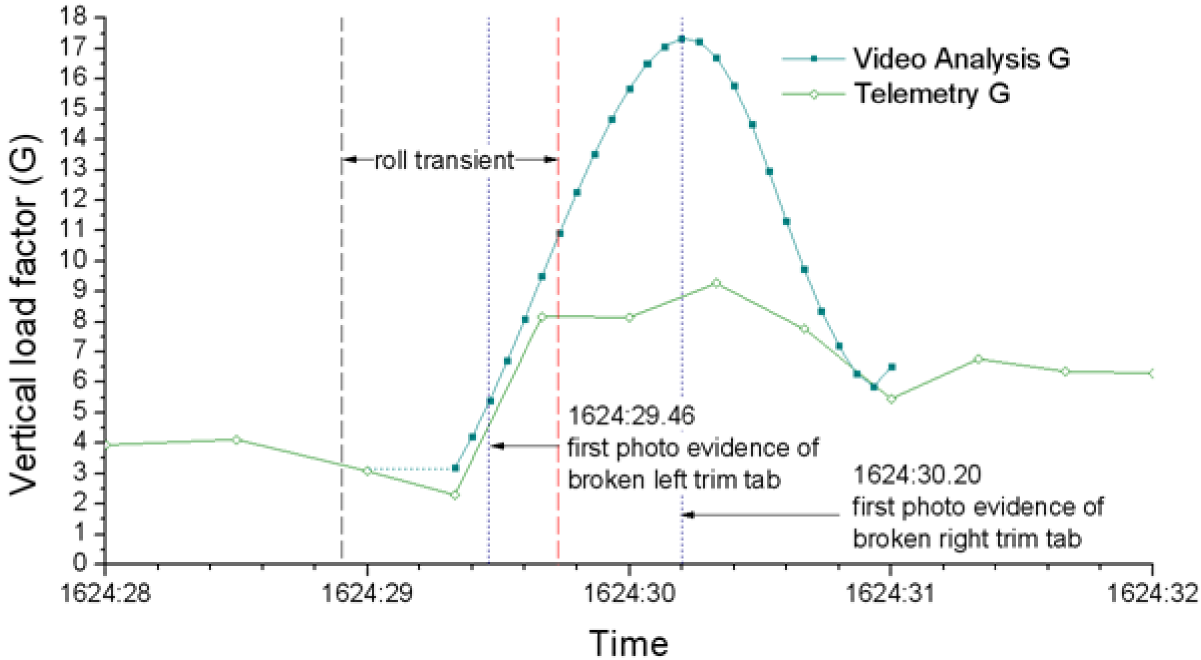

Figure 11. Airplane's vertical acceleration during upset over time. Times that correspond with specific photographs are noted.

A comparison of telemetry data and performance calculations for the accident lap with the previous two laps in the race showed that the accident airplane's true airspeed and vertical load factor during its final turn around pylon 8 (immediately preceding the accident upset) were similar to its speeds and load factors during its previous two turns around that pylon. Calculations of the airplane's lift coefficient showed that, throughout the accident race, the airplane's lift remained below the Mach buffet boundary and was lower at the time of the upset than it was earlier in the race.[35]

A comparison of information from the accident race, previous races, and qualification flights (all flown by the accident pilot) showed that the airplane's maximum 458-knot GPS ground speed between pylons 6 and 7 during the accident flight was the fastest that the airplane had flown on the course by about 35 knots. The accident flight had the highest engine manifold pressure and rpm (compared with all previous flights for which there were data) by about 15 to 20 inches of mercury and about 100 to 150 rpm, respectively. About 8 seconds before the beginning of the upset, there was a noticeable reduction in engine manifold pressure and rpm.

[34] The accident airplane's accelerometer was specified as an 8-G gauge, but it can measure up to 10 G. However, due to electrical saturation issues as the measurements near 10 G, the data certainty is best below 8 G. The telemetry vertical acceleration data recorded a number of points greater than 8 G near the end of the data recording.

[35] Exceeding the Mach buffet boundary can result in airflow separation on an airfoil, resulting in a loss of lift. For example, Mach buffet that affects one wing can induce a roll.

The second-place airplane in the accident race, *Voodoo*, was also equipped with a telemetry system. The racing team for that airplane provided its data, which enabled a comparison of the accident airplane's GPS-recorded ground speed and vertical load factor with those of *Voodoo*. A comparison of the data showed that the accident airplane's ground speed and vertical load factor were generally similar to those of *Voodoo* throughout the race before the upset.

1.10.1.3 Changes in Vibration Amplitude at Higher Racing Speeds

The telemetry data for the accident race and previous races and qualification flights on the NCAR course in 2010 and 2011 showed that the accident airplane developed a distinctive change in the vibration amplitude of the load factor and an increase in maximum load factor each time that it neared and exceeded about 400 knots GPS ground speed. This change in the vibration amplitude appeared to be most pronounced at two places on the course, near pylons 4 and 8, which were situated at the ends of short, straight segments of the course and marked the entry to the curved segments that follow.

1.10.2 Examination of Elevator Trim Components

The outboard piece of the left elevator trim tab was still attached to the elevator at its outboard and center hinges; the left elevator trim tab rod assembly, link assembly pieces, and the inboard piece of the left trim tab (which separated in flight) were recovered (see figure 12).[36] The right elevator trim tab was found attached to the elevator.

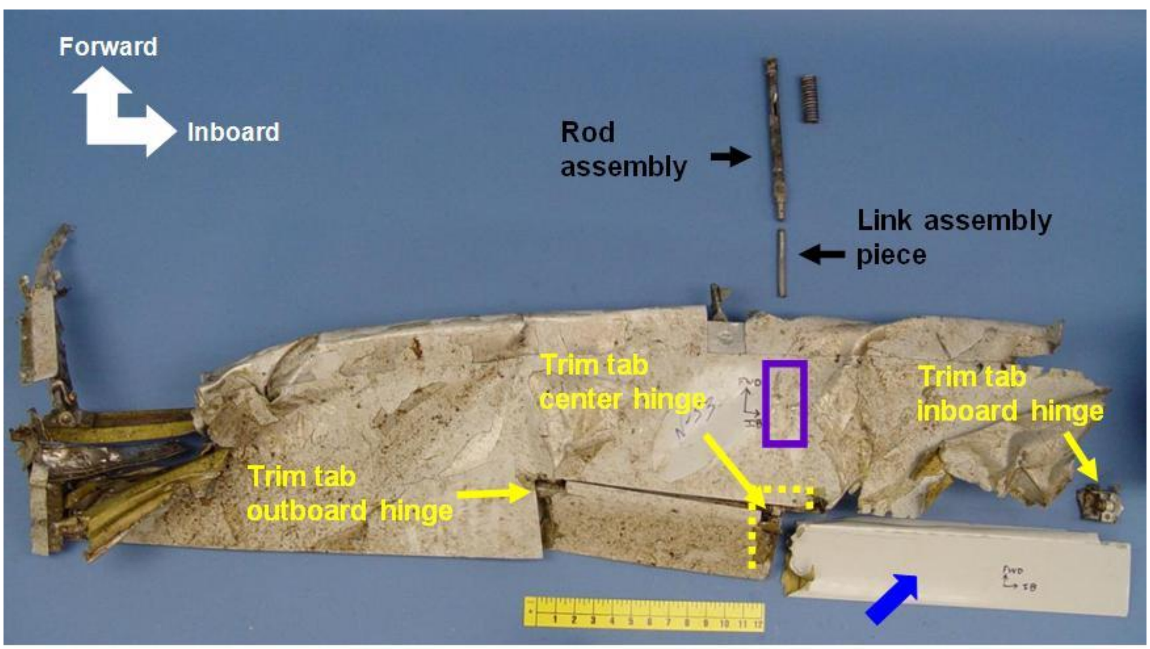

Figure 12. Left elevator showing the relative installed locations of the recovered trim tab pieces, trim tab hinges, trim tab rod assembly, and trim tab link assembly piece.

The blue arrow points to the piece of the tab that separated in flight, and the purple box shows a long, upward bulge in the upper elevator skin.

[36] Detailed information about the component examinations can be found in the Materials Laboratory Factual Report in the NTSB's public docket for this accident.

Each elevator trim tab is attached to three hinges on the elevator, with one screw per hinge (see figure 13). Examination of the left elevator trim tab pieces and the right elevator trim tab revealed that each had two intact screws (the center and outboard screws for the left tab, and the inboard and outboard screws for the right tab).

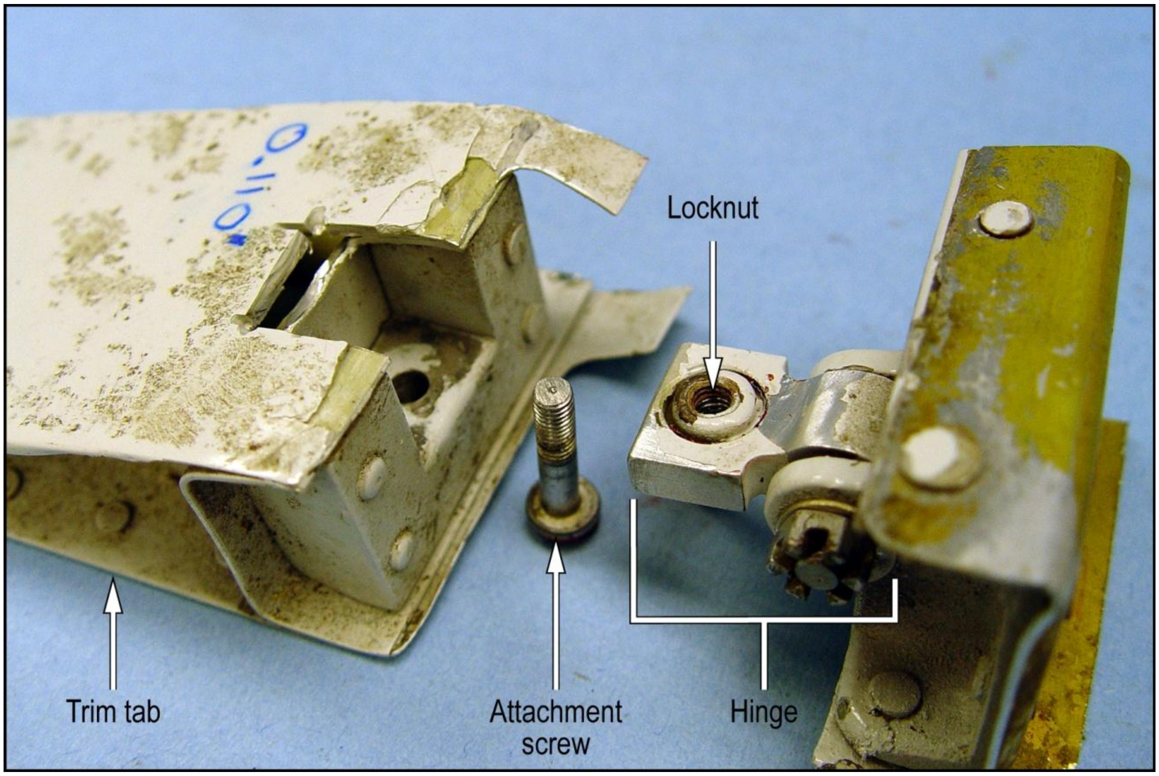

Figure 13. Section of right elevator trim tab (view of underside) showing the inboard hinge, attachment screw, and locknut.

Note: the trim tab was cut and the attachment screw disassembled for examination.

All of the intact elevator trim tab attachment screws were loose with negligible resistance from their respective locknuts. The locknuts showed evidence of yellow paint beneath the uppermost coat of paint; records show that the airplane had been painted yellow before the 1985 NCAR. For each intact screw, the fiber locknut insert material applied little to no clamping pressure on the screw threads, and all of the inserts showed evidence of age and reuse[37] (see figure 14). The mating surfaces between each trim tab and its respective outboard, center, and inboard hinges displayed varying degrees of missing paint and exposure of bare metal, consistent with relative motion due to the loose screws. The left trim tab's outboard trim tab screw was slightly shorter than specified, and the center trim tab screw was significantly shorter than specified and its tail was flush with the end of the locknut.

[37] Common maintenance guidance indicates that a locknut with a fiber or nylon insert should not be reused if it cannot meet the minimum prevailing torque values. See AC 43.13-1B, "Acceptable Methods, Techniques, and Practices – Aircraft Inspection and Repair," chapter 7, paragraph 64 (f).

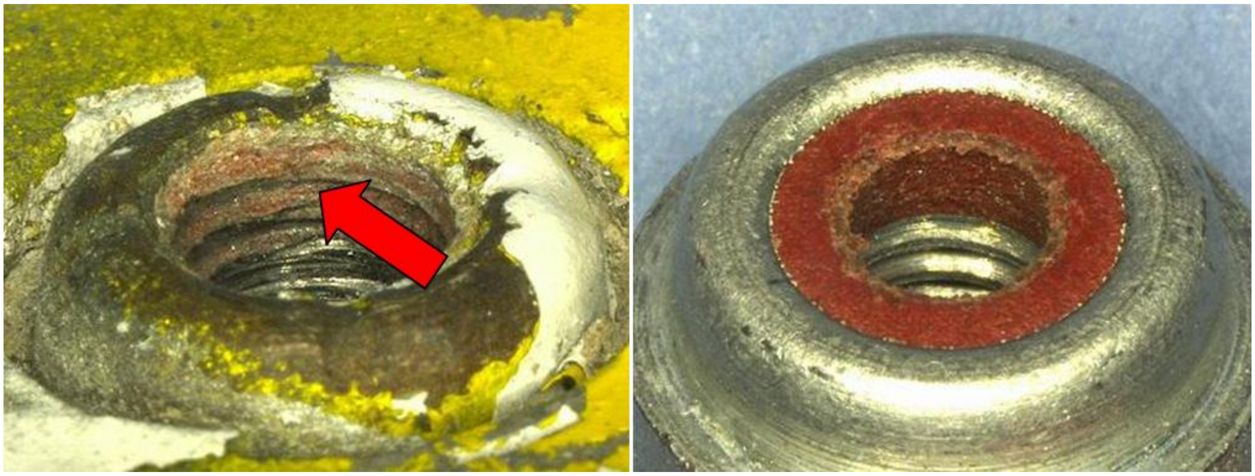

Figure 14. Locknut in the left elevator trim tab outboard hinge.

Red arrow indicates red insert material (left) and an exemplar new locknut shows intact fiber insert material (right).

The left elevator trim tab inboard hinge was found separated from the elevator. This hinge's trim tab attachment screw was fractured flush with the locknut in the hinge, and a gap was evident between the screw threads and the locknut threads. Metallurgical examination of the screw's fracture surface revealed features consistent with reverse bending fatigue with the fatigue fracture regions exhibiting mechanical damage and corrosion that obliterated most of the finer fracture features (indicative of the fracture propagating over a prolonged duration). The center portion of the fracture surface displayed features consistent with an overload failure. Examination of the skin at the outboard end of the separated inboard piece of the left elevator trim tab revealed fracture features consistent with an overload event.

The left elevator trim tab link assembly was buckled and fractured in bending overload in the threaded portion of the clevis with the bending process producing an upward bulge in the upper skin of the elevator (indicated by the purple box in figure 12). Evidence of subsequent oscillations of the free trim tab was indicated by scoring on the elevator's lower skin material, and on the fracture of the link assembly's tubing section, which showed notched fracture faces from repeated contact.

Examination of the right elevator trim tab revealed that the attachment screw for the center hinge was fractured. The fractured screw displayed evidence of directional bending (rearward deformation). The fracture surface displayed features consistent with an overload failure in shear. The threaded portion of the clevis in the right elevator trim tab link assembly was fractured in bending overload, and the link assembly exhibited a bend, consistent with compression buckling.

1.10.3 In-Flight Fuselage Deformation

Photographs of the airplane taken during the accident race showed that structural deformation was visible in flight. Figure 15, which was cropped from a photograph taken during the race's second lap, shows that diagonal wrinkles were evident on the right side of the aft fuselage. Figure 16, which is a photograph that was taken as the airplane passed pylon 2 during the accident lap, shows that similar (although less pronounced) diagonal wrinkles were evident on the airplane's left side; photographs showed that this deformation was evident during all three laps of the accident race and during qualifying flights performed on September 13, 2011. Figure 17, which was taken during the first lap of the accident race, shows that deformation was evident along the canopy and windscreen, such that a gap was visible; this deformation was also evident in photographs taken during the third lap of the accident race but was not evident in prerace photographs of the airplane on the ground.

Figure 15. Diagonal wrinkles on right side during accident race.

Photograph courtesy of Florian Schmehl.

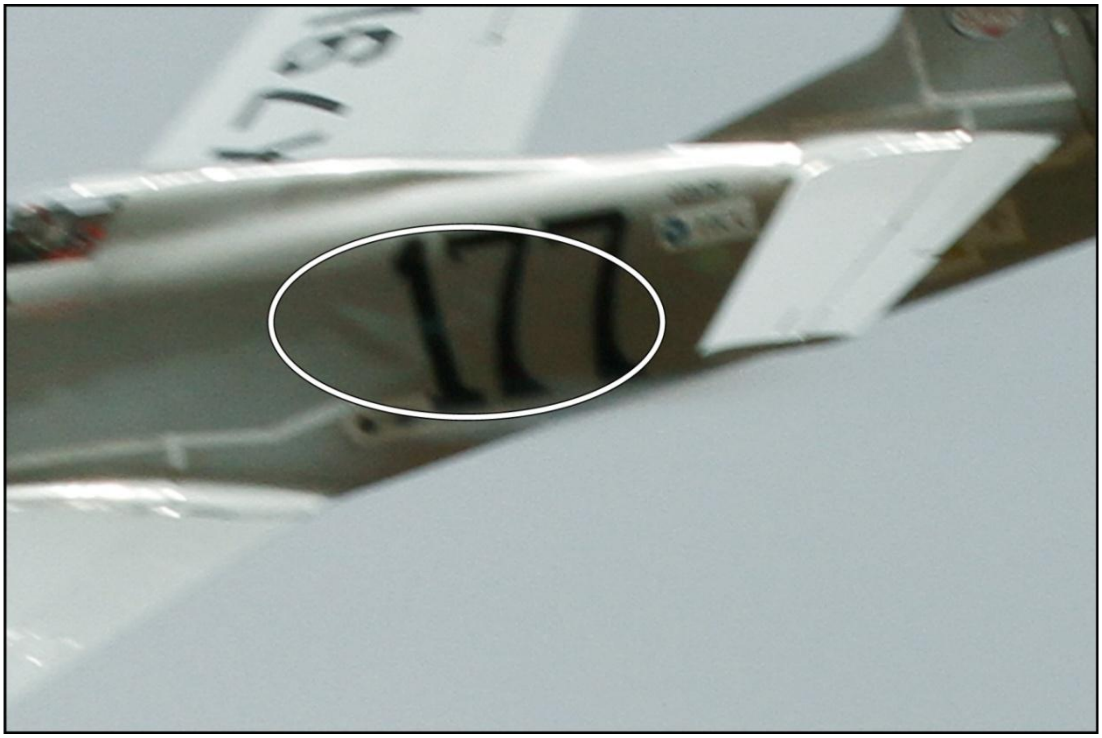

Figure 16. Diagonal wrinkles on left side during accident race.

Photograph courtesy of Doug Fisher.

Figure 17. Gap between canopy and windscreen in flight.

Photograph courtesy of Florian Schmehl.

1.10.4 Wake Encounter Evaluation

Wake vortices that trail from the wingtips of an airplane have the potential to induce roll upsets in other airplanes that encounter them. Because the accident airplane was following two other airplanes (*Voodoo* and *Strega*, which were about 4.5 and 8.8 seconds ahead, respectively) at the time of its left roll upset, the possibility of a wake encounter was evaluated.

Video footage and photographs that captured the positions of all three airplanes with reference to ground landmarks were examined to determine the relative altitude of each airplane as it traversed the location of the roll upset. The video examination showed that both *Voodoo* and *Strega* had about 70° left bank through the turn past the accident airplane's upset point. The reported wind conditions would be expected to shift each airplane's wake horizontally toward the accident airplane's upset location along the wind heading. In still air conditions, the wakes would be expected to travel downward, perpendicular to each airplane's wing (at 70° bank angle). Because of uncertainties in the GPS ground track data for *Voodoo*, it was not possible to determine *Voodoo*'s flightpath based on GPS data alone, and no data were available to determine *Strega's* flightpath. Based on the available information, neither the examinations of the video footage and photographs nor the performance study could exclude the possibility that the accident airplane intercepted a wake vortex.

1.11 ORGANIZATIONAL AND MANAGEMENT INFORMATION

The accident pilot was the president of the company that owned the accident airplane. As a racing airplane competing in the NCAR, the airplane and its operation were subject to FAA, National Air-racing Group (NAG) Unlimited Division, and RARA rules.

1.11.1 FAA Requirements

FAA airworthiness and registration records show that, on August 17, 1983, the pilot applied for and received a special airworthiness certificate for the airplane from the FAA's Long Beach, California, manufacturing inspection district office. The certificate listed the airplane in the experimental category for the purpose of air racing and exhibition, and operating limitations were issued with the same date.[38] The airplane's operating limitations specified that the airplane was to be based and maintained at Leeward Air Ranch Airport, Ocala, Florida, and that all proficiency flights were to be conducted within a 100-mile radius of that airport, with a special allowance for proficiency flights to be conducted en route to air shows or air races. According to 14 CFR 91.319(b), an aircraft having an experimental certificate may not be operated outside the specific area defined by the FAA until it has been shown that it is controllable throughout its normal range of speeds and throughout all the maneuvers to be executed and has no hazardous operating characteristics or design features.

[38] The records show that the pilot requested a replacement certificate on July 16, 2010, stating that the old certificate had been lost. The FAA's Reno, Nevada, flight standards district office issued a replacement certificate that showed the replaced certificate's issuance date (August 17, 1983), listed the airplane in the experimental category for the purpose of air racing and exhibition, and retained the existing operating limitations.

The airplane's operating limitations stated that, following major change to the airplane as defined by 14 CFR 21.93,[39] the cognizant FAA flight standards district office (FSDO) must be notified and its response received in writing before the airplane can be flown. (In the case of the accident airplane, this would have been the FSDO with jurisdiction over the Ocala, Florida, area.) The operating limitations also required that the airplane undergo a condition inspection at least every 12 months in accordance with Part 43, Appendix D, and that such inspections be documented in the airplane logbook.

FAA records show that the pilot notified the Reno, Nevada, FSDO of a major change involving the boil-off cooling system installation in 2009. Reno FSDO personnel responded that the flight testing to validate the installation should include 3 hours of flight time and three takeoffs and landings. In the correspondence, the Reno FSDO issued authorization for the pilot to conduct the tests in Minden, Nevada. Based on the photographic evidence and discussions with the airplane's ground crew and other racers, the airplane's first flight following the completion of its major modifications occurred on September 21, 2009. Ground crewmembers stated that a few test flights were performed on September 21 and 22, 2009, and that each flight lasted 15 to 20 minutes. Telemetry data showed that about 23 minutes of flight time was accrued on September 21 and 22, 2009, but the data were incomplete (the crew stated that, at the time, they had connection problems with the telemetry system).[40] There are no records that the pilot notified any FSDO of any other major modifications to the airplane.

1.11.2 NAG Unlimited Division Rules

The NAG Unlimited Division is the governing body for the pilots and airplanes that race in the unlimited class at the NCAR. It developed the NAG Unlimited Division Official Competition Rules and Bylaws document that included aircraft specifications, pilot qualification specifications, and technical inspection requirements. Each airplane must qualify to establish eligibility and starting position for the races. A qualification run consisted of two laps on the NCAR race course with the best lap speed used for qualifying.

The rules contained a provision for the RARA to add an aircraft to the qualified list, even if it had not successfully completed a qualification attempt, if "the pilot and aircraft have demonstrated their ability to perform at race speed." The mechanism for demonstrating this was not detailed in the official competition rules document. The accident airplane was entered into the 2010 NCAR under this provision because it did not have a valid qualification run. The maximum official race speed[41] for the airplane during the 2010 races was less than 325 knots. Appendix C to the official competition rules established the aircraft specifications. Specification III C, which applied to the accident airplane, specified that the airplane must

[39] Title 14 CFR 21.93 states that a minor change is one that has no appreciable effect on the weight, balance, structural strength, reliability, operational characteristics, or other characteristics affecting the airworthiness of the aircraft and that all other changes are major changes, with some exceptions.

[40] According to the telemetry data log, during the 2 days of flight testing, five flights were initiated, but data were recorded for only two flights. On September 21, 2009, about 19 minutes of data were recorded, but the recording ended about 4 minutes into the airplane's flight. On September 22, 2009, about 4 minutes of data were recorded that could not be correlated to a flight.

[41] Official race speed is the average ground speed around the course calculated using the number of laps, the optimum race path distance, and the total elapsed time for the airplane to complete the race.

demonstrate adequate maneuverability (controllability) at racing speed, which could be determined during aircraft qualification.

Appendix E established the technical inspection requirements. The technical inspection checks the aircraft for structural and functional integrity and for cleanliness and fire prevention before the aircraft is allowed to participate in the races. The document specified that the approval of the technical committee "does not constitute a representation…concerning the mechanical condition of the aircraft or whether or not it is airworthy."

The accident airplane underwent a NAG Unlimited Division technical inspection at the 2011 NCAR. The "Remarks" section of the technical inspection form noted "elev trim tab screws too short, area washer in L/H wheel well." According to technical inspectors and the airplane's ground crew, the trim tab discrepancy was due to one or more screws on the right elevator trim tab not having enough threads protruding from the nut, and there was an area washer missing in the left main landing gear wheel well. Both noted discrepancies were reportedly addressed. Members of the airplane's ground crew recalled that the trim tab screw issue was resolved by properly positioning a right trim tab screw that was found to be cross-threaded.[42] The inspection was signed off and dated September 12, 2011, and the airplane was approved to race on the course. There was no procedure to specify in writing that the noted items were addressed.

1.11.3 RARA Rules

The RARA is the overall organizer of the NCAR and provided the Official Rules of Competition document for the 2011 event. Many of the RARA rules were similar to the NAG Unlimited Division specifications. The RARA rules required that any airplane that has had major changes or alterations since the last registration or within the 12 months before the races must register and that the airplane and all documentation of any modifications performed on the aircraft or engine must be made available to the technical inspection committee. The RARA rules specifically referenced 14 CFR 21.93 (changes in type design), 14 CFR 1.1 (major alterations),[43] and 14 CFR 91.9 (operating limitations).[44]

The RARA aircraft entry forms included a question regarding the incorporation of any major changes or major alterations since the airplane last raced at the NCAR; on the 2009 entry documents for the accident airplane, "yes" was circled in response. The entry was subsequently cancelled because work being done on the airplane was not completed in time for the pilot to compete with it in the 2009 races. On the 2010 and 2011 entry documents, "no" was circled in response to the question about major changes or major alterations since the last time that the airplane raced at the NCAR.

[42] The NTSB Materials Laboratory examination noted that none of the right elevator trim tab attachment screws were found cross-threaded in their respective locknuts but that one right tab locknut showed damage consistent with previous cross-threading.

[43] Title 14 CFR 1.1 defines a major alteration as an alteration not listed in the aircraft, aircraft engine, or propeller specifications that might appreciably affect weight, balance, structural strength, performance, powerplant operation, flight characteristics, or other qualities affecting airworthiness or that is not done according to accepted practices (or cannot be done by elementary operations).

[44] Title 14 CFR 91.9 specifies that no person may operate a civil aircraft without complying with the operating limitations specified in the approved flight manual, markings, and placards, with some exceptions.

Because no qualifying speed was established for the airplane in 2010, it was entered in the 2010 races under RARA's conditional entry process. Under the conditional entry process, the airplane started in the last place in the lowest heat in the class. The airplane won a series of races and qualified to run the unlimited class gold race in 2010, but that race was cancelled due to wind. In 2011, the accident airplane qualified in fourth place for the unlimited class gold race during a flight on September 13, 2011.

1.12 ADDITIONAL INFORMATION

As a result of this investigation and the NTSB's January 10, 2012, investigative hearing on air race and air show safety, on April 10, 2012, the NTSB issued 10 safety recommendations to the RARA, the NAG Unlimited Division, and the FAA with the intent of improving the safety of air race operations. These recommendations addressed requiring engineering evaluations for aircraft with major modifications, raising the level of safety for spectators and personnel near the race course, improving FAA guidance for air races and course design, providing race pilots with high-G training, evaluating the feasibility of G-suit requirements for race pilots, and tracking the resolution of race aircraft discrepancies identified during prerace technical inspections. These safety recommendations are discussed in section 2.6 of this brief.

In addition, on April 27, 2012, a blue ribbon review team that had been formed by the RARA completed its independent review of the NCAR and presented the RARA with its final report. The RARA has indicated that it is taking the report's findings (some of which addressed subjects similar to the NTSB's safety recommendations) into consideration.

2. ANALYSIS

2.1 GENERAL

The accident airplane, a highly modified P-51D, was in third place during the third lap of the six-lap unlimited class gold race at the 2011 NCAR when it experienced a rapid left roll upset, rolling from its established approximate 73°-left-bank turn to about 93° left bank in less than 1 second. The change in the left elevator trim tab deflection evident early in the left roll upset indicated that the left elevator trim tab's link assembly was broken by that time. Following the onset of the left roll upset, substantial right-wing-down aileron deflection was evident, which likely resulted from pilot control inputs to counter the left roll, and the airplane responded with a right roll. However, during the roll events, the airplane also rapidly pitched up. The characteristics of the pitch changes were such that, within about 1 second, the vertical G levels rose from about 3 G to 17.3 G; both the rate of G onset and the high-G level exceeded human tolerance. Based on available guidance, the accident flight's rapid rate of G onset and the high-G levels were such that the pilot's time of useful consciousness was likely less than 1 second. During the brief interval before losing consciousness, the pilot's physical performance would have been limited due to the increased load on his body and extremities and the decreased blood flow to his brain. As a result, the pilot soon became completely incapacitated (which is consistent with photographs showing that the pilot was slumped in the cockpit during the climb), and the airplane's continued climb and helical descent occurred without his control. The pilot's toxicological information and medical history revealed no evidence of impairing drugs or other physical conditions that would have adversely affected his performance. The quantities of methanol and ethanol detected in samples from the pilot were attributed to sample contamination; there was no evidence that the pilot had consumed any alcohol before the flight.

The following analysis summarizes the extensive examination of the wreckage components and the analysis of the available videos, photographs, and telemetry data that were performed to determine the sequence of the elevator trim control system component failures. The analysis also discusses possible initiating events for the roll upset and summarizes other safety issues identified during the investigation. The investigation revealed significant concerns about the elevator trim system and other airplane structures regarding how they were modified, maintained, and operated in the racing environment.

2.2 EVIDENCE OF ELEVATOR TRIM TAB LOOSENESS, FLUTTER

The investigation focused on how the left elevator trim tab link assembly could buckle and fracture in bending overload in flight. Examination of the elevator trim tabs found that, of the three screws that attach each tab to its respective hinges, two screws in each tab were found intact. All of the intact screws could be rotated easily, even when fully engaged in their locknuts, and the locknuts' insert material was badly deteriorated to the extent that screw-retaining torque could not be maintained. Examination of the remnants of the two fractured screws (one in each tab) and their hinges showed evidence that these screws also had been loose before fracturing. The overload fracture of the right trim tab's center hinge screw showed evidence of directional bending occurring before a shearing action. The left trim tab's inboard hinge screw showed evidence of reverse bending fatigue, and corrosion on the fatigue fracture features indicated that the fatigue cracking had been present for a prolonged time before the screw ultimately failed in overload during the accident flight. The loose locknut connection allowed for larger load oscillations and the initiation and growth of fatigue cracks.

The deteriorated locknuts, therefore, resulted in loose elevator trim tab attachment screws and fatigue cracking in one screw, which allowed for undesirable movement of the trim tabs and a reduction of stiffness in the elevator (pitch) trim control system. In-flight movement of the tabs was evident in the damage observed on the mating surfaces of all the hinges during the postaccident examination. Because the airplane's elevator trim tab system was modified such that only the left tab was moveable, the left trim tab was subject to increased aerodynamic loads (compared to the stock system that uses two moveable trim tabs). Calculations showed that the static aerodynamic loads on the left elevator trim tab were higher at earlier times during the race (before the upset); therefore, the static loads at the time of upset would not have been sufficient to cause buckling and fracture of the link assembly. The looseness of the attachment screws and the fatigue crack in one of the screws would have allowed for reduced stiffness of the trim tab system that could have allowed a flutter condition to develop. Flutter would be capable of producing sufficient dynamic loads to buckle and fracture the link assembly.

Flutter is an aeroelastic phenomenon that can occur when an airplane's natural mode of structural vibration couples with the aerodynamic forces to produce a rapid periodic motion, oscillation, or vibration. The vibration can be somewhat stable if the natural damping of the structure prevents an increase in the vibratory forces and motions. The motion can become dynamically unstable if the damping is not adequate, resulting in increasing self-excited destructive forces being applied to the structure. Flutter can range from an annoying "buzz" of a flight control or aerodynamic surface to a violent destructive failure of the structure in a very short period of time. Aircraft speed and structural stiffness are two inputs that govern flutter; as speed increases or structural stiffness decreases, the susceptibility to flutter will increase.

The investigation determined that the increasing looseness of the elevator trim tab screws at race speeds and the fatigue crack in one screw resulted in a decrease in the elevator trim system structural stiffness, which was conducive to allowing a flutter event to develop. The addition of filler material to the elevator trim tabs (which increased their weight and moved their CG aft) also increased the potential for flutter. Excitation of the flutter resulted in dynamic compressive loads in the left tab link assembly that increased beyond its buckling strength, causing a bending fracture. The flutter and failure of the left tab link assembly excited the flutter of the right tab, increasing the dynamic compressive loads in the right tab fixed link assembly beyond its buckling strength, causing a bending fracture.

2.3 INITIATION OF LEFT ROLL UPSET, LINK ASSEMBLY BREAKAGE SCENARIOS

Initially, as the airplane rounded pylon 8 during the accident lap, its motions were similar to its turns during previous laps and to those of other airplanes in the race. Based on the photographic evidence and the controlled motion of the airplane before its upset, there is no indication that any pilot control input initiated the left roll, and the left and right elevator trim tabs were positioned as they had been for the preceding race laps and during a previous qualification run (that is, left tab trailing edge up and right tab faired with the elevator). This left tab setting likely provided the pilot with comfortable (likely negligible) forces on the control stick when racing. Although a photograph taken about 0.56 second after the onset of the left roll upset showed that the left trim tab had traveled beyond its trailing-edge-up limit (and, thus, the link assembly was broken at that time), no earlier photographs that clearly showed the trim tab were available. Other analytical methods were applied in an attempt to determine whether the left roll upset likely preceded the link assembly breakage or resulted from it. Neither a wind gust nor a trim runaway was a likely initiating scenario due to, respectively, the relatively consistent wind (in magnitude and direction) at the flight's altitude and the slow rate of trim travel when controlled by the electric actuator. Also, the investigation determined that the airplane was never operating near the Mach buffet boundary during the race; therefore, Mach buffet was not a factor.

One possible scenario that could have initiated the left roll upset was a wake vortex encounter, which is not uncommon during races and is typically countered by pilot control inputs. An evaluation determined that a wake encounter could not be ruled out. Another possible initiator of the left roll upset was the flutter-induced failure of the left elevator trim tab link assembly and the pilot's reaction to the resulting rapid change in control stick forces. To hold the right-wing-down aileron input that was evident in photographs taken throughout the race (which is discussed further in section 2.4 of this brief), the pilot would have to hold the control stick to the right of center. The failure of the left trim tab link assembly would have produced a sudden and large stick force directed aft. The sudden application of the aft force would have likely reduced the pilot's ability to precisely hold the right stick input, which resulted in a momentary left roll.

Regardless of whether the link assembly failure or a wake vortex encounter initiated the roll upset, the loss of the left trim tab's downward force on the elevator resulted in a concurrent sudden upward deflection of the elevator, a sudden and forceful aft movement of the control stick, the pitch-up of the airplane, and the rapid increase in G. The subsequent extension of the tailwheel from its housing is consistent with the progression of in-flight forces that acted on the airplane throughout the upset sequence. The separation of the inboard piece of the left elevator trim tab is consistent with the rapid oscillation of the tab after the linkage broke, causing a complete fracture of the fatigued screw.

2.4 MAINTENANCE OF TRIM TAB ATTACHMENT SCREWS, LOCKNUTS

There was no documentation for the last replacement of the trim tab attachment screws and locknuts, but the presence of yellow paint on the locknuts beneath their uppermost paint coat indicates that the locknuts had likely been installed for at least 26 years because the airplane's trim tabs were painted yellow before the 1985 NCAR. The screws were likely tightened 4 days before the accident flight when the technical inspection found a discrepancy on the right trim tab attachment screws, and the airplane had accumulated only three flights (including the accident flight) since that time. The loosening of the trim tab attachment screws and the deteriorated condition of the locknut inserts should have been noticeable to the ground crew. Based on the condition of the locknut inserts, the screws likely needed to be tightened several times over the course of the airplane's recent racing career, providing the ground crew with an indication of a recurrent problem and opportunities to identify and replace the deteriorated hardware.

2.5 EFFECTS OF MODIFICATIONS ON FLIGHT CHARACTERISTICS

The accident airplane had undergone numerous structural and flight control modifications over its racing career, presumably in an effort to make it faster. Most of the airplane's modifications were undocumented with no drawings, flight testing, or analysis related to their effects on the airplane's structural strength, performance, or flight characteristics, and the current ground crewmembers did not know why the modifications were made. The investigation discovered the modifications through wreckage examination, review of photographic evidence, and interviews with the ground crewmembers. In some cases, the reasons for a modification could not be established, and the timing of the change was unknown.

Some of the modifications likely had beneficial racing effects. For example, the airplane's shortened wingspan and tailspan decreased the aspect ratio and allowed the airplane to fly faster and withstand greater loads. This increased load factor capability, combined with the short duration of the maximum load factor during the upset, would explain the absence of a catastrophic in-flight structural failure of the wing structure at the very high loads attained during the upset sequence. The effects of other modifications are unknown. For example, although the investigation's weight and balance calculations determined that the airplane's CG remained within the stock P-51D boundaries during the accident flight, it is possible that the characteristics of the airplane were changed to the extent that a change in the CG limits of the airplane would be necessary to better ensure adequate handling qualities. No such evaluation was performed to establish acceptable forward and aft CG limits of the modified airplane.

The investigation found that some of the modifications likely had adverse effects. As mentioned previously, the elevator (pitch) trim control was modified such that the right elevator trim tab was fixed and faired, and all trim forces were applied through the left elevator trim tab, removing the system's redundancy. Although the airplane's ground crew believed that the airplane was raced with neutral trim (0° tab deflection), evidence showed that a significant amount of nose-down trim was input on the left trim tab during qualification flights and races. The investigation determined that, because of this significant trim input on one tab, the sudden breakage of the left trim tab link assembly during the accident race would have significantly increased the force needed for the pilot to hold the control stick in the original position, such that the pilot would have been unable to hold the control stick in position. It is possible that, had the airplane retained its original, redundant tab design, the pilot may have been able to maintain some control following a failure in only one tab. Losing one tab from a two-tab installation would have resulted in about half of the stick force required to hold the airplane steady. Although the pilot would not initially be able to maintain control of the airplane in such a scenario, the maximum G would have been much less than what the pilot experienced during the accident flight, and any stick force that the pilot could have provided would have further lessened the acceleration excursion. Therefore, it is conceivable that, in a scenario involving the failure of one tab in a two-tab system, the pilot could have maintained consciousness and regained control of the airplane.

Other adverse effects were evident regarding the installation of a racing canopy and turtle deck and the removal of the air scoop from beneath the wing. These modifications likely decreased the rigidity of the aft fuselage because the modified structures were not as strong or stiff as the original structures; this was evident in the diagonal deformation or wrinkles that were visible on the aft fuselage skin in photographs taken of the airplane during the accident race and during a qualifying flight a few days earlier. Such diagonal wrinkling is typical for semimonocoque structures[45] that are loaded in bending or shear, causing the thin web of skin between the longerons and frames to locally buckle. Also, the telemetry data showed that the airplane exhibited a distinctive change in vibration amplitude each time its speed neared or exceeded 400 knots, providing further evidence of potential adverse flight characteristics at the higher racing speeds.

The investigation determined that some of the adverse effects would have been noticeable to the pilot. For example, photographs showed that there was little to no aileron trim input in flight and that the left aileron was always slightly trailing edge down when the right aileron was faired with the wing. This indicates that the ailerons were not rigged properly and that the pilot maintained the airplane's left roll angles (all turns on the race course are to the left) using constant right-stick input. Further, two major modifications to the elevators each made the airplane more sensitive in pitch control: the substantially increased elevator counterweights (about twice that of a stock P-51D) that overbalanced the elevators and the substantially decreased elevator inertia weight (less than half that of stock). In addition, the in-flight canopy deformation that resulted in a separation between the canopy and the windscreen during the accident flight provided the pilot with a strong clue that the airplane was being operated beyond its structural limits and that it should be examined. It is likely that, had engineering evaluations and diligent flight testing for the airplane's modifications been performed, many of the airplane's undesirable structural and control characteristics could have been identified and corrected.

2.6 PREVIOUSLY ISSUED SAFETY RECOMMENDATIONS RELATED TO THIS INVESTIGATION

As a result of this investigation and the NTSB's January 10, 2012, investigative hearing on air race and air show safety, on April 10, 2012, the NTSB issued 10 safety recommendations to the RARA, the NAG Unlimited Division, and the FAA with the intent of improving the safety of air race operations.

2.6.1 Race Eligibility Requirements for Aircraft With Major Modifications

A review of RARA and NAG Unlimited Division eligibility conditions found that, because the accident airplane was a modified version of a previously designed and built fighter airplane, it was not subject to the more rigorous flight test and analysis that was required to be performed on custom-built airplanes to substantiate the structural loads, flutter characteristics, weight and balance limits, and flight envelope. The NTSB previously concluded that, because modifications to the structure or flight controls of aircraft may introduce unintended consequences, such aircraft should not be allowed to operate near spectators without a measured evaluation of whether they can do so safely. As a result, the NTSB issued Safety Recommendation A-12-13, which asked the RARA to do the following:

[45] A semimonocoque fuselage structure uses a combination of outer skin and internal structure to carry the applied bending, shear, and torsion load.

> Require aircraft owners, as a condition of eligibility to participate in the Reno [NCAR], to provide an engineering evaluation that includes flight demonstrations and analysis within the anticipated flight envelope for aircraft with any major modification, such as to the structure or flight controls. (A-12-13)

The RARA responded to Safety Recommendation A-12-13 in a July 9, 2012, letter and provided further comments in a July 12, 2012, letter. The RARA responded that, for years, it has worked closely with the Reno FSDO to identify those aircraft that have undergone major changes, repairs, or modifications as defined in 14 CFR 1.1 and 14 CFR 21.93 since the last time they raced in the NCAR or in the previous 12 months. The RARA stated that entries identified as having undergone such a change (based on information provided by the owner/operator in writing during the race entry process) are reviewed by both the RARA and the Reno FSDO to ensure that compliance with current FAA requirements has been met, that the operating limitations reflect the current aircraft configuration, and that all required flight testing is appropriately signed off in the aircraft logbook. The RARA also stated that it intends to work with the FAA and representatives of each of the classes of racing to make the review a special emphasis item in connection with the 2012 NCAR and that it is currently working with the FAA and race class representatives to review its existing processes and procedures to determine if they can be more effectively implemented in a manner consistent with the Federal Aviation Regulations (FARs). Also, in a July 12, 2012, letter to the NTSB, the RARA acknowledged its awareness of the FAA's July 11, 2012, issuance of draft revisions to AC 43-209A, "Recommended Inspection Procedures for Former Military Aircraft."[46] The RARA stated that it will, as part of its ongoing review of its procedures and processes, consider the draft AC and evaluate the extent to which RARA should implement the information contained in the draft revisions.

The NTSB notes that, although the RARA's actions appear to be a step in the right direction, the process that the RARA described (which is designed to ensure compliance with current FAA requirements, operating limitations that reflect the current airplane configuration, and an appropriate logbook signoff for flight testing) does not inherently ensure that an engineering evaluation that includes flight demonstrations and analysis within the anticipated flight envelope has been performed. However, the NTSB notes that the RARA is still evaluating its role in establishing the eligibility requirements with regard to the FARs. Pending the receipt of further information that shows that the process proposed by the RARA specifically requires an owner of an aircraft with a major modification to provide an engineering evaluation that includes flight demonstrations and analysis within the anticipated flight envelope, the NTSB classifies Safety Recommendation A-12-13, "Open—Acceptable Response."

Similar to the RARA recommendation, the NTSB issued Safety Recommendation A-12-09, which asked the NAG Unlimited Division to do the following:

[46] The draft of AC 43-209A was open for public comments until August 9, 2012. The draft AC proposed recommendations for the development of inspection programs for certain former military aircraft that are certificated in the experimental category for the purpose of exhibition and air racing.

> Require aircraft owners in the unlimited class to provide an engineering evaluation that includes flight demonstrations and analysis within the anticipated flight envelope for aircraft with any major modification, such as to the structure or flight controls.

In a July 6, 2012, letter to the NTSB, the NAG Unlimited Division stated that it was not prepared to comment on or implement any NTSB recommendations (including A-12-10 through -12, which are discussed in sections 2.6.4 and 2.6.5 of this brief) until the NTSB's final report on this accident investigation is issued. The NTSB was disappointed with this response and sought additional information. As a result, the NAG Unlimited Division explained in a subsequent letter on August 22, 2012, that it believed that the recommendation will improve safety for not only race fans but also the race pilots. The letter stated that the NAG Unlimited Division's race committee concluded that it should require aircraft owner/operators to provide engineering data for any major change or major alteration (as defined by the FAA) made to their aircraft since their last participation in an air racing event and to provide all approvals by the FAA for any such change or alteration to the aircraft.

The letter stated that, although the NAG Unlimited Division had not yet determined whether implementation will require a change in the organization's rules (in which case, the new rule would become effective on January 1 of the year following approval), it believed that early adoption was warranted. The letter noted that, for the 2012 NCAR, the NAG Unlimited Division has asked the RARA to provide a list of all entries that indicates whether or not the owner/operator reported an aircraft major change or major alteration. For all aircraft for which a major change or major alteration is reported, the NAG Unlimited Division has asked the RARA officials to request evidence (if required by the FAA) supporting an engineering evaluation and a flight demonstration within the anticipated flight envelope of the aircraft and to provide that evidence to the NAG Unlimited Division's class compliance team in a timely manner (as soon as it is received by the RARA but no later than the prerace inspection). The NTSB is pleased that the NAG Unlimited Division has taken steps to further scrutinize those aircraft entered in the 2012 NCAR for which a major change or major alteration has been reported since its last air racing event, and the NTSB encourages the NAG Unlimited Division to expedite its review so that rulemaking can be incorporated before the 2013 NCAR. Pending further updates on the NAG Unlimited Division's progress, Safety Recommendation A-12-09 is classified "Open—Acceptable Response."

2.6.2 Spectator Safety

On an oval race course, it is inevitable that the racing airplanes will head toward the crowd on certain segments; however, the NTSB noted in its April 10, 2012, safety recommendation letter that there may be opportunities for improving the course design to minimize spectators' exposure. As a result, the NTSB issued Safety Recommendation A-12-14, which asked the RARA to do the following:

> Evaluate the design of the unlimited class course and safety areas to minimize maneuvering near and potential conflicts with spectators; if warranted by the results of the evaluation, implement changes to the race course.

On July 9, 2012, the RARA responded that it evaluated the design of the unlimited class course and moved the racers and the race course further north than they were located during the 2011 NCAR to create and maintain a greater distance from the racers to the primary spectator viewing area. It stated that it also established another showline 500 feet east of the west airport boundary because the area had become a secondary viewing area due to a large increase in spectators on the private property adjacent to the airport. The NTSB believes that the RARA's actions are responsive to the recommendation's intent and classifies Safety Recommendation A-12-14, "Closed—Acceptable Action."

Also related to spectator safety, the NTSB noted that, although the fuel truck parked on the ramp was not hit by any debris from the accident airplane, the outcome could easily have been different. Further, although the circumstances of this accident were such that the type of barriers in front of the box seating area and crew pits was not a factor in the injuries that occurred, the NTSB concluded that more substantial barriers would help mitigate risk to spectators and personnel in the event of a less serious accident or incident. As a result, Safety Recommendation A-12-15 asked the RARA to do the following:

> Take the following actions to raise the level of safety for spectators and personnel near the race course: (1) relocate the fuel truck away from the ramp area and (2) in front of any area where spectators are present, install barriers more substantial than those currently in place.

On July 9, 2012, the RARA responded that, effective at the 2012 NCAR, the larger fuel tanker truck will be relocated away from the ramp area to the southeast side of the airfield, about 1.5 miles from the primary spectator area. The RARA also stated that, in addition to the "K Rails" currently positioned to the north side of the taxiway on the west end of runway 8, additional and more substantial barriers will be located along the entire primary spectator viewing area, extending east from the west end of the pits, through the box seats, to the general admission grandstands. The NTSB believes that the RARA's actions are responsive to the recommendation's intent and classifies Safety Recommendation A-12-15, "Closed—Acceptable Action."

2.6.3 Air Race and Course Design Guidance

FAA guidance for air races and course design is provided in FAA Order 8900.1 and AC 91-45C. A review of these documents revealed discrepancies, errors, and instances of outdated information. The NTSB previously concluded that these documents should contain current, accurate, and consistent information to support a thorough review of a race course and provide maximum safety for spectators and racers. As a result, the NTSB issued Safety Recommendation A-12-08, which asked the FAA to do the following:

> Revise [FAA] Order 8900.1, *Flight Standards Information Management System*, volume 3, chapter 6, section 1, paragraph 3-151 and [AC] 91-45C, "Waivers: Aviation Events," to correct inaccurate and incomplete information and reconcile all differences and inconsistencies between the documents.

In a June 26, 2012, letter, the FAA stated that it agrees with the recommendation and that it began drafting a revision to FAA Order 8900.1 to contain a new section that will specifically address air racing. The FAA stated that the revision will correct any inaccuracies or omissions and that AC 91-45C will be revised accordingly. Pending completion of these actions, the NTSB classified Safety Recommendation A-12-08 “Open—Acceptable Response” on July 25, 2012.

2.6.4 High-G Training and G-Suit Feasibility For Pilots

Generally, air race pilots, including those participating in the NCAR, are not required to undergo training to increase tolerance to high-G exposure by learning practices that can mitigate the effects or by wearing a G suit. Repeated, progressive exposure to high-G loads (such as during regular practice sessions) can also increase tolerance, but it can be diminished after a few days or weeks without exposure. At the NTSB’s investigative hearing, a representative of Red Bull Air Race testified that his organization requires its pilots to take G-tolerance training and wear hydrostatic G suits. The NTSB found that the RARA and NAG Unlimited Division rules provided several opportunities to address high-G training, including mitigation techniques, with pilots. The NTSB concluded that providing high-G training to pilots racing at the NCAR will help them prepare for the potential effects of high-G exposure. As a result, the NTSB issued Safety Recommendations A-12-16 and -17, which asked the RARA to do the following:

> Provide [high-G] training to pilots, including techniques to mitigate the potential effects of [high-G] exposure, as part of preparations before the Reno [NCAR] and during daily briefs at the NCAR. (A-12-16)
>
> Evaluate the feasibility of requiring pilots to wear [G] suits when racing at the Reno [NCAR]; if the evaluation determines it is feasible, implement a requirement. (A-12-17)

On July 9, 2012, in response to Safety Recommendation A-12-16, the RARA stated that, before racing, all pilots participating in the 2012 NCAR will receive formal G-awareness training that will include training packages, which will be mailed to the pilots before the race, and that a formal briefing will be provided by a qualified military flight surgeon before flight participations. Also, G awareness will be briefed in the Air Boss’ daily flight briefing, and pilots will be required to fly four to six laps on the course to improve G tolerance and awareness before attempting any qualification flights. The NTSB believes that the RARA’s actions are responsive to the recommendation’s intent and classifies Safety Recommendation A-12-16, “Closed—Acceptable Action.”

In response to Safety Recommendation A-12-17, the RARA stated in its July 9 letter that it consulted with subject matter experts (including CAMI, the National Aeronautics and Space Administration, the Air Force Research Laboratory, flight surgeons, and current and former fighter pilots) to evaluate the feasibility of requiring pilots to wear G suits when racing at the NCAR. The RARA stated that, based on these discussions, it determined that, although a G suit provides aid to G tolerance in a sustained high-G environment, it does not enhance G tolerance on the NCAR race course, which is designed for short-duration, 3.5-G turns. Moreover, a G suit would be ineffective in an environment in which there is a virtually instantaneous buildup of G loads, such as those encountered by the rapid pitch-up of an airplane. Because the evaluation determined that the benefit of a G suit is of limited, if any, value on the NCAR course, the RARA concluded that it will leave G-suit usage to the pilots' discretion and that it will focus its efforts on educating pilots regarding G tolerance and awareness. The NTSB believes that the RARA has demonstrated that it has thoroughly evaluated the issue before concluding that it is not feasible to require G suits for NCAR pilots; therefore, the NTSB classifies Safety Recommendation A-12-17, "Closed—Acceptable Action."

Similar to the RARA recommendations, the NTSB issued Safety Recommendations A-12-11 and -12, which asked the NAG Unlimited Division to do the following:

> Provide [high-G] training to pilots, including techniques to mitigate the potential effects of [high-G] exposure, as part of preparations before the Reno [NCAR] and during daily briefs at the NCAR. (A-12-11)
>
> Evaluate the feasibility of requiring pilots to wear [G] suits when racing at the Reno [NCAR]; if the evaluation determines it is feasible, implement a requirement. (A-12-12)

In its July 6, 2012, response, the NAG Unlimited Division stated that it was not yet prepared to comment on or implement these recommendations, but in a followup letter on August 22, 2012, the NAG Unlimited Division stated that all race pilots are required to attend daily briefings by RARA and that it was the NAG Unlimited Division's understanding that the RARA will provide G-awareness training during the daily briefing and require all race pilots to fly four to six laps on the race course (to increase their G-tolerance level) prior to requesting a qualification time. The NTSB notes that this information is consistent with the actions reported by the RARA. Further, the NAG Unlimited Division stated that its pilots will follow the RARA rules and will discuss G awareness during its daily class-specific briefings.

The letter also stated that the NAG Unlimited Division evaluated the feasibility of G-suit use in the NCAR race environment. The letter explained that the G loads sustained on the course are normally between 3 to 4 G, which would not require a G-suit to fly safely, and that the NAG Unlimited Division did not believe that the use of a G suit would have changed the outcome of the accident because the sudden and extreme G loads involved were far beyond any benefit of a G suit system. The letter also explained that it would be difficult to equip the very small cockpits of the race airplanes with G-suit capability and that a pilot's use of a G suit in the very hot race cockpits could introduce heat-exhaustion problems and prevent pilots from using cool suits. The NAG Unlimited Division concluded that it did not believe that the use of G suits would improve safety for race pilots or spectators and that their use may actually have a negative effect. As a result of its evaluation, the NAG Unlimited Division stated that it will not recommend a rules change to require the use of G suits but that it will not prohibit owner/operators from using G suits if, in their judgment, their use is preferred. Based on these responsive actions, Safety Recommendations A-12-11 and -12 are classified "Closed—Acceptable Action."

2.6.5 Prerace Technical Inspection Discrepancy Tracking

The NAG Unlimited Division technical inspection requirements are documented in Appendix E of the NAG Unlimited Division Official Competition Rules and Bylaws document.

The technical inspection of the accident airplane for the 2011 NCAR found two discrepancies. Although interviews established that the discrepancies had been addressed, the investigation found that there was no established procedure to confirm that noted discrepancies have been resolved. The NTSB previously concluded that developing a tracking mechanism for the resolution of discrepancies is important to ensuring that inspection items are addressed before a race. As a result, the NTSB issued Safety Recommendation A-12-10, which asked the NAG Unlimited Division to do the following:

> Develop a system that tracks any discrepancies noted during prerace technical inspections and verifies that they have been resolved.

Although the NAG Unlimited Division stated on July 6, 2012, that it was not yet prepared to comment on or implement this recommendation, a followup letter on August 22, 2012, stated that the NAG Unlimited Division had revised its prerace inspection form to include a written acknowledgement of discrepancies noted and corrective actions taken. The letter stated that an aircraft with noted discrepancies will not be allowed to enter the race course for any reason until this written acknowledgement by the aircraft owner/operator is received and the aircraft is reinspected by the inspection team. The NTSB notes that this revised form will be used at the 2012 NCAR. Based on the NAG Unlimited Division's responsive action, Safety Recommendation A-12-10 is classified "Closed—Acceptable Action."

2.7 OTHER IDENTIFIED ISSUES

2.7.1 Noncompliance with Operating Limitations, Flight Testing Requirements

The airplane's operating limitations specified that the airplane was to be based and maintained in Ocala, Florida, and that proficiency flights must be conducted there or en route to air shows and racing locations. However, the investigation found that the airplane had not been based in Ocala, Florida, since April 2007. The airplane was in Arizona and later Texas before it was moved to Nevada in 2009. After the completion of the modifications in 2009, the airplane remained based in Minden, Nevada, and all of the flights were conducted in the vicinity of the Minden airport or at the NCAR. Therefore, the airplane was not in compliance with this aspect of its operating limitations.

The operating limitations also specified that the cognizant FSDO (the one with jurisdiction over the airplane's specified base) must be notified of major changes. FAA records show that the pilot notified the Reno FSDO[47] of the installation of the boil-off cooling system in 2009 and that FSDO personnel responded that the flight testing to validate the installation should include 3 hours of flight time and three takeoffs and landings. Although the telemetry data (which recorded about 23 minutes of flight time during the 2 days of flight testing) were incomplete, there was no evidence that the airplane had accumulated 3 hours of flight time before the pilot signed off the testing as completed. For example, the telemetry log showed that five flights were initiated during the 2 days of testing, and ground crewmembers reported that the

[47] Per the airplane's operating limitations that specified that it was to be based in Ocala, Florida, the FSDO responsible for that area should be the cognizant FSDO. However, because the airplane was actually based in Minden, Nevada, the pilot was correct in contacting the Reno FSDO.

test flights typically lasted 15 to 20 minutes. If it is assumed that all five flights were completed and each lasted 20 minutes, that would represent only 1 hour 40 minutes of flight time. Also, there was no record that any FSDO was ever notified of other major modifications, such as the lower air scoop removal, the elevator and rudder counterweight increases, the elevator inertia weight decrease, the right elevator trim tab change (from controllable to fixed and faired), and the horizontal and vertical stabilizer incidence changes. Had the FAA been notified, it likely would have required a more substantial flight testing program for the airplane.

According to 14 CFR 91.319(b), the accident airplane should have had a flight test program performed in a specific area defined by the FAA to show that it was controllable throughout its normal range of speeds and throughout all the maneuvers to be executed and had no hazardous operating characteristics or design features. Before the race, the airplane had not been flown through its normal range of racing speeds under the unique load factor regime required to negotiate the course; therefore, the airplane was not in compliance with the flight test program requirements.

On December 21, 2011, the FAA issued a deviation to FAA Order 8130.2G, chapter 4, section 10, which clarified the operating limitations placed on experimental airplanes being operated for the purposes of exhibition and air racing. The revised order contains revisions that would now apply to airplanes like the accident airplane; these revisions include requiring the owner/operator to submit an annual program letter to the geographically responsible FSDO where the aircraft is based. The revised order states that the program letter must specify the aircraft's home base, the person responsible for its operation and maintenance, a list of events at which the aircraft will be exhibited, and a map or detailed description of the proficiency area. It also specifies procedures for a change of aircraft home base or ownership.

2.7.2 Discrepancies in Pilot-Reported Information on Racing Entry Documents

The NAG Unlimited Division official competition rules contain a provision for the RARA to add an aircraft to the qualified list, even if it has not successfully completed a qualification attempt. The rules allow for this if "the pilot and aircraft have demonstrated their ability to perform at race speed." The accident airplane did not have a valid qualification run for the 2010 NCAR, so it was entered under this provision. However, there was no evidence that the pilot had demonstrated the ability to perform at race speeds in the accident airplane since the 2009 modifications; therefore, he should not have been eligible to enter the 2010 race with the accident airplane.

The RARA rules require that any airplane that has had major changes or alterations since the last registration or within the 12 months before the races must register and that the airplane and all documentation of any modifications performed on the aircraft or engine must be made available to the technical inspection committee. The 2009 entry documents for the accident airplane indicated that a major change or major alteration was made since the airplane last raced at the NCAR; however, the airplane was never inspected by the technical committee because it never arrived to race in 2009. On the 2010 entry documents, "no" was circled in response to the question about major changes or alterations since the last NCAR. It is possible that the pilot circled "no" on the 2010 form because he had previously registered the airplane with "yes" circled. However, because the airplane never raced in the 2009 NCAR, its major alterations should have been reported in 2010. Therefore, the pilot was not in compliance with the RARA rules regarding documentation of major changes and should not have been eligible to race the airplane in the 2010 or 2011 NCAR.

On the pilot's 2009, 2010, and 2011 NCAR entry forms, he reported having flown at least 1,000 more hours in the accident airplane than its logbooks showed it had ever accumulated, and he inexplicably underreported his age in 2009 and 2010. Also, although the airplane's logbooks showed that it had accumulated only about 25 total hours between its assembly in 2009 and its July 2011 inspection, the pilot's NCAR entry form for 2011 reported that he had accumulated about 200 flight hours in it since the previous year. Although there is no evidence that the pilot's age or experience in the accident airplane had any role in the accident, it is unclear why he submitted such inaccurate information to RARA.

2.8 SUMMARY

During the third lap of the six-lap race, the accident airplane experienced a rapid left roll upset and high-G pitch-up. The change in the left elevator trim tab deflection evident early in the left roll upset indicated that the link assembly for the left elevator trim tab had broken. With the link assembly broken, the left elevator trim could no longer provide downward force on the elevator, and the high-G pitch-up caused the pilot to lose consciousness and control of the airplane. The investigation determined that the looseness of the elevator trim tab attachment screws and a fatigue crack in one of those screws caused a decrease in the structural stiffness of the elevator trim tab system. At racing speeds, the decreasing stiffness was sufficient to allow aerodynamic flutter of the elevator trim tabs. Excitation of the flutter resulted in dynamic compressive loads in the left elevator trim tab's link assembly that increased beyond its buckling strength, causing a bending fracture. The flutter and the failure of the left elevator trim tab's link assembly excited the flutter of the right elevator trim tab, increasing the dynamic compressive loads in the right elevator trim tab's fixed link assembly beyond its buckling strength, causing a bending fracture. The condition of the trim tab attachment screws' locknut inserts, which showed evidence of age and reuse, rendered them ineffective at providing sufficient clamping pressure on the trim tab attachment screws to keep the surfaces tight against their hinges.

The accident airplane had undergone many structural and flight control modifications that were undocumented and for which no flight testing or analysis had been performed to assess their effects on the airplane's structural strength, performance, or flight characteristics. The investigation determined that some of these modifications had undesirable effects. For example, the use of a single, controllable elevator trim tab (which was installed on the left elevator) increased the aerodynamic load on the left trim tab (compared to the stock airplane, which has one tab on each elevator). Also, filler material on the elevator trim tabs increased the potential for flutter because it increased the weight of the tabs and moved their CG aft, and modifications to the elevator counterweights and inertia weight made the airplane more sensitive in pitch control. It is likely that, had engineering evaluations and diligent flight testing for the modifications been performed, many of the airplane's undesirable structural and control characteristics could have been identified and corrected.

3. PROBABLE CAUSE

The National Transportation Safety Board determines that the probable cause of this accident was the reduced stiffness of the elevator trim tab system that allowed aerodynamic flutter to occur at racing speeds. The reduced stiffness was a result of deteriorated locknut inserts that allowed the trim tab attachment screws to become loose and to initiate fatigue cracking in one screw sometime before the accident flight. Aerodynamic flutter of the trim tabs resulted in a failure of the left trim tab link assembly, elevator movement, high flight loads, and a loss of control. Contributing to the accident were the undocumented and untested major modifications to the airplane and the pilot's operation of the airplane in the unique air racing environment without adequate flight testing.

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