CHALLENGER REMEMBERED
The Shuttle Challenger's Final Voyage

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Editor's Note...

I prepared the following copy based on files and material assembled in the weeks and months following Challenger's final flight. I was Cape Canaveral bureau chief for United Press International on Jan. 28, 1986, and witnessed Challenger's launch from the Kennedy Space Center press site. I covered the ensuing investigation and reported from Washington the following June when the Rogers Commission report was released.

These files are not intended to be inclusive. They originally were part of an internal CBS News reference document and are posted here to provide a quick source of accurate information about Challenger's final flight. Over the years, memories have faded and I frequently find myself answering questions about just what happened that cold day in January when America's space program changed forever. Readers may find one or more of these files useful in that regard.

The page dealing with the fate of Challenger's crew may be unpleasant for some readers. It is included here to correct rumors and misinformation. As always, comments and corrections welcomed.

Launch Day

The events leading up to Challenger's launch and its immediate aftermath.

> **"We're not going to launch this thing and take any kind of risk because we have that schedule pressure. We're going to continue to abide by the flight rules that we've established in this program and we'll sit on the ground until we all believe it's safe to fly." - Jesse Moore , associate administrator for space flight, Jan. 26, 1986**

In a sense, the shuttle Challenger's fate was sealed by a sequence of events that conspired to push the launch date, originally set for July 1985, into January 1986. Like most shuttle missions, flight 51-L evolved through a series of changes that inevitably affected its launch date, including 10 major payload revisions. Blastoff ultimately was set for Jan. 22, but problems launching the shuttle Columbia in December 1985 forced Challenger's date to slip even further behind. This was a major concern to NASA because on board Challenger were two time-critical satellites. One was needed to complete an around-the-world space communications system, and the other, a small automated science platform, was set to study Halley's comet , which was racing toward its close encounter with the sun on Feb. 9. With each launch delay, the time available to study the fabled comet before it disappeared into the sun's glare was running out.

The first sign of last-minute trouble came on Dec. 19, 1985, when Columbia's countdown reached 14 seconds to launch at 7:54 a.m. EST only to be interrupted when the shuttle's four flight computers detected high turbine speeds in a hydraulic assembly used to steer the right-side solid-fuel booster rocket's nozzle. Columbia's countdown was recycled to the T-minus 20 minute point but it was hopeless: the launch would have to be delayed. NASA subsequently decided to replace the hydraulic assembly and Columbia's launch was rescheduled for Jan. 4. Challenger's flight remained scheduled for Jan. 22, but Columbia's problems were not yet over. Launch was rescheduled for Jan. 6 to give launch crews the Christmas holidays off and to allow Columbia's crew two additional days of practice in flight simulators at the Johnson Space Center in Houston.

At the same time, Challenger's launch was rescheduled for Jan. 23 and then to Jan. 24 to give its crew additional training time. On Jan. 6, Columbia was grounded for the third time because of a sluggish oxygen propellant supply valve in one of its three liquid-fueled main engines. Launch on Tuesday, Jan. 7, was postponed a fourth time because of bad weather . Launch was rescheduled for Jan. 9, but the day before, engineers discovered a temperature sensor had broken off inside a fuel line, requiring another delay for repairs. The same day, Challenger's crew practiced launch procedures in the cockpit on pad 39B , just a mile and a half away from Columbia on pad 39A . Incredibly, Columbia was grounded on Jan. 10 by driving rain, but finally, at 6:55 a.m. on Jan. 12, Columbia took off.

Three days later, NASA rescheduled Challenger's launch for Saturday, Jan. 25.

Challenger's crew planned to fly to the Kennedy Space Center on Wednesday, Jan. 22, to prepare for blastoff. But dust kicked up by desert storms reduced visibility at an emergency landing field at Dakar , Senegal, where the crew would have to attempt an emergency landing in the event of an engine failure during the latter phases of the ascent. While mission managers debated their options, including use of the municipal runway at the Casablanca airport on Africa's East Coast, Challenger's crew was told to delay the trip to Florida for 24 hours. Later that day, launch was rescheduled for Sunday at 9:36 a.m. and Challenger's countdown began on time Thursday at 10 a.m. The astronauts arrived in Florida later that day to begin final preparations. All seven shuttle fliers appeared at ease dressed in light blue NASA flight suits. It was an especially joyous moment for school teacher Christa McAuliffe , whose dream of one day flying in space was about to pay off. During Challenger's six-day mission, she planned to teach two lessons from orbit to classrooms across the nation as the first teacher in space, indeed, the first truly private citizen to win a seat on a space shuttle.

"I'm so excited to be here!" she said, standing on the tarmac at the Kennedy Space Center 's 3-mile-long shuttle runway. "I don't think any teacher has ever been more ready to have two lessons in my life. I've been preparing these since September and I just hope everybody tunes in to watch the teacher teaching from space."
But Challenger's planned Sunday blastoff quickly turned into a cliff-hanger. A cold front from Texas was barreling toward the Cape bringing menacing cloud cover and weather conditions in Africa showed little sign of improvement. "We may not know until the last minute Sunday whether we can launch," said NASA spokesman Charles Redmond .

At a management meeting that began at 10 p.m. Saturday, launch engineers were told by Air Force weather officers that fog, low clouds, rain and thunderstorms could be expected in the launch area Sunday morning. At 10:16 p.m., the decision was made to recycle the countdown, which was at T-minus nine hours, to the 11-hour mark targeted for a launch at 9:37 a.m. Monday in a bid to thread a narrow one-day "window" and get Challenger off the ground between two threatening weather systems. As it turned out, the front slowed dramatically overnight and Challenger could have taken off safely on Sunday, Jan. 26. But it was too late - the countdown already had been recycled for a Monday launch try. The seven Challenger crew members took the delays in stride and relaxed in their motel-like quarters at the Operations and Checkout building near Kennedy Space Center headquarters, boning up on their flight plans. McAuliffe and Hughes satellite engineer Gregory Jarvis went for a bicycle ride to unwind, only to be intercepted by a television crew. McAuliffe , appearing ill at ease but smiling, said she was looking forward to launch on Monday. It was the last time she ever spoke in public.

"We're not going to launch this thing and take any kind of risk because we have that schedule pressure," said Jesse Moore , associate administrator for space flight. "We're going to continue to abide by the flight rules that we've established in this program and we'll sit on the ground until we all believe it's safe to fly."

The Jan. 27 Launch Attempt

At 1:26 a.m. Monday, engineers began loading a half-million gallons of supercold liquid oxygen and liquid hydrogen fuel into Challenger's giant external fuel tank . The crew was awakened at 5:07 a.m. for a traditional breakfast of steak and eggs before donning their light blue flight suits. Smiling and waving to NASA employees and news photographers, the astronauts left their quarters about 6:50 a.m., climbed aboard NASA's silver "Astrovan ," a modified Airstream mobile home, and headed for the launch pad. Launch director Gene Thomas ordered extra weather balloons to be launched as blastoff time neared to get additional data. High winds were a concern because of the shuttle's record payload weight - 48,361 pounds - and its stability during the thunderous climb to orbit.

The shuttle fliers assembled in the "white room" at the pad. One launch pad technician greeted McAuliffe wearing an academic mortarboard, to the teacher's obvious delight. Each astronaut then donned an airtight helmet and a sort of high-tech Mae West life vest before climbing aboard, assisted by technicians who dutifully wiped the bottom of each crew member's shoes to make sure no one tracked dirt into the pristine environment of Challenger's cockpit . Once inside, the astronauts connected hoses from their flight helmets to the cabin's oxygen supply system and to "personal egress air packs, called "PEAPs ," which provided a six-minute supply of unpressurized air for use during an emergency exit when dangerous fumes might be in the area. With all seven aboard and strapped securely to their seats by 7:56 a.m. and with the external fuel tank topped off with its load of propellant, the technicians closed Challenger's hatch. Incredibly, they were unable to get indications from microswitches that the hatch was locked shut.

"If we have a preference, we'd like to have one of the guys who's very familiar with the latches to come inside, close the door, check them to make sure they're all OK and send him back out again," commander Dick Scobee radioed launch control.

Meanwhile, cloud cover began to roll over the Cape and Challenger's three-hour "launch window" was quickly running out. The countdown was delayed at 9:10 a.m. to give technicians time to fix the hatch. The microswitch problem was quickly corrected but engineers had run into trouble removing a special tool from the hatch used to dog it shut. They called for a drill to bore out a stripped bolt. The drill came but its batteries were dead. The technicians sent out for fresh batteries. At 10:30 a.m., launch control was forced to recalibrate the shuttle's navigation equipment so the ship's computers would know where they were after the delay, an hour-long procedure. Meanwhile, the astronauts remained strapped in their seats. Launch was rescheduled for 12:06 p.m., but high winds were kicking up at the spaceport and finally, at 12:36 p.m., at the end of Challenger's launch window, blastoff was postponed for the day because crosswinds at the nearby shuttle landing strip were beyond acceptable limits in the event Challenger's crew was forced to attempt an emergency landing because of an engine failure or other problem during the first four minutes of flight. The countdown was recycled to the T-minus six-hour mark.

"We have just had an announcement from launch director Gene Thomas to the crew and the launch team that we are going to scrub for today," said NASA spokesman Hugh Harris.

It was a frustrating delay for the crew and for thousands of spectators, including McAuliffe 's husband and two children, and scores of educators and teachers who stood by in chilly weather awaiting the space teacher's pyrotechnic launching. The astronauts, appearing none the worse for the wear but clearly disappointed, climbed out of Challenger at 1:06 p.m. after spending more than five hours on their backs. Scobee inspected the ship's balky hatch. Blastoff was rescheduled for 9:38 a.m. Tuesday, Jan. 28, and while the weather was expected to be clear, temperatures were predicted to dip below freezing overnight, prompting implementation of a special weather plan to prevent key launch pad water systems from freezing. The astronauts left the shuttle and returned to crew quarters for what turned out to be their last day on Earth.

The Launch-Eve Debate

While the crew slept, engineers with NASA's Marshall Space Flight Center in Huntsville, Ala., and with Morton Thiokol Inc., builder of the shuttle's giant solid-fuel booster rockets, held an unscheduled teleconference to discuss the effects of the record cold weather on sensitive rubber O-ring seals in Challenger's booster rockets. The boosters, the largest solid-fuel rockets ever flown, are assembled in sections, with four fuel segments making up each motor. The O-ring seals are used in the joints between fuel segments to maintain internal pressure and prevent hot gas or flame from escaping in a catastrophic "burn through ." Morton Thiokol engineers unanimously recommended a launch postponement because they feared the O-rings might not seat properly because of the cold weather.

But NASA managers at Marshall , where the solid rocket program is managed, strongly objected to the Morton Thiokol recommendation, claiming the engineers did not have enough data to support their concerns, despite a known history of past O-ring erosion during flight. This philosophy of "prove it's not safe to fly" was a direct reversal of a long-standing NASA tradition of "prove it's safe or we won't launch." Bowing to pressure from NASA, Morton Thiokol managers who originally voted with the engineers to delay launch, reversed the decision and sent a telefax to the Kennedy Space Center approving blastoff. Word of the debate was never passed on to higher level NASA managers because the issue had been resolved.

Launch Preparations

Other problems also surfaced during the night. The Liberty Star and the Freedom Star , ships used to recover spent booster casings after they fall away from the shuttle, were unable to stay on station because of high seas and had to point into the wind and head toward shore for safety. Arnold Aldrich , manager of the shuttle program at the Johnson Space Center , was told the recovery crew probably would not be able to salvage the booster parachutes and forward nose cones because of the wind and the time it would take the ships to return to station. Aldrich decided to proceed with the countdown anyway, judging it was more important to get Challenger aloft given the upcoming flight schedule than to worry about recovery of relatively minor hardware. And throughout the night, engineers worried about the buildup of ice on the launch pad.

And so, engineers nursed Challenger through another final countdown, hampered by howling wind and ice and battling wind chills of 10 degrees below zero. Keeping a lookout for ice buildups in critical launch pad systems, workers evacuated the pad and began pumping another load of liquid oxygen and liquid hydrogen into Challenger's external tank about 1:25 a.m. But less than 20 minutes later, the carefully timed procedure was aborted, before any fuel had reached the tank, because of trouble with a computer interface system that routed data from hydrogen fire detectors and other safety equipment to launch controllers during the hazardous fueling operation. Two hours later, the fueling procedure was still on hold but mission managers took advantage of the delay to send an ice inspection team back to the launch pad, which was closed during the fueling operation, to inspect water systems for ice damage. After using up all of the countdown's available "hold" time, technicians were able to fix the trouble with the fire detector system and they were cleared to resume loading fuel at 3:55 a.m. Blastoff was tentatively rescheduled for 10:38 a.m.

So in the early morning darkness at the Kennedy Space Center , Challenger stood bathed in million-candlepower spotlights, clearly visible to travelers on Interstate 95 more than 10 miles away. The crew was allowed to sleep an extra hour because of the fueling delay but they got up on time anyway. After another "last" breakfast, the astronauts made their way to the Astrovan . McAuliffe was wearing gloves to keep out the cold. The white room technicians at the pad who greeted McAuliffe with mortarboards the day before, presented her with a shiny red apple this time around and the crew appeared relaxed and calm as they went through the now familiar ritual of climbing aboard beginning at 8:23 a.m. It was 61 degrees inside the shuttle's unheated crew cabin. Infrared scans of the boosters showed temperatures at the base of the right-side rocket were well below freezing.

"Let's hope we go today," orbiter test conductor Roberta Wyrick radioed the crew from launch control some four miles away.

"We'd like to do that," Scobee replied.

This time, the hatch worked properly - astronaut Ronald McNair took a moment to inspect the now famous handle - but launch was delayed until 11:08 a.m. to give inspection teams more time to assess ice buildups on the launch pad. It was the first indication launch controllers were seriously concerned about ice.

"One of the concerns is these icicles, some of which are several feet long, could possibly break off during liftoff and damage the orbiter and its thermal protection system," launch commentator Harris said.

By 8:44 a.m., the ice team had completed its second inspection of pad facilities. Aldrich decided to delay the countdown to allow more time for ice to melt. At 11:15 a.m., a second ice inspection had been completed and finally, Moore gave the final "go" to pick up the countdown, shooting for liftoff at 11:38 a.m. Computers in launch control were reconfigured for the terminal countdown phase and the shuttle's guidance and navigation systems were updated. A final "poll" of the launch control console operators was taken and the engineers voted to proceed with blastoff. The countdown clock began ticking once more at 11:29 a.m. at T-minus nine minutes to launch.

As commander, Scobee was strapped into the cockpit 's left forward seat with pilot Michael Smith sitting to his right, his white flight helmet clearly visible in photographs taken by launch pad cameras. In front of them were banks of instruments and controls along with three computer screens to help them monitor the shuttle's trajectory and the performance of the ship's three high-tech liquid-fueled main engines. Seated between the two pilots directly behind them was Judy Resnik, working as "flight engineer" during launch to help monitor critical instruments. To her right, up against the wall of the cockpit, was Ellison Onizuka and below in the cabin's middeck area, McNair was seated just inside the shuttle's hatch. Ahead and to his right was McAuliffe and seated to her right, Jarvis. Of the three crew members in the middeck, only McNair would have a view during the climb to space through a small window in the hatch to his left. There was no way out barring a safe landing .

Shuttle Abort Options Reviewed

When the space shuttle was designed in the early 1970s, engineers faced a crucial decision: what escape systems were possible and which could be economically implemented? For the Mercury and Apollo programs, NASA opted to use solid-fuel rockets to pull the crew capsule away from a malfunctioning booster. For the two-man Gemini program, ejection seats were employed and for the first four shuttle flights, Columbia was equipped with rocket-powered ejection seats to allow the two-man crews to catapult away from a major malfunction. But with the completion of the fourth shuttle mission, the program was declared "operational" and crew sizes were increased. The flight deck of the crew module could only accommodate two ejection seats and the two aboard Columbia later were removed. The other three shuttles in NASA's fleet were never so equipped. Instead, NASA designed the shuttle for "intact" aborts , meaning no matter what the emergency, barring the most extreme catastrophe, the shuttle would be able to make an intact landing somewhere.

The shuttle launch phase is broken down into four basic abort regimes, based on the weight of the spaceship and the thrust level of its main engines. From liftoff through about four minutes, the shuttle could attempt a "return to launch site" abort, or RTLS , in the event one or more of the ship's main engines failed, which would leave the shuttle with too little power to reach orbit. After four minutes, the shuttle is too far from Florida to make it back to the Kennedy Space Center and so the next abort regime is called the "transAtlantic Landing," or TAL , contingency. In this scenario, if one or more main engines fail the crew would attempt to land at an emergency runway in Europe or Africa. But this option is only good between slightly before the end of the RTLS "window" and about seven minutes after blastoff. Depending on the weight of the shuttle's payload, two other abort options may be available, both preferable to the first two: abort once around, in which the crew loops around the planet for an emergency landing in California, or an abort to orbit , in which the shuttle is high enough and going fast enough to achieve a lower-than-planned orbit. In practice, the abort scenarios come in many combinations depending on the weight of the shuttle and the main engine thrust level.

Here are the actual abort regime times for Challenger's flight:

- 2:44 - Two engine TAL at Dakar in the event of a single engine failure
- 3:24 - Two engine TAL at Casablanca
- 3:51 - End of RTLS regime
- 5:20 - Single engine TAL at Dakar in the event of two engine failures
- 5:20 - Shuttle can achieve lower-than-planned orbit with single engine failure
- 6:01 - Last chance for two-engine TAL at Casablanca
- 7:07 - Shuttle can reach lower-than-planned orbit with a single engine at 104%
- 7:14 - Last chance for a three-engine or two-engine TAL at Dakar

7:26 - Last chance for TAL at Dakar with single engine running
8:26 - MECO - normal "main engine cutoff" in orbit

All four of these contingency aborts were designed with two problems in mind: main engine failures or major on-board system malfunctions, such as loss of cabin air pressure or electrical power. In fact, on July 29, 1985, Challenger's No. 3 main engine shut down prematurely when two temperature sensors failed, misleading the shuttle's flight computers into believing the powerplant was overheating. The failure happened five minutes, 45 seconds after blastoff and commander Gordon Fullerton was able to complete a safe abort to orbit .

All abort modes are inherently risky affairs and the prospect of multiple engine failures is especially disconcerting. Here's how former shuttle commander Robert Overmyer once described the consequences of multiple engine failures during an RTLS .

"If you lost that second prior to starting the RTLS , you're in (an ocean) ditch capability," he said in an interview. "If you lose three engines, forget it, you're probably dead. We advertise all kinds of neat things about tricks we might pull, but the chances of pulling that off are slim to none. We do practice, and that's one of the hardest flying tasks that I've ever had to try and fly, and we practice all the time, killing that second engine and flying the rest of the RTLS on one engine, and because you're getting some aerodynamics, you're at about 225,000 feet but you're starting to get some aerodynamics, the vehicle wants to yaw around on you a little bit and if the only engine you've got running is one of the side engines, it's problematical and nobody has a whole lot of success in completing those in the simulator.

"Things happen so fast that before you can even spit you're out of control. You might recover but by the time you recover, you've lost so much energy you're not going to make it back to the runway, anyway. I can't say we don't pull it off occasionally but losing two engines on an RTLS is a very bad day."

The intact abort modes do not begin until about 30 seconds after SRB separation. During the first two minutes of flight when the solid-fuel boosters are firing a shuttle crew has no survivable abort options.

Early on during the design of the shuttle, engineers considered whether to attempt implementation of systems that would allow survival in the event of a solid rocket booster - SRB - failure. Milton Silveira , a former chief engineer of NASA, said the agency considered the addition of small solid rockets attached to the rear of the shuttle that would help blow the craft away from the solid rockets and external fuel tank in the event of an impending catastrophe. Such rockets would be needed because simply detaching from the fuel tank during SRB firing would result in the rear of the shuttle crashing into the base of the external tank because of aerodynamic forces. Silveira said such systems were prohibitively costly in terms of money and extra weight but perhaps more important, because of additional complexity and risk. For example, such systems would require an extensive network of sensors to detect the problems in the first place and with each new level of complexity the odds go up for potential malfunctions.
The shuttle builders were, of course, aware of this two-minute period of vulnerability. In any case, the decision was made to design the shuttle's booster rockets so they would be fail proof. Because as everyone in the program knew, a major booster problem would doom a shuttle and its crew.

T-Minus 9 and Counting

At nine minutes to launch, a final 10-minute hold in Challenger's countdown ended and an automatic computer sequence began to initiate the terminal countdown. McAuliffe and Jarvis were strapped tightly into seats on the shuttle's lower deck and had nothing to look at during the climb to space but rows of lockers just a few feet in front of them bathed in the soft glow of fluorescent lights. As the countdown finally picked up at the T-minus nine-minute point at 11:29 a.m., they must have looked over at each other and smiled, elated that their grand adventure was about to begin. McNair, sitting behind and to their left by the lower hatch window, probably enjoyed the view, not having the responsibilities of his colleagues on the flight deck. Then again, he might have been thinking ahead to his role in the deployment of the TDRS satellite later in the day.

At seven minutes, 30 seconds to launch, McNair was able to watch the white room slowly pull away from the side of the orbiter. At five minutes to launch, co-pilot Smith fired up the shuttle's three auxiliary power units, the devices that provide the power to move the shuttle's engine nozzles for steering and operate the wing flaps and rudder. The ground computer ordered Challenger's engine nozzles, wing flaps and rudder to move through a programmed pattern to make sure they would be ready to steer the shuttle after blastoff. At three minutes to launch, the "beany cap" on the nose of the shuttle's external tank, which had been carrying oxygen vapor away to prevent ice buildups during fueling, lifted up and rotated out of the way as the two propellant tanks that made up the external fuel tank were brought up to flight pressure.

"OK, there goes the LOX (liquid oxygen) arm," Smith said over the shuttle's intercom system.

"Doesn't it go the other way?" Onizuka joked. With his crewmates laughing, he continued, "Now I see it; I see it."

"God, I hope not, Ellison," Smith replied.

At 31 seconds to launch, Challenger's four flight computers took over the countdown. It was a beautiful day for a shuttle launch and Scobee took time to update the astronauts below on the middeck of the countdown status: "Thirty seconds down there."

At T-minus 30 seconds, launch commentator Harris read through the final paragraphs of his prepared script: "And we've had a go for auto sequence start. The SRB hydraulic power units have started. T-minus 21 seconds and the solid rocket booster engine gimbal now underway. T-minus 15 seconds...."

The shuttle's flight computers moved the solid rocket booster engine nozzles through a programmed pattern to ensure they would be ready to steer the giant spaceship during the first two minutes of flight. At 13 seconds to launch, huge valves at the base of a nearby water tower opened to direct torrents of water to the launch pad to muffle the acoustic shock of booster ignition. The countdown now carried a sense of urgency with events happening with computer-driven rapidity. At 11 seconds to launch, the self destruct systems of each 14-story-tall solid rocket booster were armed. In the event of a catastrophe, shaped explosives would blow the rocket casings open to neutralize thrust , preventing an out of control rocket from reaching any populated areas. Unlike the liquid-fueled main engines, once an SRB is fired it cannot be shut down until its fuel is exhausted. At 10 seconds to launch, the ground computers gave a final "go" for main engine start and two big sparklers under Challenger's three main engines ignited with a shower to burn away any excess hydrogen that may have accumulated prior to engine start.
"T-minus 10 seconds, GLS (ground launch sequencer) go for main engine start," a technician said over the NASA audio circuit. Harris picked up the final countdown: "...10, 9, 8, 7, 6..."

At 9.5 seconds to launch, the engine start sequence began and prevalves were commanded open to allow liquid hydrogen and liquid oxygen to flow to the engine turbopumps. At eight seconds to launch, Challenger switched to internal cooling and recirculation of liquid hydrogen through key engine systems was terminated. Finally, the shuttle thundered to life. Main engine No. 3 shuddered and belched fire 6.6 seconds before zero, its dirty orange flame quickly changing to a nearly transparent bluish white as the fuel mixture stabilized. Engine No. 2 followed suit 120 milliseconds later and at 6.3 seconds to go, engine No. 1 flashed into action.

"There they go, guys," Scobee told his crewmates over the intercom.

"All right!" Resnik exclaimed.

During the next three seconds, each $35 million Rocketdyne powerplant throttled up to 100 percent power and Challenger's flight computers dutifully checked to make sure the engines were operating properly. They were, and because the nozzles are offset from Challenger's vertical axis, the entire shuttle "stack" leaned toward the external tank with the tip of the tank actually moving some 25 inches before the vehicle rebounded in a phenomenon the astronauts call the "twang."

At three seconds to launch, mechanical systems engineer K.A. Reiley in mission control at the Johnson Space Center in Houston told flight director Jay Greene vents in Challenger's fuselage had opened as planned to maintain proper pressurization in the 60-foot-long payload bay during the ascent. Even at this late stage in the countdown, the ground computers monitoring the shuttle could have called a halt and shut the engines down if a malfunction had been detected. But all systems were "go."

Challenger Takes Off

Harris: "...3, 2, 1 and liftoff..." An electronic command was sent to each solid rocket booster and eight giant exploding bolts at the base of each SRB detonated, freeing Challenger from the launch pad. A scant quarter of a second later, the first continuous vertical motion was recorded and Challenger was triumphantly on its way, committed to flight.

"Aaall Riight," Resnik drawled over the intercom.

"Here we go," Smith chimed in a second later.

The flight deck crew and McNair on the middeck could see the launch pad tower dropping away to their left, agonizingly close the the screaming spaceship. Smith, as a rookie, no doubt carefully watched his instruments, making sure all three main engines throttled up to 104 percent power as planned seconds before tower clear. At this point, the shuttle was in "attitude hold " with the flight computers steering the ship straight up. At four seconds after launch, the flight computers switched to "major mode 102 ," a computer program that allowed solid rocket steering once the shuttle had cleared the tower. The 36-story Apollo Saturn 5 moon rockets took 17 seconds to clear the top of the launch pad tower. Challenger did the job in just seven seconds - zero to 70 mph straight up - and immediately began executing its "roll program ." The shuttle's computers moved the booster nozzles in opposite directions to roll Challenger about its vertical axis so as the ship climbed toward space, the shuttle would be positioned below the external tank with the crew upside down relative to Earth and the shuttle's wings level in relation to the horizon. This reduces aerodynamic loads on the spaceship and ensures alignment on the proper trajectory.

Scobee and Resnik were busy monitoring their own banks of instruments as the commander called Houston in a routine communications check to note the beginning of Challenger's roll program . Over the intercom, Smith said: "Go you mother" and Resnik reminded the pilot to check his attitude instrumentation.

For observers three miles away at the press site, Challenger's launch was a visual feast. As usual, several seconds went by after main engine ignition before the sound caught up and a low-pitched but smooth roar suddenly snapped into being with almost physical force. A huge cloud of steam billowed into the sky to the right of the launch pad as the flame from the main engines instantly vaporized water being poured on the launch stand to reduce acoustic energy. At the moment of SRB ignition, a gush of dirty brown smoke shot out to the left of the pad and Challenger instantly began moving, coming into view over the top of its launch tower, the flame from the SRBs almost too bright to believe, rivaling the very light of the sun. And then the sound reached the press site from those awesome boosters: a crackling, booming roar that shakes an observer with its raw power. The shock wave from the ignition hit like a minor earthquake and books fell off shelves in press trailers as the shuttle majestically climbed toward space.

Challenger's launch was unique in that it took off from launch pad 39B in the first use of that Apollo moon rocket facility since 1975 when three astronauts blasted off in a Saturn 1B rocket to link up with two Soviet cosmonauts in the Apollo-Soyuz Test Project. The previous 24 shuttle missions were launched from pad 39A and the new perspective made Challenger's take off all the more dramatic to observers.

Harris (continuing) "... Liftoff of the 25th space shuttle mission, and it has cleared the tower." TV tracking cameras show Challenger climbing smoothly and rolling over on its back.

"Houston, (this is) Challenger. Roll program," Scobee radioed eight seconds after blastoff. Astronaut Richard Covey in mission control, serving as "capcom ," or capsule communicator for Challenger's flight, reassuringly replied: "Roger roll, Challenger."

Mission Control spokesman Steven Nesbitt in Houston then came up on the Public Affairs audio loop to report on the progress of the flight from inside mission control: "Good roll program confirmed. Challenger now heading downrange." The shuttle, trailing incandescent streamers of flame from its solid rockets arced up through a crystalline blue sky and out over the Atlantic Ocean. Twenty eight seconds after blastoff, Nesbitt reported Challenger's three main engines were decreasing power, as planned, to reduce flight loads as the shuttle approached the region of maximum aerodynamic pressure, called "Max Q."

Aboard Challenger, the crew felt a stronger than remembered buffeting as the shuttle knifed through upper air turbulence with Smith saying over the intercom: "Looks like we've got a lot of wind here today." Indeed, NASA said later wind shear was more extreme for flight 51-L than for any of the previous 24 shuttle missions. Nonetheless, the array of instruments in the cockpit showed all systems operating normally and within guidelines. Nesbitt came back up on the audio loop to report: "Engines beginning throttling down, now at 94 percent. Normal throttle (setting) for most of the flight is 104 percent. We'll throttle down to 65 percent shortly."

At 45 seconds into the flight, Nesbitt said: "Engines are at 65 percent. Three engines running normally, three good fuel cells. Three good APUs (auxiliary power units). Velocity 2,257 feet per second (1,539 mph), altitude 4.3 nautical miles, downrange distance 3 nautical miles...

"Engines are throttling up," Nesbitt said 67 seconds after blastoff. "Three engines now at 104 percent."

"Challenger, go at throttle up," astronaut Dick Covey radioed Scobee. This call told Scobee and Smith that flight engineers agreed with onboard instruments that showed Challenger's systems were operating normally. Scobee and Smith already knew that but the calls from mission control are more verification than anything else and both were looking forward to the "PC less than 50" readout on their computer screens indicating chamber pressure in the solid rockets was less than 50 pounds per square inch, a precursor to SRB separation.

"Roger, go at throttle up," Scobee calmly replied to mission control, still watching his instruments.

Then, suddenly and without any warning, Smith said, "Uh oh," the crew was thrown to the right and almost immediately jolted back to the left. Then, in the blink of an eye, the astronauts may have seen a rush of cotton-candy like smoke wash over the cockpit windows, possibly accompanied by a brief burst of brilliant orange flame. Almost simultaneously, the astronauts were crushed down in their seats by a force at least 12 times greater than gravity as Challenger's fuselage torqued to the left, ripping away from the crew module.

As the nose continued its supersonic climb, at least three astronauts had the presence of mind to activate their "personal egress air packs," emergency air supplies available to each crew member. Of four "PEAPs " recovered after the incident, one, which belonged to Scobee, had not been activated. Smith's had, and because it would have been extremely difficult if not impossible for him to reach the activation switch given its location, NASA officials believe Resnik or Onizuka reached up and turned it on. Smith's PEAP air gauge indicated more than three quarters of the supply was used.

Milliseconds after the nose ripped away from the fuselage, the crew cabin instruments went dead. Scobee may have tried to radio mission control out of reflex, but Challenger's fuel cells, which generate the ship's electricity, were left behind in the fuselage along with the crew's oxygen supply.

Viewed from the press site, Challenger had disappeared behind the exhaust plume of its solid rockets as the shuttle arced out over the Atlantic Ocean. Just as Scobee acknowledged the throttle-up call from mission control, NASA tracking cameras switched to a closeup view of the shuttle. A strange, pinkish glow trailed the rear of the external fuel tank , but for those watching the launch on television, events happened too fast for conscious thought.
Suddenly, the image of the shuttle was swallowed in a mushrooming fireball, a terribly beautiful maelstrom of flaming debris. A sharp crackle of static, unnoticed at the time, came over the air-to-ground audio circuit. From the ground, observers at the press site did not realize what had happened. They saw the exhaust plume suddenly expand dramatically and there was an impression of debris flying through the air. First one and then two solid rocket boosters streaked away from the fireball, apparently intact, certainly still firing at full power. The shuttle was nowhere to be seen and a sense of numbed unreality settled over the Kennedy Space Center . Some observers at the press site thought Scobee was attempting a return to launch site abort. No one seemed able to translate the terrible images in the sky above, framed by the scorpion-like pincers of the booster contrails, into the reality they represented. Thick contrails of white smoke arced away from the explosion, falling toward the Atlantic Ocean. Nesbitt, reading instruments on his console, did not see Challenger's demise and he inadvertently heightened the sense of unreality by continuing, momentarily, to read off figures for a normal ascent.

"One minute 15 seconds," Nesbitt said. "Velocity 2,900 feet per second (1,977 mph). Altitude nine nautical miles. Downrange distance seven nautical miles."

Nesbitt's voice trailed away.

On television screens in mission control, the awful reality was clear. One camera zoomed in on a single solid rocket, firing wildly and gyrating through the sky, a strangely riveting sight for NASA engineers because no shuttle solid rocket booster had ever before been seen firing on its own. In the same view, contrails from what must have been remains of the shuttle or its external tank arced toward the sea. Some 10 seconds went by in silence before Nesbitt spoke again: "Flight controllers here are looking very carefully at the situation. Obviously a major malfunction... we have no downlink..."

Finally, Nesbitt confirmed the worst fears of thousands of onlookers at the cape and millions glued to television sets across the nation.

"We have a report from the flight dynamics officer that the vehicle has exploded," he said, voice cracking. "The flight director confirms that. We are looking at checking with the recovery forces to see what can be done at this point."

The flight of mission 51-L was over.

The Ascent Timeline: 73 Seconds of History

A detailed timeline of STS-51L launch events

Editor's Note
The following timeline was written by William Harwood with technical assistance from Rob Navias, UPI Radio correspondent with United Press International at the time of the accident. The timeline is based on telemetry radioed from the shuttle as listed in the Rogers Commission accident report; transcripts of the mission control flight director's loop; the NASA-SELECT audio circuit; and the intercom transcript (times given in seconds after launch at 11:38 a.m. EST, Jan. 28, 1986).

0.000 - Solid rocket ignition command is sent.
Astronaut Judy Resnik, intercom: "Aaall Riight!"

0.008 - First of eight 25-inch-long, 7-inch-wide exploding bolts fire, four at the base of each booster, freeing Challenger from launch pad.

0.250 - First continuous vertical motion is recorded.

0.678 - Film developed later shows the first evidence of abnormal black smoke appearing slightly above the suspect O-ring joint in Challenger's right-hand solid rocket booster.

0.836 - The black smoke appears darkest; jets in puffs of three per second, roughly matching harmonic characteristics of the shuttle vehicle at launch.

0.890 - Ground launch sequence computers begin post-liftoff "safing" of launch pad structures and equipment.

1.000 - Shuttle pilot Michael Smith, intercom: "Here we go."

2.733 - Last positive evidence of smoke above the aft attach fitting that holds the rear of the right-side booster to the external fuel tank . The aft attach fitting is a little less than two feet above the fuel segment joint.

3.375 - Last positive visual indication of smoke swirling under the bottom of the external fuel tank .
Launch commentator Hugh Harris, NASA-SELECT television: "... Liftoff of the 25th space shuttle mission, and it has cleared the tower."

4.339 - The three liquid-fueled main engines throttle up from 90 percent thrust to 104 percent thrust as planned.

5.000 - Data processing systems (DPS) engineer A.F. Algate, mission control, Houston: "Liftoff confirmed."
Flight director Jay Greene, Houston: "Liftoff..."

5.000 - Loss of data from the shuttle at NASA's Merritt Island antenna complex for four data frames. Four more "data BIT-synch dropouts" occur in the next one minute and six seconds. These are normal and are caused by flame and objects on the horizon that attenuate radio signals.

5.615 - The backup flight system computer aboard Challenger commands the S-band PM (phase modulated) and S-band FM radio systems to switch antennas to maintain communications during the upcoming roll maneuver.

5.674 - Internal pressure in the right-side booster is recorded as 11.8 pounds per square inch higher than normal.

7.724 - The shuttle clears the launch pad tower and begins a maneuver to roll over, putting the crew in a "heads down" position below the external tank.

8.000 - Shuttle commander Dick Scobee, air-to-ground: "Houston, Challenger. Roll program."

10.000 - Astronaut Dick Covey, mission control: "Roger roll, Challenger."
Flight dynamics officer (FIDO) Brian Perry, mission control: "Good roll, flight."
Greene: "Rog, good roll."

11.000 - Smith, intercom: "Go you mother."

12.000 - Another antenna switch is ordered to transfer data to the Ponce De Leon tracking station.

14.000 - Resnik, intercom: "LVLH." Resnik is reminding Scobee and Smith about proper cockpit ADI configurations. "LVLH" is an acronym that stands for "local vertical, local horizontal."

15.000 - Resnik, intercom: "Shit hot!"
Scobee: "OK."

16.000 - Mission Control spokesman Steve Nesbitt in Houston, NASA-SELECT television: "Good roll program confirmed. Challenger now heading downrange."

19.000 - Smith, intercom: "Looks like we've got a lot of wind here today."
Scobee: "Yeah."

19.859 - Challenger's three main engines receive commands to begin throttling down to 94 percent power, as planned.

21.124 - The roll maneuver is completed and Challenger is on the proper trajectory.

21.604 - Right hand SRB thrust decreases before shuttle reaches maximum dynamic pressure. This is accomplished by the burn down of ridges in the solid propellant of the forward fuel segment. Thrust is a function of surface area of propellant burning.

22.000 - Scobee, intercom: "It's a little hard to see out my window here."

22.204 - Left hand SRB thrust decreases as planned.

27.000 - Booster systems engineer (Booster) Jerry Borrer, mission control: "Throttle down to 94." Challenger's three main engines begin throttling down as planned as the shuttle approaches the region of maximum aerodynamic pressure.
Greene: "Ninety four..."

28.000 - Smith, intercom: "There's 10,000 feet and Mach point five." The shuttle is 10,000 feet high traveling at half the speed of sound.
Nesbitt: "Engines beginning throttling down, now at 94 percent. Normal throttle (setting) for most of the flight is 104 percent. We'll throttle down to 65 percent shortly.

35.000 - Scobee, intercom: "Point nine."

35.379 - The three main engines begin throttling down to 65 percent power as planned.

36.990 - Telemetry data shows the shuttle's computer system responds properly to wind shear to adjust the ship's flight path.

40.000 - Smith, intercom: "There's Mach 1."
Scobee: "Going through 19,000."

43.000 - Scobee, intercom: "OK, we're throttling down."

45.000 - Nesbitt: "Engines are at 65 percent. Three engines running normally..."

45.217 - A flash is observed downstream of the shuttle's right wing.

48.118 - A second flash is seen trailing the right wing.

48.418 - A third unexplained flash is seen downstream of the shuttle's right-hand wing. 70 mm tracking camera closeup: A brilliant orange ball of flame, apparently, emerges from under the right wing and quickly merges with the plume of the solid rocket boosters. This phenomenon, observed during analysis of tracking film after launch, has been seen on previous launches but has never been explained.

48.900 - Booster systems engineer (unknown): "Three at 65."
Nesbitt: "... Three good fuel cells. Three good APUs (auxiliary power units)..."
Greene: Sixty-five, FIDO..."
FIDO: "T-del confirms throttles." The flight dynamics officer is referring to computer software monitoring the flight in real-time.
Greene: "...Thank you."

51.860 - Challenger's main engines receive commands from the onboard flight computers to begin throttling back up to 104 percent thrust as planned.

52.000 - Nesbitt: "Velocity 2,257 feet per second (1,539 mph), altitude 4.3 nautical miles, downrange distance 3 nautical miles..."

57.000 - Scobee, intercom: "Throttling up."
Smith: "Throttle up."
Scobee: "Roger."

58.788 - Tracking cameras show the first evidence of an abnormal plume on the right-hand solid rocket booster facing away from the shuttle. Scobee and Smith had no data on the performance of the solid rockets except for a software system that would have alerted them to malfunctions in the booster steering mechanism.

59.000 - Challenger passes through the region of maximum aerodynamic pressure, experiencing 720 pounds per square foot.

59.262 - A continuous "well defined intense plume" of exhaust is seen on the side of the suspect booster by tracking cameras. This is clear evidence of an O-ring joint burn through .

59.753 - First visual evidence of flame on the right-side booster. 70 mm tracking camera closeup: A flickering tongue of flame appears on the side of the right-side booster away from the shuttle and quickly becomes continuous.

60.000 - Smith, intercom: "Feel that mother go!"
Unknown, intercom: "Wooooo Hooooo!"

60.004 - Data radioed from Challenger shows the internal pressure in the right-side SRB begins dropping. This is because of the rapidly increasing hole in the failed joint.

60.238 - First evidence of flame from the rupture deflecting and impinging on the external fuel tank .

60.248 - First evidence of the anomalous plume "attaching" to the fitting that couples the aft end of the right-side rocket to the base of the external fuel tank .

60.988 - The plume deflection is continuous. 70 mm tracking camera closeup: A thick, well-defined plume of flame arcs away from right solid rocket booster.

61.724 - The shuttle rolls slightly in response to high winds aloft.

62.000 - Smith, intercom: "Thirty-five thousand, going through one point five."

62.084 - The steering mechanism of the left-hand booster suddenly moves on computer command as Challenger's flight control system compensates for wind shear. It is later noted that wind shear during Challenger's launch was more extreme than for any of the previous 24 shuttle missions, although still within design limits.

62.484 - Challenger's computers order the shuttle's right-hand "elevon," or wing flap, to move suddenly in response to wind.

63.924 - A pressure change is recorded in the right-hand outboard elevon, indicating movement.

63.964 - The shuttle's computers order a planned change in Challenger's pitch to ensure the proper angle of attack during this phase of the trajectory.

64.660 - The plume from the burn through changes shape suddenly, indicating a leak has started in the shuttle's liquid hydrogen tank to fuel the fire.

64.705 - A bright, sustained glow is photographed on the side of the external fuel tank .

64.937 - The main engine nozzles move through large arcs, trying to keep the shuttle on course as the flight computers attempt to compensate for the unbalanced thrust produced by the booster burn through . The shuttle stops the minute pitching. It is doubtful the crew was aware of the computers' efforts to keep the ship on course. At this point in the launch phase, the crew is experiencing normal longitudinal vibrations and steadily increasing acceleration forces.

65.000 - Scobee, intercom: "Reading four eighty six on mine." This is a routine airspeed indicator check.
Smith: "Yep, that's what I've got, too."

65.164 - First recorded evidence of Challenger experiencing transient motion.

65.524 - Data shows the left wing's outboard elevon moves suddenly.

66.000 - Booster systems engineer: "Throttle up, three at 104."
Greene: "Capcom (Covey), go at throttle up."

66.174 - Tracking cameras show a bright spot suddenly appears in the exhaust plume from the side of the right-side solid rocket motor and bright spots are detected on the side of the rocket facing the belly of the shuttle.

66.764 - The pressure in the shuttle's external liquid hydrogen tank begins to drop, indicating a massive leak. Smith had real-time readings of pressure in the liquid hydrogen tank, but it is doubtful he noticed anything unusual because of the rapidity of the failure. It made no difference, ultimately, because even if Challenger's pilots had suspected an SRB problem there was nothing they could have done about it. While the shuttle separates from its external fuel tank shortly before reaching orbit, it does so with no engines firing and in a benign aerodynamic environment. As Scobee and Smith well knew, separating from the tank while the SRBs were firing would drive the shuttle into the bottom of the fuel tank.

67.650 - The abnormal plumes on the bottom and top of the booster appear to merge into one. This means the flame has wrapped around the joint as the leak deteriorated.

67.684 - Telemetry indicates falling pressure in the 17-inch-wide liquid oxygen propellant lines feeding the three main engines.

68.000 - Nesbitt: "Engines are throttling up. Three engines now at 104 percent."
Covey: "Challenger, go at throttle up."

70.000 - Scobee calmly responds, air-to-ground: "Roger, go at throttle up."

72.204 - Data shows divergent up and down motions in nozzles of both solid rocket boosters.

72.284 - The two solid rocket boosters change position relative to each other, indicating the right-side booster apparently has pulled away from one of the two struts that connected its aft end to the external fuel tank . TV tracking camera: A large ball of orange fire appears higher on the other side of main fuel tank, closer to Challenger's cabin, and grows rapidly.

72.478 - A "major high rate actuator command" is recorded from one of the boosters, indicating extreme nozzle motions.

72.497 - The nozzles of the three liquid-fueled main engines begin moving at high rates: Five degrees per second.

72.525 - Data shows a sudden lateral acceleration to the right jolts the shuttle with a force of .227 times normal gravity. This may have been felt by the crew.

72.564 - Start of liquid hydrogen pressure decrease. Solid rocket boosters again demonstrate high nozzle motion rates.

72.624 - Challenger beams back what turns out to be its final navigation update.

72.964 - Main engine liquid oxygen propellant pressures begin falling sharply at turbopump inlets.

73.000 (approximate) - Smith, intercom: "Uh oh..." This is the last comment captured by the crew cabin intercom recorder. Smith may have been responding to indications on main engine performance or falling pressures in the external fuel tank .

73.010 - Last data is captured by the Tracking and Data Relay Satellite in orbit overhead, indicating structural breakup has begun in that area.

73.044 - Start of sharp decrease in liquid hydrogen pressure to the main engines.

73.045 - Another lateral acceleration, this one to the left, is possibly felt by the crew. Lateral acceleration equals .254 time the force of gravity.

73.124 - Internal pressure in the right-side rocket booster is recorded as 19 pounds per square inch below that of its counterpart, indicating about 100,000 pounds less thrust . Tracking cameras detect evidence of a circumferential white pattern on the left side of the base of the external tank indicating a massive rupture near the SRB -tank attach ring. The is nothing less than the aft dome of the liquid hydrogen tank blowing out and backwards. The resulting forward acceleration blasts the tank up into the liquid oxygen tank in the tip of the external fuel tank .

73.137 - Vapors appear near the intertank section separating the hydrogen and oxygen sections accompanied by liquid hydrogen spillage from the aft dome of the external tank.

73.143 - All three main engines respond to loss of oxygen and hydrogen inlet pressure.

73.162 - Ground cameras show a sudden cloud of rocket fuel appearing along the side of the external tank. This indicates the nose of the right-hand booster may have pivoted into the intertank area, compounding the liquid oxygen rupture.

73.191 - A sudden brilliant flash is photographed between the shuttle and the external tank. TV tracking camera: Fireballs merge into bright yellow and red mass of flame that engulfs Challenger. A single crackling noise is heard on air-to-ground radio. Engineers later say the sound is the result of ground transmitters searching the shuttle's frequency range for a signal.

73.211 - Telemetry data from the main engines exhibits interference for the next tenth of a second.

73.213 - An explosion occurs near the forward part of the tank where the solid rocket boosters attach.

73.282 - The explosion intensifies and begins consuming the external fuel tank . Television tracking camera: a ball of brilliant white erupts from the area beneath the shuttle's nose.

73.327 - The white flash in the intertank area greatly intensifies.

73.377 - Tank pressure for on board supplies of maneuvering rocket fuel begins to fluctuate.

73.383 - Data indicates the liquid-fueled main engines are approaching redline limits on their powerful fuel pumps.

73.482 - Channel A of main engine No. 2's control computer votes for engine shutdown because of high pressure fuel turbopump discharge temperature. Channel B records two strikes for shutdown.

73.503 - Main engine No. 3 begins shutdown because of high temperatures in its high pressure fuel pump. Last data captured by main engine No. 3's controller.

73.523 - Main engine No. 1 begins shutdown because of high temperatures in high pressure fuel pump.

73.543 - Last telemetry from main engine No. 1.

73.618 - The last valid telemetry from the shuttle is recorded as it breaks up: pressure fluctuations in a fuel tank in the left rocket pod at Challenger's rear and chamber pressure changes in auxiliary power unit No. 1's gas generator.

73.631 - End of last data frame.

74.130 - Last radio signal from orbiter.

74.587 - A bright flash is observed in the vicinity of the orbiter's nose. Television tracking camera closeup: The nose of the shuttle and the crew compartment suddenly engulfed in brilliant orange flame as rocket fuel in forward maneuvering jet supplies ignites.

"At that point in its trajectory, while traveling at a Mach number of 1.92 (twice the speed of sound) at an altitude of 46,000 feet, the Challenger was totally enveloped in the explosive burn," said the Rogers Commission report. "The Orbiter, under severe aerodynamic loads, broke into several large sections which emerged from the fireball. Separate sections that can be identified on film include the main engine/tail section with the engines still burning, one wing of the Orbiter, and the forward fuselage trailing a mass of umbilical lines pulled loose from the payload bay."

The nose section had ripped away from the payload bay cleanly, although a mass of electrical cables and umbilicals were torn from the cargo hold, fluttering behind the crew cabin as it shot through the thin air, still climbing. Challenger's fuselage was suddenly open like a tube with its top off. Still flying at twice the speed of sound, the resulting rush of air that filled the payload bay overpressurized the structure and it broke apart from the inside out, disintegrating in flight. Challenger's wings cartwheeled away on their own but the aft engine compartment held together, falling in one large piece toward the Atlantic Ocean, its engines on fire. The TDRS satellite in Challenger's cargo bay and its solid-fuel booster rocket were blown free as was the Spartan-Halley spacecraft. All this happened as the external tank gave up its load of fuel, which ignited in the atmosphere in what appeared to be an explosion. It was more of a sudden burning than an explosion. In any case, the two solid rockets emerged from the fireball of burning fuel and continued on, bereft of guidance from the shuttle's now-silent flight computers.

75.000 - Nesbitt (not realizing immediately there had been an explosion): "One minute 15 seconds. Velocity 2,900 feet per second (1,977 mph). Altitude 9 nautical miles. Downrange distance 7 nautical miles."

76.437 - The nose cap of the right hand solid rocket booster separates and its drogue parachute deploys. Tracking camera closeup: A lone parachute seen emerging from the plume of a solid rocket booster.

79.000 - TV tracking camera, different view: White streamers of smoking debris blossom from the cloud of smoke and flame marking the spot where Challenger had been. One large burning piece falls toward the ocean. Two solid rocket boosters emerge from the fireball and corkscrew through the sky on their own. Nesbitt's commentary stops.

89.000 - Greene in mission control utters the first words since the explosion 13 seconds ago: "FIDO, trajectories..."
FIDO: "Go ahead."
Greene: "Trajectory, FIDO."
FIDO: "Flight, FIDO, filters (radar) got discreting sources. We're go."
Ground control (GC) engineer N.R. Talbott, mission control: "Flight, GC, we've had negative contact, loss of downlink (of radio voice or data from Challenger)."
Greene: "OK, all operators, watch your data carefully."
FIDO: "Flight, FIDO, till we get stuff back he's on his cue card for abort modes."
Greene: "Procedures, any help?"
Unknown: "Negative, flight, no data."

110.250 - Range safety control officers send radio signals that detonate the self-destruct package on right-hand solid rocket.

110.252 - The left-hand booster self destructs. Tracking camera closeup: a thick cloud of black smoke suddenly engulfs rocket and brilliant but quick explosion ensues. Numerous fragments of the booster emerge from the fireball, including what appears to be a complete aft fuel segment, slowly tumbling.

(following times in minutes and seconds)
1:56 - Nesbitt: "Flight controllers here are looking very carefully at the situation. Obviously a major malfunction."

2:01 - Ground control officer: "Flight, GC, negative downlink."
Greene: "Copy."

2:08 - Nesbitt: "We have no downlink."

2:20 - TV tracking camera: falling bits of debris create white contrails arching through the blue sky. A larger object, trailing a thin cloud of vapor, plummets toward the ocean.

2:25 - FIDO: "Flight, FIDO."
Greene: "Go ahead."
FIDO: "RSO (range safety officer) reports vehicle exploded."
Greene (long pause): "Copy. FIDO, can we get any reports from recovery forces?"
FIDO: "Stand by."

2:45 - Greene: "GC, all operators, contingency procedures in effect."

2:50 - Nesbitt: "We have a report from the flight dynamics officer that the vehicle has exploded. The flight director confirms that. We are looking at checking with the recovery forces to see what can be done at this point."

3:03 - Greene: "FIDO, flight..."
FIDO: "Go ahead."
Greene: "LSO and recovery forces, any contacts?"

3:09 - Nesbitt: "Contingency procedures are in effect..."
FIDO: "We're working with them, flight."
Greene: "OK."

3:22 - Nesbitt: "We will report more as we have information available. Again, to repeat, we have a report relayed through the flight dynamics officer that the vehicle has exploded. We are now looking at all the contingency operations and awaiting word from any recovery forces in the downrange field."

3:25 - TV tracking camera: The first pieces of debris can be seen splashing into the ocean.

3:53 - FIDO: "Flight, FIDO, for what it's worth, the filter shows 'em in the water."
Greene: "Copy."

3:58 - Challenger's crew cabin smashes into the Atlantic Ocean at about 200 mph. The astronauts, still strapped in their seats, experience a braking force of 200 times normal gravity. The crew cabin disintegrates and settles to the bottom 100 feet below.

4:15 - Television tracking camera closeup shows ocean surface east of Patrick Air Force Station. A large cloud of ruddy brown smoke hangs over surface of water as objects splash on impact nearby. The cloud probably was caused by hydrazine rocket fuel from wreckage that hit the water.

4:27 - Greene: "FIDO, flight. ... FIDO flight."
FIDO: "Go ahead."
Greene: "Did the RSO's have an impact point?"
FIDO: "Stand by."

5:03 - Nesbitt: "This is mission control, Houston. We have no additional word at this time."

5:05 - FIDO: "Flight, FIDO."
Greene: "Go ahead."
FIDO: "The vacuum IP (impact point) is 28.64 North, 80.28 West."
Greene: "How does that stack with the solid (rocket) recovery forces?" Greene is referring to the Liberty Star and the Freedom Star , two NASA ships on station in the Atlantic to recover Challenger's boosters after a normal launch.
FIDO: "We're still talking to them."
Greene: "OK."

5:24 - Nesbitt: "Reports from the flight dynamics officer indicate that the vehicle apparently exploded and that impact in the water (was) at a point approximately 28.64 degrees North, 80.28 degrees West."

5:36 - TV tracking camera: A dark, irregularly shaped piece of debris - thought to be one of Challenger's wings - cartwheels down from the sky and splashes into the Atlantic. It is the largest piece of Challenger seen on TV impacting in the ocean.

5:46 - Nesbitt: "We are awaiting verification as to the location of the recovery forces in the field to see what may be possible at this point and we will keep you advised as further information is available. This is mission control."

6:15 - NASA television switches from ocean views to the grandstand area at the press site. A large cloud of white smoke remains visible towering into the sky, twisted by winds aloft and slowly dissipating. Small, helical streamers mark contrails of the solid rocket boosters.

6:41 - Greene: "OK, everybody stay off the telephones, make sure you maintain all your data, start pulling it together."

7:17 - Greene: "Flight, FIDO..."
FIDO: "FIDO, flight, go ahead sir."
Greene: "Are the LSO's on the loop?"
FIDO: "We can get 'em."
Greene: "Get 'em up on the loop, please."
LSO (coordinating recovery activity; identity unknown): "Yes sir, this is the LSO."
Greene: "OK, are there any forces headed out that way?"
LSO: "Yes sir. DOD (Department of Defense) LSO reports that all ... forces have been scrambled and they are on their way."

Greene: "OK, do we have an ETA?"
LSO: "Negative, sir."

8:00 - Greene conducts a poll of his flight controllers to determine if any data indicates what may have gone wrong.
Greene: "Booster, flight."
Booster: "Flight, booster."
Greene: "Did you see anything?"
Booster: "Nothing, sir, I looked at all the turbine temps were perfect (sic), right on the prediction. All the redlines were in good shape."
Greene: "RMU?"
Remote manipulator system, mechanical and upper stage systems officer K.A. Reiley: "We looked good, flight."
Greene: "ECOM? ECOM, flight."
Electrical, environmental, consumables and mechanical systems engineer John Rector: "Flight, ECOM, we looked normal."
Greene: "DPS?"
Data processing systems engineer A.F. Algate: "All our data's normal, flight."
Greene: "PROP?"
Propulsion systems engineer A.J. Ceccacci: "Everything looked good, flight."
Greene: "GNC?"
Guidance, navigation and control systems engineer J.W. Bantle: "Flight, the roll maneuver looked fine, what we saw of it. We were on our way decreasing roll rate as we lost data."
Greene: "Copy."

8:03 - NASA select television shows launch pad 39-B with smoke still hanging over the mobile launch platform.

8:37 - NASA select television focuses on a small parachute seen slowly drifting down out to sea.

9:11 - FIDO: "That's, uh, probably a paramedic." Later it is determined that this is the nose cap to one of the solid rocket boosters swinging from its drogue parachute.

9:19 - Nesbitt: "This is mission control, Houston. We are coordinating with recovery forces in the field. Range safety equipment, recovery vehicles intended for the recovery of the SRBs in the general area."

9:36 - Greene: "LSO, flight. LSO, flight..."
Nesbitt: "Those parachutes believed to be paramedics going into that area..."
FIDO: "We're getting them, flight."
Nesbitt: "...To repeat, we had an apparently normal ascent with the data..."
LSO: "This is LSO on flight loop."
Greene: "Rog, are you getting any inputs?"
LSO: "Sir, we've got a Jolly 1 (helicopter) on route right now. We've got ships on the way and we've got a C-130 on the way out."
Greene: "Rog."

9:41 - Nesbitt: "...coming from all positions being normal up through approximately time of main engine throttle back up to 104 percent. At about approximately a minute or so into the flight, there was an apparent explosion. The flight dynamics officer reported that tracking reported that the vehicle had exploded and impact into the water in an area approximately located at 28.64 degrees North, 80.28 degrees West, recovery forces are proceeding to the area including ships and a C-130 aircraft. Flight controllers reviewing their data here in mission control. We will provide you with more information as it becomes available. This is mission control, Houston."

11:05 - NASA select television shows the interior of mission control at the Johnson Space Center in Houston. Covey and astronaut Frederick Gregory sit silently at the Capcom console, obviously stunned.

11:39 - LSO: "Flight, LSO."
Greene: "Go ahead."
LSO: "Uh, Jolly's have not been cleared in yet, there's still debris coming down."
Greene: "Copy. Who's controlling this operation, please?"
LSO: "S & R (search and recovery) forces out of Patrick (Air Force Base)."

Greene: "Rog. Do we have a coordination loop with those people?"
LSO: "We're working with the SOC on DDMS coord right now." He is referring to a radio network used by Defense Department personnel.
LSO: "Flight, LSO."
Greene: LSO..."
LSO: "Would you like us to try to get up on DDMS coord also?"
Greene: Yes. GC, flight."
GC: "Flight, GC."
Greene: "Take that loop into one of the playback loops please, internal to the building only."
GC: "I didn't copy what you said."
Greene: "DDMS coord, patch it into one of the playback loops internal to the building."
GC: "Copy."

12:37 - Greene: "GC, flight."
GC: "Flight, GC."
Greene: "Checkpoint status, have we taken one?"
GC: "Negative."
Greene: "Take one now."
GC: "Copy."

13:27 - GC: "All flight controllers, hold inputs, lock checkpoint in progress." This is a procedure to take a "snapshot" of all computer data recorded so far to ensure its recovery for documentation.

14:24 - Greene: LSO, flight."
LSO: "LSO here, sir."
Greene: "Any updates?"
LSO: "No sir. No sir, nothing to report."

15:06 - Greene: "Operators, contingency plan copies are coming to each console position. If you have an FCOH (flight control operations handbook) you can start on the checklist, page 27 dash 4, that's page 27-4. Don't reconfigure your console, take hard copies of all your displays, make sure you protect any data source you have."
LSO: "Flight, LSO."
Greene: "LSO?"
LSO: "Looks like about 50 minutes, five zero minutes, before the helicopters are cleared in because of debris."
Greene: "Fifty minutes from what time, LSO?"
LSO: "OK, from the time of the explosion."

21:53 - Nesbitt: "This is mission control, Houston. Repeating the information that we have at this time. We had an apparently nominal liftoff this morning at 11:38 Eastern time. The ascent phase appeared normal through approximately the completion of the roll program and throttle down and engine throttle back to 104 percent. At that point, we had an apparent explosion. Subsequent to that, the tracking crews reported to the flight dynamics officer that the vehicle appeared to have exploded and that we had an impact in the water down range at a location approximately 28.64 degrees North, 80.28 degrees west.

"At that time, the data was lost with the vehicle. According to a poll by the flight director, Jay Greene, of the positions here in mission control, there were no anomalous indications, no indications of problems with engines or with the SRBs or with any of the other systems at that moment through the point at which we lost data. Again, this is preliminary information. It is all that we have at the moment and we will keep you advised as other information becomes available. We had, there are recovery forces in the general area. Others being deployed, including aircraft and ships. We saw what we believed to be paramedics parachuting into impact area and we have no additional word at this point. We will keep you advised as details become available to us. This is mission control, Houston."

The Fate of the Crew

Setting the record straight on what happened to Challenger's crew.

Editor's Note...
Many misconceptions remain regarding the fate of Challenger's crew. The following is intended to give readers a detailed look at the facts of the matter. Any interpretation after that is, of course, up to the reader.

> **"NASA is unable to determine positively the cause of death of the Challenger astronauts but has established that it is possible, but not certain, that loss of consciousness did occur in the seconds following the orbiter breakup." NASA Press Release**

> **"We have now turned our full efforts to the future, but will never forget our seven friends who gave their lives to America's space frontier." - Rear Adm. Richard Truly, Associate Administrator for Space Flight**

The Rogers Commission did not discuss the fate of the crew or provide much detail about the crew cabin wreckage. Indeed, all references to "contact 67," the crash site of the crew compartment, were deleted from the official record, including charts that mapped various debris areas. This was done, perhaps, to preclude the possibility that anyone could find out the latitude and longitude of the cabin wreck site for diving and personal salvage. But ultimately, it was simply an extension of NASA's policy of no comment when it came to the astronauts. After all, hundreds of reporters knew the exact coordinates by eavesdropping on Navy radio. In any case, while the astronauts were not discussed in the commission report, the crew module was.

Analysis of crew cabin wreckage indicates the shuttle's windows may have survived the explosion. It is thus possible the crew did not experience high-altitude cabin decompression. If so, some or all of the astronauts may have been alive and conscious all the way to impact in the Atlantic some 18 miles northeast of the launch pad. The cabin hit the water at better than 200 mph on Scobee's side. The metal posts of the two forward flight deck seats, for example, were bent sharply to the right by force of impact when the cabin disintegrated.

"The internal crew module components recovered were crushed and distorted, but showed no evidence of heat or fire," the commission report said. "A general consistency among the components was a shear deformation from the top of the components toward the +Y (to the right) direction from a force acting from the left. Components crushed or sheared in the above manner included avionics boxes from all three avionics bays, crew lockers, instrument panels and the seat frames from the commander and the pilot. The more extensive and heavier crush damage appeared on components nearer the upper left side of the crew module. The magnitude and direction of the crush damage indicates that the module was in a nose down and steep left bank attitude when it hit the water.

"The fact that pieces of forward fuselage upper shell were recovered with the crew module indicates that the upper shell remained attached to the crew module until water impact. Pieces of upper forward fuselage shell recovered or found with the crew module included cockpit window frames, the ingress/egress hatch, structure around the hatch frame and pieces of the left and right sides. The window glass from all of the windows, including the hatch window, was fractured with only fragments of glass remaining in the frames."

Several large objects were tracked by radar after the shuttle disintegrated. One such object, classified as "Object D," hit the water 207 seconds after launch about 18 nautical miles east of launch pad 39B . This apparently was the crew cabin. "It left no trail and had a bright white appearance (black and white recording) until about T+175 seconds," an appendix to the Rogers Commission report said. "The image then showed flashes of both white and black until T+187 seconds, after which time it was consistently black. The physical extent of the object was estimated from the TV recording to be about 5 meters." This description is consistent with a slowly spinning crew module, which had black heat-shield tiles on its bottom with white tiles on its side and top.

The largest piece of crew cabin wreckage recovered was a huge chunk of the aft bulkhead containing the airlock hatch that led into the payload bay and one of the two flight deck windows that looked out over the cargo hold. The bulkhead wreckage measured 12 feet by 17 feet.

Here is a chronology of the crew cabin recovery operation and the efforts to determine the fate of the astronauts:

- Mid-March - Four astronaut "personal egress air packs," called PEAPs , are recovered along with other cabin wreckage.

- April 18 - NASA announced the crew cabin recovery operation was complete and that identifiable remains of all seven astronauts were on shore undergoing analysis.
- April 25 - The Armed Forces Institute of Pathology notified NASA it had been unable to determine a cause of death from analysis of remains. Joseph Kerwin, director of life sciences at the Johnson Space Center , began an in-depth analysis of the wreckage in a search for the answer.
- May 20 - Johnson Space Center crew systems personnel began analysis of the four PEAPs , emergency air packs designed for use if a shuttle crew must attempt an emergency exit on the ground when dangerous vapors might be in the area.
- May 21 - Investigators found evidence some of the PEAPs had been activated.
- June 4 - Investigators determined PEAP activation was not caused by crew cabin impact in the ocean.
- June 9 - Smith's PEAP was identified by serial number.
- June 25 - The PEAPs were sent to th Army Depot in Corpus Christi, Texas, for further analysis.
- June 27 - Scobee's PEAP was identified by serial number; Army investigators determined that three of the four air packs had been activated.
- July 18 - Truly received Kerwin's preliminary report on the fate of the astronauts. On July 24, NASA began informing the astronauts' families about what the investigation had found.

Some of the first wreckage recovered included four flight computers and both the cabin's operational flight recorders, used to record data about various shuttle systems and also used for the cabin's intercom system. It was on this tape that NASA heard Smith say "Uh oh" an instant before the shuttle broke apart, showing that at least some of the astronauts had a brief moment of awareness before the explosion that would claim their lives.

On July 28, six months to the day after the disaster, NASA staged a news conference in Washington to discuss the investigation. Kerwin said the cause and time of death remained unknown.

"The findings are inconclusive," he wrote in a letter to Truly. "The impact of the crew compartment with the ocean surface was so violent that evidence of damage occurring in the seconds which followed the explosion was masked.

Our final conclusions are:

- The cause of death of the Challenger astronauts cannot be positively determined;
- The forces to which the crew were exposed during orbiter breakup were probably not sufficient to cause death or serious injury; and
- The crew possibly, but not certainly, lost consciousness in the seconds following orbiter breakup due to in-flight loss of crew module pressure."

Accelerometers, instruments that measure the magnitude and direction of forces acting on the shuttle during flight, lost power when the nose section ripped away two tenths of a second after structural break up began. Independent analysis of all recovered data and wreckage concluded the nose pitched down as soon as it broke away and then slowed rapidly from aerodynamic forces. Calculations and analysis of launch photography indicate the acceleration forces the astronauts felt were between 12 and 20 times the force of gravity in a vertical direction, that is, as the cabin broke away, the astronauts were violently pushed down in their seats.

"These accelerations were quite brief," Kerwin wrote. "In two seconds, they were below four G's; in less than 10 seconds, the crew compartment was essentially in free fall. Medical analysis indicates that these accelerations are survivable, and that the probability of major injury to crew members is low."

When Challenger broke up, it was traveling at 1.9 times the speed of sound at an altitude of 48,000 feet. The crew module continued flying upward for some 25 seconds to an altitude of about 65,000 feet before beginning the long fall to the ocean. From breakup to impact took two minutes and 45 seconds. Impact velocity was 207 mph, subjecting the module to a braking force of approximately 200 times the force of gravity. Any astronauts still alive at that moment were killed instantly.

When the cabin ripped away from the fuselage, the crew's oxygen supplies were left behind in the payload bay, "except for a few seconds supply in the lines," Kerwin said. But each astronaut's airtight flight helmet also was connected to a PEAP that contained about six minutes of breathing air. Kerwin said because of the design of the activation switch, it was highly unlikely the PEAPs were turned on by impact. But unlike the oxygen system, the PEAPs did not provide pressurized air and if the cabin lost pressure, they would not have allowed the crew to remain conscious.

"It is possible, but not certain, that the crew lost consciousness due to an in-flight loss of crew module pressure," Kerwin wrote. "Data to support this is:

- The accident happened at 48,000 feet and the crew cabin was at that altitude or higher for al most a minute. At that altitude, without an oxygen supply, loss of cabin pressure would have caused rapid loss of consciousness and it would not have been regained before water impact.
- PEAP activation could have been an instinctive response to unexpected loss of cabin pressure.
- If a leak developed in the crew compartment as a result of structural damage during or after breakup (even if the PEAPs had been activated), the breathing air available would not have prevented rapid loss of consciousness.
- The crew seats and restraint harnesses showed patterns of failure which demonstrates that all the seats were in place and occupied at water impact with all harnesses locked. This would likely be the case had rapid loss of consciousness occurred, but it does not constitute proof."

Despite NASA's best efforts, engineers were never able to determine if cabin pressure was lost. Astronaut Crippen said later he was convinced it did, however, because had the cabin maintained pressure there would have been no need to activate the PEAPs . He said in his view, the astronauts made a "desperate" attempt to survive by activating the PEAPs when pressure was suddenly lost.

Of the four PEAPs recovered, the one that belonged to Scobee had not been activated. Of the other three, one was identified as Smith's and because of the location of the activation switch on the back of his seat, Truly said he believed Resnik or Onizuka turned the pilot's emergency air supply on in a heroic bid to save his life. The exact sequence of events will never be known.

The Rogers Commission

Recovering from history's worst space disaster.

The Rogers Commission
From Executive Order 12546, Feb. 3, 1986:
Sec. 2. Functions

1. The Commission shall investigate the accident to the Space Shuttle Challenger, which occurred on January 28, 1986.

2. The Commission shall:

1. Review the circumstances surrounding the accident to establish the probable cause of the accident; and

2. Develop recommendations for corrective or other action based upon the Commission's findings and determinations.

3. The Commission shall submit its final report to the President and the Administrator of the National Aeronautics and Space Administration within one hundred and twenty days of the date of this order.

"The commission urges that NASA continue to receive the support of the Administration and the nation. The agency constitutes a national resource that plays a critical role in space exploration and development. It also provides a symbol of national pride and technological leadership. The Commission applauds NASA's spectacular achievements of the past and anticipates impressive achievements to come. The findings and recommendations presented in this report are intended

> to contribute to the future NASA successes that the nation both expects and re quires as the 21st century approaches." - Conclusion of the Rogers Commission Report

The Rogers Commission report was delivered on June 6 to Camp David, Md., where President Reagan was spending the weekend. A formal presentation with the members of the commission was scheduled for Monday at 2 p.m. in the Rose Garden at the White House. While the general conclusions were well known, reporters were especially interested in what the commission report said about NASA management and recommendations for change.

Throughout the weekend, re porters and news agencies kept tabs on each other fearing a leak from the commission. But remarkably, Saturday and Sunday passed uneventfully. To prevent early disclosure of the report, the commission laid down stiff ground rules: the report would be available Monday morning at 6 a.m. but its publication or broadcast were embargoed until 2 p.m.

The wire services, however, were free to begin filing copy at 10 a.m. as long as the stories carried an embargo advisory at the top. A throng of reporters and camera crews showed up at commission headquarters Monday morning, picked up copies of the document and raced back to news rooms across Washington to study its conclusions. Again, and just as remarkably, the embargo held up, perhaps because the general thrust of the report was well known by that point. In any case, the Rogers Commission had discharged its duty and NASA would never be the same again.

The 256-page report was divided into nine chapters. The first two chapters presented a brief history of the shuttle program and past flights and detailed the events leading up to Challenger's launching on Jan. 28. The commission also presented a detailed timeline of the disaster before getting down to business in Chapter 4.

The Cause of the Accident

The Rogers Commission listed 16 findings on the primary cause of the accident before stating the following conclusion:

> "The commission concluded that the cause of the Challenger accident was the failure of the pressure seal in the aft field joint of the right Solid Rocket Motor. The failure was due to a faulty design unacceptably sensitive to a number of factors. These factors were the effects of temperature, physical dimensions, the character of materials, the effects of reusability, processing and the reaction of the joint to dynamic loading."

A thorough analysis of all available evidence showed no abnormalities with the external fuel tank , Challenger and its three main engines or the shuttle's payload and records showed all the hardware used in flight 51-L met NASA specifications. Launch processing, from the initial stacking of the rocket boosters to work done at the launch pad was normal, but during assembly of the right-side booster, engineers ran into snags. One of the fuel segments that mated at the aft field joint was severely out of round and had to be forced into the proper shape with a high-power hydraulic tool. In addition, measurements showed that because of previous use, the two fuel segments in question had slightly larger diameters than normal but they still were within specifications.

Recall for a moment the construction of the joint. The upper rim of the bottom fuel segment, called a clevis , was an upward-facing U-shaped groove. The lower rim of the fuel segment above, called a tang , slid into the clevis and the resulting interlocking joint was bolted together with 177 high-strength steel pins. Running around the interior of the inner leg of the clevis were the two rubber O-ring seals. Because of the larger than normal joint diameters, at the moment of ignition, the tang and clevis had an average gap of .004 inches, which would have compressed the O-rings severely. Because the fuel segments were slightly out of round, the smallest gap was in the area where the rupture occurred during flight, although it is not known if the high compression on the O-ring was present at liftoff.

It was a record 36 degrees when Challenger took off and infrared measurements taken at the launch pad showed the temperature around the circumference of the aft field joint was in the neighborhood of 28 degrees in the area where the rupture occurred, the coldest spot on the booster. To understand the significance of the temperature factor, consider again the operation of the rocket motor at ignition when internal pressure shoots from zero to nearly 1,000 pounds per square inch. This tremendous force pushes outward and causes the joints to bulge slightly, a phenomenon known as joint rotation. During the ignition transient, the tang and clevis typically separate as much as .017 and .029 inches where the primary and secondary O-rings are located. The gap opening reaches maximum about 600 milliseconds after ignition when the motor reaches full pressure. To keep the joint sealed as the tang-clevis separation increases during ignition, the O-rings must seat properly and the commission said cold O-rings take longer to reach the proper position.

> "At the cold launch temperature experienced, the O-ring would be very slow in returning to its normal rounded shape. It would not follow the opening of the tang -to-clevis gap. It would remain in its compressed position in the O-ring channel and not provide a space between itself and the upstream channel wall. Thus, it is probable the O-ring would not be pressure actuated to seal the gap in time to preclude joint failure due to blow-by and erosion from hot combustion gases," the report said.

Further, the commission found that experimental evidence showed other factors, such as humidity and the performance of the heat-shielding putty in the joint "can delay pressure application to the joint by 500 milliseconds or more." Records showed that in each shuttle launch in temperature below 61 degrees, one or more booster O-rings showed signs of erosion or the effects of heat. Complicating the picture, there was the possibility of ice in the suspect joint because Challenger had been exposed to seven inches of rainfall during its month on the launch pad prior to blastoff. Research showed ice could have prevented proper sealing by the secondary O-ring.

Launch pad cameras showed puffs of black smoke shooting from the region of the aft field joint beginning about the same time the motor reached full pressure. The commission said two overall failure scenarios were possible: a small leak could have developed at ignition that slowly grew to the point that flame erupted through the joint as photographs indicated some 58 seconds after blastoff. More likely, however, the gap between the burned O-rings and the clevis probably was sealed up by "deposition of a fragile buildup of aluminum oxide and other combustion debris. The resealed section of the joint could have been disturbed by thrust vectoring (steering), space shuttle motion and flight loads induced by changing winds aloft." NASA revealed after the accident that wind shear was higher for Challenger's mission than for any previous shuttle flight.

That the shuttle booster joints were faulty and overly dependent on a variety of factors was clear. The commission's findings on the secondary causes of the disaster were more subtle but just as damning to the space agency.

The Contributing Cause of the Accident

The decision to launch the Challenger was flawed," the Rogers Commission said. "Those who made that decision were unaware of the recent history of problems concerning the O-rings and the joint and were unaware of the initial written recommendation of the contractor advising against the launch at temperatures below 53 degrees Fahrenheit and the continuing opposition of the engineers at Thiokol after the management reversed its position. They did not have a clear understanding of Rockwell's concern that it was not safe to launch because of ice on the pad. If the decision makers had known all of the facts, it is highly unlikely that they would have decided to launch 51-L on January 28, 1986."

Before shuttles are cleared for flight, a formal "flight readiness review" is held by top NASA managers to discuss any open items that might affect a launch. Previous flights are reviewed to make sure any problems had been addressed before committing the next shuttle for launch. Mulloy testified NASA management was well aware of the O-ring issue and cited the flight readiness review record as proof. He was correct in that during several preceding flight readiness reviews, the O-ring problem was mentioned. But it was only mentioned in the context that it was an acceptable risk and that the boosters had plenty of margin. It was not mentioned at all during the 51-L readiness review.

"It is disturbing to the commission that contrary to the testimony of the solid rocket booster project manager, the seriousness of concern was not conveyed in Flight Readiness Review to Level 1 and the 51-L readiness review was silent."

Commission members said later the real turning point in the commission investigation came on Feb. 10 during a closed hearing in Washington. It was there the commission learned of the launch-eve debate over clearing Challenger for launch. Thiokol booster engineer Roger Boisjoly would later recall the events of Jan. 27 in this manner:

Boisjoly : "I felt personally that management was under a lot of pressure to launch and that they made a very tough decision, but I didn't agree with it. One of my colleagues that was in the meeting summed it up best. This was a meeting where the determination was to launch and it was up to us to prove beyond a shadow of a doubt that it was not safe to do so. This is in total reverse to what the position usually is in a preflight conversation or a flight readiness review. It is usually exactly opposite that."

Commission member Arthur B.C. Walker : "Do you know the source of the pressure on management that you alluded to?"

Boisjoly : "Well, the comments made over the [teleconference network] is what I felt, I can't speak for them, but I felt it, I felt the tone of the meeting exactly as I summed up, that we were being put in a position to prove that we should not launch rather then being put in the position and prove that we had enough data for launch. And I felt that very real."

The Rogers Commission concluded that a "well structured" management system with the emphasis on flight safety would have elevated the booster O-ring issue to the status it deserved and that NASA's decision-making process was clearly faulty. One can only wonder how many other launch-eve debates occurred during the previous 24 missions that were never mentioned because the flight turned out to be a success.

"Had these matters been clearly stated and emphasized in the flight readiness process in terms reflecting the views of most of the Thiokol engineers and at least some of the Marshall engineers, it seems likely that the launch of 51-L might not have occurred when it did," the commission said.

The commission also determined that the waiving of launch constraints based on previous success came at the expense of flight safety because the waivers did not necessarily reach top-level management for a decision. Finally, the commission charged engineers at the Marshall Space Flight Center where the booster program was managed had a "propensity" for keeping knowledge of potentially serious problems away from other field centers in a bid to address them internally.

An Accident Rooted in History

"The Space Shuttle's Solid Rocket Booster problem began with the faulty design of its joint and increased as both NASA and contractor management first failed to recognize it as a problem, then failed to fix it and finally treated it as an acceptable flight risk," the Rogers Commission said.

Morton Thiokol won the contract to build shuttle boosters in 1973. Of the four competitors, Thiokol ranked at the bottom for design and development but came in first in the management category. NASA later said Thiokol was selected because "cost advantages were substantial and consistent throughout all areas evaluated." The result was an $800 million cost-plus-award-fee contract.

Morton Thiokol hoped to keep costs down by borrowing heavily from the design of the Titan 3 solid rocket motors. Both systems, for example, used tang and clevis joints but the shuttle design had major differences as well. Unlike in the Titan, which relied on a single O-ring seal, two rubber O-rings were employed in the shuttle booster and both faced heavy pressure loads at launch.

The way the seals worked in the shuttle boosters was elegant in its simplicity. Before fuel joints were to be mated, an asbestos-filled putty would be used to fill in the gap between the two propellant faces of the fuel segments. The putty, then, would serve as a barrier to prevent hot gas from reaching the O-ring seals. But the putty was plastic so when the rocket was ignited, internal pressure would force the putty to flow toward the outside of the joint. In doing so, air between the putty and the O-ring would become pressurized, forcing the O-ring to "extrude" into the minute gap between the clevis and tang . In this manner, the joint would be sealed and even if the primary O-ring failed to operate, the secondary seal would fill in the gap, so to speak. To make sure the O-rings were, in fact, able to seal the joints prior to ignition, Thiokol included a "leak test port" in each booster joint. Once assembled, the space between the two O-rings could be pressurized with 50 psi air. If the pressure stayed steady, engineers would know the joint was airtight and that no path from the propellant to the primary O-ring existed for hot gas or flame.

So much for theory. When testing began, results were not what the engineers expected.

The design of the joint had led engineers to believe that once pressurized, the gap between the tang and clevis actually would decrease slightly, thereby improving the sealing action of the O-rings. To test the booster's structural integrity, Thiokol conducted "hydroburst " tests in 1977. In these tests, water was pumped inside a booster case and pressurized to 1.5 times actual operating pressure. Careful measurements were made and to their surprise, engineers realized that the tang and clevis joint actually bulged outward, widening the gap between the joint members. While Thiokol tended to downplay the significance of the finding at the time, engineers at Marshall were dismayed by the results.

John Q. Miller , a chief booster engineer at the Alabama rocket center, wrote a memo on Jan. 9, 1978, to his superiors, saying, "We see no valid reason for not designing to accepted standards" and that improvements were mandatory "to prevent hot gas leaks and resulting catastrophic failure." This memo and another along the same lines actually were authored by Leon Ray , a Marshall engineer, with Miller 's agreement. Other memos followed but the Rogers Commission said Thiokol officials never received copies. In any case, the Thiokol booster design passed its Phase 1 certification review in March 1979. Meanwhile, ground test firings confirmed the clevis -tang gap opening. An independent oversight committee also said pressurization through the leak test port pushed the primary O-ring the wrong way so that when the motor was ignited, the compression from burning propellant had to push the O-ring over its groove in order for it to extrude into the clevis-tang gap. Still, NASA engineers at Marshall concluded "safety factors to be adequate for the current design" and that the secondary O-ring would serve as a redundant backup throughout flight.

On Sept. 15, 1980, the solid rocket booster joints were classified as criticality 1R, meaning the system was redundant because of the secondary O-ring. Even so, the wording of the critical items list left much room for doubt: "Redundancy of the secondary field joint seal cannot be verified after motor case pressure reaches approximately 40 percent of maximum expected operating pressure." The joint was classified as criticality 1R until December 1982 when it was changed to criticality 1. Two events prompted the change: the switch to a non-asbestos insulating putty - the original manufacturer had discontinued production - and the results of tests in May 1982 that finally convinced Marshall management that the secondary O-ring would not function after motor pressurization. Criticality 1 systems are defined as those in which a single failure results in loss of mission, vehicle and crew. Even though the classification was changed, NASA engineers and their counterparts at Morton Thiokol still considered the joint redundant through the ignition transient. The Rogers Commission found this to be a fatal flaw in judgment.
Criticality 1 systems must receive a formal "waiver" to allow flight. On March 28, 1983, Michael Weeks, associate administrator for space flight (technical) signed the document that allowed con tinued shuttle missions despite the joint concerns.

"We felt at the time, all of the people in the program I think felt that this solid rocket motor in particular ... was probably one of the least worrisome things we had in the program," Weeks said.

Then came the flight of mission 41-B, the 10th shuttle mission, launched Feb. 3, 1984. Prior to that time, only two flights had experienced O-ring damage: the second shuttle mission and the sixth. In both cases, only a single joint was involved. But after 41-B, inspectors found damage to a field joint and a nozzle joint. Marshall engineers were concerned about the unexpected damage, but a problem assessment report concluded: "This is not a constraint to future launches." For the next shuttle flight, 41-C, NASA managers were advised launch should be approved but that there was a possibility of some O-ring erosion. Meanwhile, to make absolutely sure the O-rings were seated properly prior to launch, the leak test pressure was increased to 100 psi and later to 200 psi, even though Marshall engineers realized that increased the possibility of creating blow holes through the insulating putty. Such blow holes, in turn, could provide paths for hot gas to reach the O-rings. In any case, the statistics are simple: of the first nine shuttle flights, when joints were tested with 50 psi or 100 psi pressure, only one field joint problem was noticed. With the 200 psi tests, more than 50 percent of the shuttle missions exhibited some field joint O-ring erosion.

So even though research was underway to improve the joint design, shuttles continued flying. On Jan. 24, 1985, Discovery took off on the first classified military shuttle mission, flight 51-C. The temperature at launch time was a record 53 degrees and O-ring erosion was noted in both boosters after recovery. Damage was extensive: both booster nozzle primary O-rings showed signs of blow by during ignition and both the primary and secondary seals in the right booster's center segment field joint were affected by heat. Thiokol engineers would later say temperature apparently increased the chances for O-ring damage or erosion by reducing resiliency. Concern mounted after the flight of mission 51-B in April 1985 when engineers discovered a nozzle pri mary O-ring had been damaged and failed to seat at all and that the secondary seal also was eroded. This was serious and more studies were ordered. Mulloy then instituted a launch constraint, meaning a waiver was required before every succeeding mission. Mulloy signed such waivers six flights in a row before Challenger took off for the last time.

On Aug. 19, 1985, NASA managers in Washington were briefed on the O-ring issue and the next day, Morton Thiokol established an O-ring task force because "the result of a leak at any of the joints would be catastrophic." But company engineers told the commission the task force ran into red tape and a lack of cooperation.

"The genesis of the Challenger accident - the failure of the joint of the right solid rocket motor - began with decisions made in the design of the joint and in the failure by both Thiokol and NASA's solid rocket booster project office to understand and respond to facts obtained during testing," the Rogers Commission concluded.

The panel said NASA's testing program was inadequate, that engineers never had a good understanding of the mechanics of joint sealing and that the material presented to NASA management in August 1985 "was sufficiently detailed to require corrective action prior to the next flight."

Pressures on the System

"With the 1982 completion of the orbital test flight series, NASA began a planned acceleration of the Space Shuttle launch schedule," the Rogers Commission said. "One early plan contemplated an eventual rate of a mission a week, but realism forced several downward revisions. In 1985, NASA published a projection calling for an annual rate of 24 flights by 1990. Long before the Challenger accident, however, it was becoming obvious that even the modified goal of two flights a month was overambitious."

When the shuttle program was conceived, it was hailed as the answer to the high cost of space flight. By building a reusable space vehicle, the United States would be able to lower the cost of placing a payload into orbit while at the same time, increase its operational capability on the high frontier. The nation's space policy then focused on the shuttle as the premier launcher in the American inventory and expendable rockets were phased out. Once shuttle flights began, NASA quickly fell under pressure to meet a heavy schedule of satellite launches for commercial, military and scientific endeavors. And as the flight rate increased, the space agency's resources became stretched to the limit. Indeed, the Rogers Commission said evidence indicated even if the 51-L disaster had been avoided, NASA would have been unable to meet the 16-launch schedule planned for 1986.

But NASA's can-do attitude refused to let the agency admit its own limitations as it struggled along against increasingly significant odds and diminishing resources. The Rogers Commission found that astronaut training time was being cut back, that frequent and late payload changes disrupted flight planning and that a lack of spare parts was beginning to manifest itself in flight impacts at the time of the Challenger accident.

Conclusions

1. "The capabilities of the system were stretched to the limit to support the flight rate in winter 1985/1986," the commission wrote. "Projections into the spring and summer of 1986 showed a clear trend; the system, as it existed, would have been unable to deliver crew training software for scheduled flights by the designated dates. The result would have been an unacceptable compression of the time available for the crews to accomplish their required training.

2. "Spare parts are in short supply. The shuttle program made a conscious decision to postpone spare parts procurements in favor of budget items of perceived higher priority. Lack of spare parts would likely have limited flight operations in 1986.

3. "Stated manifesting policies [rules governing payload assignments] are not enforced. Numerous late manifest changes (after the cargo integration review) have been made to both major payloads and minor payloads throughout the shuttle program.

4. "The scheduled flight rate did not accurately reflect the capabilities and resources.

5. "Training simulators may be the limiting factor on the flight rate; the two current simulators can not train crews for more than 12-15 flights per year.

6. "When flights come in rapid succession, current requirements do not ensure that critical anomalies occurring during one flight are identified and addressed appropriately before the next flight."

Other Safey Considerations

The Rogers Commission also identified a number of safety considerations to be addressed by NASA before the resumption of shuttle flights. The realization that Challenger's crew had no survivable abort options during solid rocket flight prompted the commission to recommend a re-evaluation of all possible abort schemes and escape options.

Two types of shuttle aborts were possible at the time of the Challenger accident: the four intact aborts, in which the shuttle crew attempts an emergency landing on a runway, and contingency aborts, in which the shuttle is not able to make it to a runway and instead "ditches" in the ocean. But the commission said tests at NASA's Langely Research Center showed an impact in the ocean probably would cause major structural damage to the orbiter's crew cabin. In addition, "payloads in the cargo bay are not designed to withstand decelerations as high as those expected and would very possibly break free and travel forward into the crew cabin." Not a pleasant prospect.

"My feeling is so strong that the orbiter will not survive a ditching, and that includes land, water or any unprepared surface," astronaut Weitz told the commission. "I think if we put the crew in a position where they're going to be asked to do a contingency abort, then they need some means to get out of the vehicle before it contacts earth."

If there was a clear "winner" in the Rogers Commission report it was the astronauts. Nearly every concern raised by the astronaut corps was addressed and NASA managers privately grumbled that with the re-emergence of "astronaut power," the agency would become so conservative it would be next to impossible to get a shuttle off the ground.

Recommendations

The Rogers Commission made nine recommendations to conclude its investigation of the worst disaster in space history.

1. A complete redesign of the solid rocket booster segment joints was required with the emphasis on gaining a complete understanding of the mechanics of seal operation; the joints should be as structurally stiff as the walls of the rockets and thus less susceptible to rotation; and NASA should consider vertical test firings to ensure duplication of the loads experienced during a shuttle launch. In addition, the panel recommended that NASA ask the National Research Council to set up an independent review committee to oversee the redesign of the booster joints.
2. NASA's shuttle program management system should be reviewed and restructured, with the program manger given more direct control over operations, and NASA should "encourage the transition of qualified astronauts into agency management positions" to utilize their flight experi ence and to ensure proper attention is paid to flight safety. In addition, the commission said NASA should establish a shuttle safety advisory panel.
3. The commission recommended a complete review of all criticality 1, 1R, 2 and 2R systems before resumption of shuttle flights.
4. NASA was told to set up an office of Safety, Reliability and Quality Control under an associate administrator reporting to the administrator of the space agency. This office would operate autonomously and have oversight responsibilities for all NASA programs.
5. Communications should be improved to make sure critical information about shuttle systems makes it from the lowest level engineer to the top managers in the program. "The commission found that Marshall Space Flight Center project managers, because of a tendency at Marshall to management isolation, failed to provide full and timely information bearing on the safety of flight 51-L to other vital elements of shuttle program management," the panel said. Astronauts should participate in flight readiness reviews, which should be recorded, and new policies should be developed to "govern the imposition and removal of shuttle launch constraints."
6. NASA should take action to improve safety during shuttle landings by improving the shuttle's brakes, tires and steering system and terminating missions at Edwards Air Force Base, Calif., until weather forecasting improvements are made at the Kennedy Space Center .
7. "The commission recommends that NASA make all efforts to provide a crew escape system for use during controlled gliding flight." In addition, NASA was told to "make every effort" to develop software modifications that would allow an intact landing even in the event of multiple engine failures early in flight.
8. Pressure to maintain an overly ambitious flight rate played a role in the Challenger disaster and the Rogers Commission recommended development of new expendable rockets to augment the shuttle fleet.
9. "Installation, test and maintenance procedures must be especially rigorous for space shuttle items designated criticality 1. NASA should establish a system of analyzing and reporting perfor mance trends in such items." In addition, the commission told NASA to end its practice of cannibalizing parts from one orbiter to keep another flying and instead to restore a healthy spare parts program despite the cost.