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Columbia's Last Flight

The inside story of the investigation—and the catastrophe it laid bare

BY WILLIAM LANGEWIESCHE

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Space flight is known to be a risky business, but during the minutes before dawn last February 1, as the doomed shuttle Columbia began to descend into the upper atmosphere over the Pacific Ocean, only a handful of people—a few engineers deep inside of NASA—worried that the vehicle and its seven souls might actually come to grief. It was the responsibility of NASA's managers to hear those suspicions, and from top to bottom they failed. After the fact, that's easy to see. But in fairness to those whose reputations have now been sacrificed, seventeen years and eighty-nine shuttle flights had passed since the Challenger explosion, and within the agency a new generation had risen that was smart, perhaps, but also unwise—confined by NASA's walls and routines, and vulnerable to the self-satisfaction that inevitably had set in.

Moreover, this mission was a yawn—a low-priority "science" flight forced onto NASA by Congress and postponed for two years because of a more pressing schedule of construction deliveries to the International Space Station. The truth is, it had finally been launched as much to clear the books as to add to human knowledge, and it had gone nowhere except into low Earth orbit, around the globe every ninety minutes for sixteen days, carrying the first Israeli astronaut, and performing a string of experiments, many of which, like the shuttle program itself, seemed to suffer from something of a make-work character—the examination of dust in the Middle East (by the Israeli, of course); the ever popular ozone study; experiments designed by schoolchildren in six countries to observe the effect of weightlessness on spiders, silkworms, and other creatures; an exercise in "astroculture" involving the extraction of essential oils from rose and rice flowers, which was said to hold promise for new perfumes; and so forth. No doubt some good science was done too—particularly pertaining to space flight itself—though none of it was so urgent that it could not have been performed later, under better circumstances, in the under-booked International Space Station. The astronauts aboard the shuttle were smart and accomplished people, and they were deeply committed to human space flight and exploration. They were also team players, by intense selection, and nothing if not wise to the game. From orbit one of them had radioed, "The science we're doing here is great, and it's fantastic. It's leading-edge." Others had dutifully reported that the planet seems beautiful, fragile, and borderless when seen from such altitudes, and they had expressed their hopes in English and Hebrew for world peace. It was Miracle Whip on Wonder Bread, standard NASA fare. On the ground so little attention was being paid that even the radars that could have been directed upward to track the Columbia's re-entry into the atmosphere—from Vandenberg Air Force Base, or White Sands Missile Range—were sleeping. As a result, no radar record of the breakup exists—only of the metal rain that drifted down over East Texas, and eventually came into the view of air-traffic control.

Along the route, however, stood small numbers of shuttle enthusiasts, who had gotten up early with their video cameras and had arrayed themselves on hills or away from city lights to record the spectacle of what promised to be a beautiful display. The shuttle came into view, on track and on schedule, just after 5:53 Pacific time, crossing the California coast at about 15,000 mph in the superthin air 230,000 feet above the Russian River, northwest of San Francisco. It was first picked up on video by a Lockheed engineer in suburban Fairfield, who recorded a bright meteor passing almost directly overhead, not the shuttle itself but the sheath of hot gases around it, and the long, luminous tail of ionized air known as plasma. Only later, after the engineer heard about the accident on television, did he check his tape and realize that he had recorded what appeared to be two pieces coming off the Columbia in quick succession, like little flares in its wake. Those pieces were recorded by others as well, along with the third, fourth, and fifth "debris events" that are known to have occurred during the sixty seconds that it took the shuttle to cross California. From the top of Mount Hamilton, southeast of San Francisco, another engineer, the former president of the Peninsula Astronomical Society, caught all five events on tape but, again, did not realize it until afterward. He later said, "I'd seen four re-entries before this one. When we saw it, we did note that it was a little brighter and a little bit whiter in color than it normally is. It's normally a pink-magenta color. But you know, it wasn't so different that it really flagged us as something wrong. With the naked eye we didn't see the particles coming off."

One minute after the Columbia left California, as it neared southwestern Utah, the trouble was becoming more obvious to observers on the ground. There had been a bright flash earlier over Nevada, and now debris came off that was large enough to cause multiple secondary plasma trails. North of the Grand Canyon, in Saint George, Utah, a man and his grown son climbed onto a ridge above the county hospital, hoping for the sort of view they had seen several years before, of a fireball going by. It was a sight they remembered as "really neat." This time was different, though. The son, who was videotaping, started yelling, "Jesus, Dad, there's stuff falling off!" and the father saw it too, with his naked eyes.

The Columbia was flying on autopilot, as is usual, and though it continued to lay flares in its wake, the astronauts aboard remained blissfully unaware of the trouble they were in. They passed smoothly into dawn above the Arizona border, and sailed across the Navajo reservation and on over Albuquerque, before coming to the Texas Panhandle on a perfect descent profile, slowing through 13,400 mph at 210,000 feet five minutes after having crossed the California coastline. Nineteen seconds later, at 7:58:38 central time, they got the first sign of something being a little out of the ordinary: it was a cockpit indication of low tire pressures on the left main landing gear. This was not quite a trivial matter. A blown or deflated main tire would pose serious risks during the rollout after landing, including loss of lateral control and the possibility that the nose would slam down, conceivably leading to a catastrophic breakup on the ground. These scenarios were known, and had been simulated and debated in the inner world of NASA, leading some to believe that the best of the imperfect choices in such a case might be for the crew to bail out—an alternative available only below 30,000 feet and 220 mph of dynamic airspeed.

Nonetheless, for Columbia's pilots it was reasonable to assume for the moment that the indication of low pressure was due to a problem with the sensors rather than with the tires themselves, and that the teams of Mission Control engineers at NASA's Johnson Space Center, in Houston, would be able to sort through the mass of automatically transmitted data—the so-called telemetry, which was far more complete than what was available in the cockpit—and to draw the correct conclusion. The reverse side of failures in a machine as complex as the shuttle is that most of them can be worked around, or turn out to be small. In other words, there was no reason for alarm. After a short delay the Columbia's commander, Rick Husband, calmly radioed to Mission Control, "And, ah, Houston ..." Sheathed in hot atmospheric gases, the shuttle was slowing through 13,100 mph at 205,000 feet.

Houston did not clearly hear the call.

With the scheduled touchdown now only about fifteen minutes ahead, it was a busy time at Mission Control. Weather reports were coming in from the landing site at the Kennedy Space Center, in Florida. Radar tracking of the shuttle, like the final accurate ground-based navigation, had not yet begun. Sitting at their specialized positions, and monitoring the numbers displayed on the consoles, a few of the flight controllers had begun to sense, just barely, that something was going seriously wrong. The worry was not quite coherent yet. One of the controllers later told me that it amounted to an inexplicable bad feeling in his gut. But it was undeniable nonetheless. For the previous few minutes, since about the time when the shuttle had passed from California to Nevada, Jeff Kling, an engineer who was working the mechanical-systems position known as MMACS (pronounced Macs), had witnessed a swarm of erratic indications and sensor failures. The pattern was disconcerting because of the lack of common circuitry that could easily explain the pattern of such failures—a single box that could be blamed.

Kling had been bantering good-naturedly on an intercom with one of his team, a technician sitting in one of the adjoining back rooms and monitoring the telemetry, when the technician noted a strange failure of temperature transducers on a hydraulic return line. The technician said, "We've had some hydraulic 'ducers go off-scale low."

Kling had seen the same indications. He said, "Well, I guess!"

The technician said, "What in the world?"

Kling said, "This is not funny. On the left side."

The technician confirmed, "On the left side ..."

Now Kling got onto the main control-room intercom to the lead controller on duty, known as the flight director, a man named Leroy Cain. In the jargon-laced language of the control room Kling said, "Flight, Macs."

Cain said, "Go ahead, Macs."

"FYI, I've just lost four separate temperature transducers on the left side of the vehicle, hydraulic return temperatures. Two of them on system one, and one in each of systems two and three."

Cain said, "Four hyd return temps?"

Kling answered, "To the left outboard and left inboard elevon."

"Okay, is there anything common to them? DSC or MDM or anything? I mean, you're telling me you lost them all at exactly the same time?"

"No, not exactly. They were within probably four or five seconds of each other."

Cain struggled to assess the meaning. "Okay, where are those ... where is that instrumentation located?"

Kling continued to hear from his back-room team. He said, "All four of them are located in the aft part of the left wing, right in front of the elevons ... elevon actuators. And there is no commonality."

Cain repeated, "No commonality."

But all the failing instruments were in the left wing. The possible significance of this was not lost on Cain: during the launch a piece of solid foam had broken off from the shuttle's external fuel tank, and at high speed had smashed into the left wing; after minimal consideration the shuttle program managers (who stood above Mission Control in the NASA hierarchy) had dismissed the incident as essentially unthreatening. Like almost everyone else at NASA, Cain had taken the managers at their word—and he still did. Nonetheless, the strange cluster of left-wing failures was an ominous development. Kling had more-specific reasons for concern. In a wonkish, engineering way he had discussed with his team the telemetry they might observe if a hole allowed hot gases into the wing during re-entry, and had come up with a profile eerily close to what was happening now. Still, he maintained the expected detachment.

Cain continued to worry the problem. He asked for reassurance from his "guidance, navigation, and control" man, Mike Sarafin. "Everything look good to you, control and rates and everything is nominal, right?"

Sarafin said, "Control's been stable through the rolls that we've done so far, Flight. We have good trims. I don't see anything out of the ordinary."

Cain directed his attention back to Kling: "All other indications for your hydraulic systems indications are good?"

"They're all good. We've had good quantities all the way across."

Cain said, "And the other temps are normal?"

"The other temps are normal, yes, sir." He meant only those that the telemetry allowed him to see.

Cain said, "And when you say you lost these, are you saying they went to zero ..."

"All four of them are off-scale low."

"... or off-scale low?"

Kling said, "And they were all staggered. They were, like I said, within several seconds of each other."

Cain said, "Okay."

But it wasn't okay. Within seconds the Columbia had crossed into Texas and the left-tire-pressure indications were dropping, as observed also by the cockpit crew. Kling's informal model of catastrophe had predicted just such indications, whether from blown tires or wire breaks. The end was now coming very fast.

Kling said, "Flight, Macs."

Cain said, "Go."

"We just lost tire pressure on the left outboard and left inboard, both tires."

Cain said, "Copy."

At that moment, twenty-three seconds after 7:59 local time, the Mission Control consoles stopped receiving telemetry updates, for reasons unknown. The astronaut sitting beside Cain, and serving as the Mission Control communicator, radioed, "And Columbia, Houston, we see your tire-pressure messages, and we did not copy your last call."

At the same time, on the control-room intercom, Cain was talking again to Kling. He said, "Is it instrumentation, Macs? Gotta be."

Kling said, "Flight, Macs, those are also off-scale low."

From the speeding shuttle Rick Husband—Air Force test pilot, religious, good family man, always wanted to be an astronaut—began to answer the communicator. He said, "Roger, ah," and was cut off on a word that began with "buh ..."

It turned out to be the Columbia's last voice transmission. Brief communication breaks, however, are not abnormal during re-entries, and this one raised no immediate concern in Houston.

People on the ground in Dallas suddenly knew more than the flight controllers in Houston. Four seconds after eight they saw a large piece leave the orbiter and fall away. The shuttle was starting to come apart. It continued intermittently to send telemetry, which though not immediately displayed at Mission Control was captured by NASA computers and later discovered; the story it told was that multiple systems were failing. In quick succession two additional chunks fell off.

Down in the control room Cain said, "And there's no commonality between all these tire-pressure instrumentations and the hydraulic return instrumentations?"

High in the sky near Dallas the Columbia's main body began to break up. It crackled and boomed, and made a loud rumble.

Kling said, "No, sir, there's not. We've also lost the nose-gear down talkback, and right-main-gear down talkback."

"Nose-gear and right-main-gear down talkbacks?"

"Yes, sir."

At Fort Hood, Texas, two Dutch military pilots who were training in an Apache attack helicopter locked on to the breakup with their optics and videotaped three bright objects—the main rocket engines—flying eastward in formation, among other, smaller pieces and their contrails.

Referring to the loss of communications, one minute after the main-body breakup, Laura Hoppe, the flight controller responsible for the communications systems, said to Cain, "I didn't expect, uh, this bad of a hit on comm."

Cain asked another controller about a planned switchover to a ground-based radio ahead, "How far are we from UHF? Is that two-minute clock good?"

Kling, also, was hanging on to hope. He said, "Flight, Macs."

Cain said, "Macs?"

Kling said, "On the tire pressures, we did see them go erratic for a little bit before they went away, so I do believe it's instrumentation."

"Okay."

At about that time the debris began to hit the ground. It fell in thousands of pieces along a swath ten miles wide and 300 miles long, across East Texas and into Louisiana. There were many stories later. Some of the debris whistled down through the leaves of trees and smacked into a pond where a man was fishing. Another piece went right through a backyard trampoline, evoking a mother's lament: "Those damned kids ..." Still another piece hit the window of a moving car, startling the driver. The heaviest parts flew the farthest. An 800-pound piece of engine hit the ground in Fort Polk, Louisiana, doing 1,400 mph. A 600-pound piece landed nearby. Thousands of people began to call in, swamping the 911 dispatchers with reports of sonic booms and metal falling out of the sky. No one, however, was hit. This would be surprising were it not for the fact, so visible from above, that the world is still a sparsely populated place.

In Houston the controllers maintained discipline, and continued preparing for the landing, even as they received word that the Merritt Island radar, in Florida, which should by now have started tracking the inbound craft, was picking up only false targets. Shuttles arrive on time or they don't arrive at all. But, repeatedly, the communicator radioed, "Columbia, Houston, UHF comm check," as if he might still hear a reply. Then, at thirteen minutes past the hour, precisely when the Columbia should have been passing overhead the runway before circling down for a landing at the Kennedy Space Center, a phone call came in from an off-duty controller who had just seen a video broadcast by a Dallas television station of multiple contrails in the sky. When Cain heard the news, he paused, and then put the contingency plan into effect. To the ground-control officer he said, "GC, Flight."

"Flight, GC."

"Lock the doors."

"Copy."

The controllers were stunned, but lacked the time to contemplate the horror of what had just happened. Under Cain's direction they set about collecting numbers, writing notes, and closing out their logs, for the investigation that was certain to follow. The mood in the room was somber and focused. Only the most basic facts were known: the Columbia had broken up at 200,000 feet doing 12,738 mph, and the crew could not possibly have survived. Ron Dittemore, the shuttle program manager, would be talking to reporters later that day, and he needed numbers and information. At some point sandwiches were brought in and consumed. Like the priests who harvest faith at the bedsides of the dying, grief counselors showed up too, but they were not much used.

Cain insisted on control-room discipline. He said, "No phone calls off site outside of this room. Our discussions are on these loops—the recorded DVIS loops only. No data, no phone calls, no transmissions anywhere, into or out."

Later this was taken by some critics to be a typical NASA reaction—insular, furtive, overcontrolling. And it may indeed have reflected certain aspects of what had become of the agency's culture. But it was also, more simply, a rule-book procedure meant to stabilize and preserve the crucial last data. The room was being frozen as a crime scene might be. Somewhere inside NASA something had obviously gone very wrong—and it made sense to start looking for the evidence here and now.

Less than an hour later, at 10:00 a.m. eastern time, a retired four-star admiral named Hal Gehman met his brother at a lawyer's office in Williamsburg, Virginia. At the age of sixty, Gehman was a tall, slim, silver-haired man with an unlined face and soft eyes. Dressed in civilian clothes, standing straight but not stiffly so, he had an accessible, unassuming manner that contrasted with the rank and power he had achieved. After an inauspicious start as a mediocre engineering student in the Penn State Naval ROTC program ("Top four fifths of the class," he liked to say), he had skippered a patrol boat through the thick of the Vietnam War and gone on to become an experienced sea captain, the commander of a carrier battle group, vice-chief of the Navy, and finally nato Atlantic commander and head of the U.S. Joint Forces Command. Upon his retirement, in 2000, from the sixth-ranked position in the U.S. military, he had given all that up with apparent ease. He had enjoyed a good career in the Navy, but he enjoyed his civilian life now too. He was a rare sort of man—startlingly intelligent beneath his guileless exterior, personally satisfied, and quite genuinely untroubled. He lived in Norfolk in a pleasant house that he had recently remodeled; he loved his wife, his grown children, his mother and father, and all his siblings. He had an old Volkswagen bug convertible, robin's-egg blue, that he had bought from another admiral. He had a modest thirty-four-foot sloop, which he enjoyed sailing in the Chesapeake, though its sails were worn out and he wanted to replace its icebox with a twelve-volt refrigeration unit. He was a patriot, of course, but not a reactionary. He called himself a fiscal conservative and a social moderate. His life as he described it was the product of convention. It was also the product of a strict personal code. He chose not to work with any company doing business with the Department of Defense. He liked power, but understood its limitations. He did not care to be famous or rich. He represented the American establishment at its best.

In the lawyer's office in Williamsburg his brother told him that the Columbia had been lost. Gehman had driven there with his radio off and so he had not heard. He asked a few questions, and absorbed the information without much reaction. He did not follow the space program and, like most Americans, had not been aware that a mission was under way. He spent an hour with the lawyer on routine family business. When he emerged, he saw that messages had been left on his cell phone, but because the coverage was poor, he could not retrieve them; only later, while driving home on the interstate, was he finally able to connect. To his surprise, among mundane messages he found an urgent request to call the deputy administrator of NASA, a man he had not heard of before, named Fred Gregory. Like a good American, Gehman made the call while speeding down the highway. Gregory, a former shuttle commander, said, "Have you heard the news?"

Gehman said, "Only secondhand."

Gregory filled him in on what little was known, and explained that part of NASA's contingency plan, instituted after the Challenger disaster of 1986, was the activation of a standing "interagency" investigation board. By original design the board consisted of seven high-ranking civilian and military officials who were pre-selected mechanically on the basis of job titles—the institutional slots that they filled. For the Columbia, the names were now known: the board would consist of three Air

Force generals, John Barry, Kenneth Hess, and Duane Deal; a Navy admiral, Stephen Turcotte; a NASA research director, G. Scott Hubbard; and two senior civil-aviation officials, James Hallock and Steven Wallace. Though only two of these men knew much about NASA or the space shuttle, in various ways each of them was familiar with the complexities of large-scale, high-risk activities. Most of them also had strong personalities. To be effective they would require even stronger management. Gregory said that it was NASA's administrator, Sean O'Keefe, who wanted Gehman to come in as chairman to lead the work. Gehman was not immune to the compliment, but he was cautious. He had met O'Keefe briefly years before, but did not know him. He wanted to make sure he wasn't being suckered into a NASA sideshow.

O'Keefe was an able member of Washington's revolving-door caste, a former congressional staffer and budget specialist—and a longtime protégé of Vice President Dick Cheney—who through the force of his competence and Republican connections had briefly landed the position of Secretary of the Navy in the early 1990s. He had suffered academic banishment through the Clinton era, but under the current administration had re-emerged as a deputy at the Office of Management and Budget, where he had been assigned to tackle the difficult problem of NASA's cost overruns and lack of delivery, particularly in the Space Station program. It is hard to know what he thought when he was handed the treacherous position of NASA administrator. Inside Washington, NASA's reputation had sunk so low that some of O'Keefe's former congressional colleagues snickered that Cheney was trying to kill his own man off. But O'Keefe was not a space crusader, as some earlier NASA administrators had been, and he was not about to pick up the fallen banners of the visionaries and try to lead the way forward; he was a tough, level-headed money man, grounded in the realities of Washington, D.C., and sent in on a mission to bring discipline to NASA's budget and performance before moving on. NASA's true believers called him a carpetbagger and resented the schedule pressures that he brought to bear, but in fairness he was a professional manager, and NASA needed one.

O'Keefe had been at NASA for just over a year when the Columbia self-destructed. He was in Florida standing at the landing site beside one of his deputies, a former shuttle commander named William Readdy. At 9:05 eastern time, ten minutes before the scheduled landing, Readdy got word that communications with the shuttle, which had been lost, had not been re-established; O'Keefe noticed that Readdy's face went blank. At 9:10 Readdy opened a book to check a time sequence. He said, "We should have heard the sonic booms by now. There's something really wrong." By 9:29 O'Keefe had activated the full-blown contingency plan. When word got to the White House, the executive staff ducked quickly into defensive positions: President Bush would grieve alongside the families and say the right things about carrying on, but rather than involving himself by appointing an independent presidential commission, as Ronald Reagan had in response to the Challenger accident, he would keep his distance by expressing faith in NASA's ability to find the cause. In other words, this baby was going to be dropped squarely onto O'Keefe's lap. The White House approved Gehman's appointment to lead what would essentially be NASA's investigation—but O'Keefe could expect little further communication. There was a chance that the President would not even want to receive the final report directly but would ask that it be deposited more discreetly in the White House in-box. He had problems bigger than space on his mind.

Nonetheless, that morning in his car Gehman realized that even with a lukewarm White House endorsement, the position that NASA was offering, if handled correctly, would allow for a significant inquiry into the accident. Gregory made it clear that Gehman would have the full support of NASA's engineers and technical resources in unraveling the physical mysteries of the accident—what actually had happened to the Columbia out there in its sheath of fire at 200,000 feet. Moreover, Gehman was confident that if the investigation had to go further, into why this accident had occurred, he had the experience necessary to sort through the human complexities of NASA and emerge with useful answers that might result in reform. This may have been overconfident of him, and to some extent utopian, but it was not entirely blind: he had been through big investigations before, most recently two years earlier, just after leaving the Navy, when he and a retired Army general named William Crouch had led an inquiry into the loss of seventeen sailors aboard the USS Cole, the destroyer that was attacked and nearly sunk by suicide terrorists in Yemen in October of 2000. Their report found fundamental errors in the functioning of the military command structure, and issued recommendations (largely classified) that are in effect today. The success of the Cole investigation was one of the arguments that Gregory used on him now. Gehman did not disagree, but he wanted to be very clear. He said, "I know you've got a piece of paper in front of you. Does it say that I'm not an aviator?"

Gregory said, "We don't need an aviator here. We need an investigator."

And so, driving down the highway to Norfolk, Gehman accepted the job. When he got home, he told his wife that he was a federal employee again and that there wouldn't be much sailing in the spring. That afternoon and evening, as the faxes and phone calls came in, he began to exercise control of the process, if only in his own mind, concluding that the board's charter as originally written by NASA would have to be strengthened and expanded, and that its name should immediately be changed from the absurd International Space Station and Space Shuttle Mishap Interagency Investigations Board (the ISSSSMIIB) to the more workable Columbia Accident Investigation Board, or CAIB, which could be pronounced in one syllable, as Cabe.

NASA initially did not resist any of his suggestions. Gregory advised Gehman to head to Barksdale Air Force Base, in Shreveport, Louisiana, where the wreckage was being collected. As Gehman began to explore airline connections, word came that a NASA executive jet, a Gulfstream, would be dispatched to carry him, along with several other board members, directly to Barksdale. The jet arrived in Norfolk on Sunday afternoon, the day after the accident. One of the members already aboard was Steven Wallace, the head of accident investigations for the FAA. Wallace is a second-generation pilot, an athletic, tightly wound man with wide experience in government and a skeptical view of the powerful. He later told me that when Gehman got on the airplane, he was dressed in a business suit, and that, having introduced himself, he explained that they might run into the press, and if they did, he would handle things. This raised some questions about Gehman's motivations (and indeed Gehman turned out to enjoy the limelight), but as Wallace soon discovered, grandstanding was not what Gehman was about. As the Gulfstream proceeded toward Louisiana, Gehman rolled up his sleeves and, sitting at the table in the back of the airplane, began to ask for the thoughts and perspectives of the board members there—not about what might have happened to the Columbia but about how best to find out. It was the start of what would become an intense seven-month relationship. It was obvious that Gehman was truly listening to the ideas, and that he was capable of integrating them quickly and productively into his own thoughts. By the end of the flight even Wallace was growing impressed.

But Gehman was in some ways also naive, formed as he had been by investigative experience within the military, in which much of the work proceeds behind closed doors, and conflict of interest is not a big concern. The Columbia investigation, he discovered, was going to be a very different thing. Attacks against the caib began on the second day, and by midweek, as the board moved from Shreveport to Houston to set up shop, they showed no signs of easing. Congress in particular was thundering that Gehman was a captive investigator, that his report would be a whitewash, and that the White House should replace the caib with a Challenger-style presidential commission. This came as a surprise to Gehman, who had assumed that he could just go about his business but who now realized that he would have to accommodate these concerns if the final report was to have any credibility at all. Later he said to me, "I didn't go in thinking about it, but as I began to hear the independence thing—'You can't have a panel appointed by NASA investigating itself!'—I realized I'd better deal with Congress." He did this at first mainly by listening on the phone. "They told me what I had to do to build my credibility. I didn't invent it—they told me. They also said, 'We hate NASA. We don't trust them. Their culture is no good. And their cost accounting is no good.' And I said, 'Okay.'"

More than that, Gehman came to realize that it was the elected representatives in Congress—and neither O'Keefe nor NASA—who constituted the caib's real constituency, and that their concerns were legitimate. As a result of this, along with a growing understanding of the depth and complexity of the work at hand, he forced through a series of changes, establishing a congressional-liaison office, gaining an independent budget (ultimately of about $20 million), wresting the report from O'Keefe's control, re-writing the stated mission to include the finding of "root causes and circumstances," and hiring an additional five board members, all civilians of unimpeachable reputation: the retired Electric Boat boss Roger Tetrault, the former astronaut Sally Ride, the Nobel-laureate physicist Douglas Osheroff, the aerodynamicist and former Air Force Secretary Sheila Widnall, and the historian and space-policy expert John Logsdon. Afterward, the loudest criticism faded away. Still, Gehman's political judgment was not perfect. He allowed the new civilian members to be brought on through the NASA payroll (at prorated annual salaries of $134,000)—a strange lapse under the circumstances, and one that led to superficial accusations that the caib remained captive. The Orlando Sentinel ran a story about the lack of public access to the caib's interviews under the ambiguous headline "board paid to ensure secrecy." The idea evoked laughter among some of the investigators, who knew the inquiry's direction. But unnecessary damage was done.

Equally unnecessary was Gehman's habit of referring to O'Keefe as "Sean," a clubbish mannerism that led people to conclude, erroneously, that the two men were friends. In fact their relationship was strained, if polite. Gehman told me that he had never asked for the full story behind his selection on the morning of the accident—maybe because it would have been impossible to know the unvarnished truth. Certainly, though, O'Keefe had had little opportunity to contemplate his choice. By quick view Gehman was a steady hand and a good establishment man who could lend the gravitas of his four stars to this occasion; he was also, of course, one of the men behind the Cole investigation. O'Keefe later told me that he had read the Cole report during his stint as a professor, but that he remembered it best as the subject of a case study presented by one of his academic colleagues as an example of a narrowly focused investigation that, correctly, had not widened beyond its original mandate. This was true, but a poor predictor of Gehman as a man. His Cole investigation had not widened (for instance, into assigning individual blame) for the simple reason that other investigations, by the Navy and the FBI, were already covering that ground. Instead, Gehman and Crouch had gone deep, and relentlessly so. The result was a document that bluntly questioned current American dogma, identified arrogance in the command structure, and critiqued U.S. military assumptions about the terrorist threat. The tone was frank. For example, while expressing understanding of the diplomatic utility of labeling terrorists as "criminals," the report warned against buying into that language, or into the parallel idea that these terrorists were "cowards." When, later, I expressed my surprise at his freedom of expression, Gehman did not deny that people have recently been decried as traitors for less. But freedom of expression was clearly his habit: he spoke to me just as openly about the failures of his cherished Navy, of Congress, and increasingly of NASA.

When I mentioned this character trait to one of the new board members, Sheila Widnall, she laughed and said she'd seen it before inside the Pentagon, and that people just didn't understand the highest level of the U.S. military. These officers are indeed the establishment, she said, but they are so convinced of the greatness of the American construct that they will willingly tear at its components in the belief that its failures can be squarely addressed. Almost all of the current generation of senior leaders have also been through the soul-searching that followed the defeat in Vietnam.

O'Keefe had his own understanding of the establishment, and it was probably sophisticated, but he clearly did not anticipate Gehman's rebellion. By the end of the second week, as Gehman established an independent relationship with Congress and began to break through the boundaries initially drawn by NASA, it became clear that O'Keefe was losing control. He maintained a brave front of wanting a thorough inquiry, but it was said that privately he was angry. The tensions came to the surface toward the end of February, at about the same time that Gehman insisted, over O'Keefe's resistance, that the full report ultimately be made available to the public. The caib was expanding to a staff of about 120 people, many of them professional accident investigators and technical experts who could support the core board members. They were working seven days a week out of temporary office space in the sprawling wasteland of South Houston, just off the property of the Johnson Space Center. One morning several of the board members came in to see Gehman, and warned him that the caib was headed for a "shipwreck."

Gehman knew what they meant. In the days following the accident O'Keefe had established an internal Mishap Investigation Team, whose job was to work closely with the caib, essentially as staff, and whose members—bizarrely—included some of the decision-makers most closely involved with the Columbia's final flight. The team was led by Linda Ham, a razor-sharp manager in the shuttle program, whose actions during the flight would eventually be singled out as an egregious example of NASA's failings. Gehman did not know that yet, but it dawned on him that Ham was in a position to filter the inbound NASA reports, and he remembered a recent three-hour briefing that she had run with an iron hand, allowing little room for spontaneous exploration. He realized that she and the others would have to leave the caib, and he wrote a careful letter to O'Keefe in Washington, requesting their immediate removal. It is a measure of the insularity at the Johnson Space Center that NASA did not gracefully acquiesce. Ham and another manager, Ralph Roe, in particular reacted badly. In Gehman's office, alternately in anger and tears, they refused to leave, accusing Gehman of impugning their integrity and asking him how they were supposed to explain their dismissal to others. Gehman suggested to them what Congress had insisted to him—that people simply cannot investigate themselves. Civics 101. Once stated, it seems like an obvious principle.

O'Keefe had a master's degree in public administration, but he disagreed. It was odd. He had not been with the agency long enough to be infected by its insularity, and as he later promised Congress, he was willing—no, eager—to identify and punish any of his NASA subordinates who could be held responsible for the accident. Nonetheless, he decided to defy Gehman, and he announced that his people would remain in place. It was an ill-considered move. Gehman simply went public with his letter, posting it on the caib Web site. Gehman understood that O'Keefe felt betrayed—"stabbed in the back" was the word going around—but NASA had left him no choice. O'Keefe surrendered. Ham and the others were reassigned, and the Mishap Investigation Team was disbanded, replaced by NASA staffers who had not been involved in the Columbia's flight and would be more likely to cooperate with the caib's investigators. The board was never able to overcome completely the whiff of collusion that had accompanied its birth, but Gehman had won a significant fight, even if it meant that he and "Sean" would not be friends.

The space shuttle is the most audacious flying machine ever built, an engineering fantasy made real. Before each flight it stands vertically on the launch pad at the Kennedy Space Center, as the core component of a rocket assembly 184 feet tall. The shuttle itself, which is also known as the orbiter, is a winged vehicle roughly the size of a DC-9, with three main rocket engines in the tail, a large unpressurized cargo bay in the midsection, and a cramped two-level crew compartment in the nose. It is attached to a huge external tank containing liquid fuel for the three main engines. That tank in turn is attached to two solid-fuel rockets, known as boosters, which flank the assembly and bear its full weight on the launch pad. Just before the launch, the weight is about 4.5 million pounds, 90 percent of which is fuel. It is a dramatic time, ripe with anticipation; the shuttle vents vapors like a breathing thing; the ground crews pull away until finally no one is left; the air seems unusually quiet.

Typically there are seven astronauts aboard. Four of them sit in the cockpit, and three on the lower level, in the living quarters known as the mid-deck. Because of the shuttle's vertical position, their seats are effectively rotated backward 90 degrees, so they are sitting on their backs, feeling their own weight in a way that tends to emphasize gravity's pull. At the front of the cockpit, positioned closer to the instrument panel than is necessary for the typical astronaut's six-foot frame, the commander and the pilot can look straight ahead into space. They are highly trained. They know exactly what they are getting into. Sometimes they have waited years for this moment to arrive.

The launch window may be just a few minutes wide. It is ruled by orbital mechanics, and defined by the track and position of the destination—usually now the unfinished International Space Station. Six seconds before liftoff the three main engines are ignited and throttled up to 100 percent power, producing more than a million pounds of thrust. The shuttle responds with what is known as "the twang," swaying several feet in the direction of the external tank and then swaying back. This is felt in the cockpit. The noise inside is not very loud. If the computers show that the main engines are operating correctly, the solid rocket boosters ignite. The boosters are ferocious devices—the same sort of monsters that upon failure blew the Challenger apart. Each of them produces three million pounds of thrust. Once ignited, they cannot be shut off or throttled back. The shuttle lifts off. It accelerates fast enough to clear the launch tower doing about 100 mph, though it is so large that seen from the outside, it appears to be climbing slowly.

The flying is done entirely by autopilot unless something goes wrong. Within seconds the assembly rotates and aims on course, tilting slightly off the vertical and rolling so that the orbiter is inverted beneath the external tank. Although the vibrations are heavy enough to blur the instruments, the acceleration amounts to only about 2.5 Gs—a mild sensation of heaviness pressing the astronauts back into their seats. After about forty seconds the shuttle accelerates through Mach 1, 760 mph, at about 17,000 feet, climbing nearly straight up. Eighty seconds later, with the shuttle doing about 3,400 mph and approaching 150,000 feet, the crew can feel the thrust from the solid rocket boosters begin to tail off. Just afterward, with a bright flash and a loud explosion heard inside the orbiter, the rocket boosters separate from the main tank; they continue to travel upward on a ballistic path to 220,000 feet before falling back and parachuting into the sea. Now powered by the main engines alone, the ride turns smooth, and the forces settle down to about 1 G.

One pilot described the sensations to me on the simplest level. He said, "First it's like, 'Hey, this is a rough ride!' and then, 'Hey, I'm on an electric train!' and then, 'Hey, this train's starting to go pretty darned fast!'" Speed is the ultimate goal of the launch sequence. Having climbed steeply into ultra-thin air, the shuttle gently pitches over until it is flying nearly parallel to Earth, inverted under the external tank, and thrusting at full power. Six minutes after launch, at about 356,000 feet, the shuttle is doing around 9,200 mph, which is fast, but only about half the speed required to sustain an orbit. It therefore begins a shallow dive, during which it gains speed at the rate of 1,000 mph every twenty seconds—an acceleration so fast that it presses the shuttle against its 3 G limit, and the engines have to be briefly throttled back. At 10,300 mph the shuttle rolls to a head-up position. Passing through 15,000 mph, it begins to climb again, still accelerating at 3 Gs, until, seconds later, in the near vacuum of space, it achieves orbital velocity, or 17,500 mph. The plumes from the main engines wrap forward and dance across the cockpit windows, making light at night like that of Saint Elmo's fire. Only eight and a half minutes have passed since the launch. The main engines are extinguished, and the external tank is jettisoned. The shuttle is in orbit. After further maneuvering it assumes its standard attitude, flying inverted in relation to Earth and tail first as it proceeds around the globe.

For the astronauts aboard, the uphill flight would amount to little more than an interesting ride were it not for the possibility of failures. That possibility, however, is very real, and as a result the launch is a critical and complicated operation, demanding close teamwork, tight coordination with Mission Control, and above all extreme concentration—a quality often confused with coolness under fire. I was given a taste of this by an active shuttle commander named Michael Bloomfield, who had me strap in beside him in NASA's full-motion simulator in Houston, and take a realistic run from the launch pad into space. Bloomfield is a former Air Force test pilot who has flown three shuttle missions. He had been assigned to assist the caib, and had been watching the investigation with mixed emotions—hopeful that some effects might be positive, but concerned as well that the inquiry might veer into formalism without sufficiently taking into account the radical nature of space flight, or the basic truth that every layer of procedure and equipment comes at a cost, often unpredictable. Bloomfield called this the "risk versus risk" tradeoff, and made it real not by defending NASA against specific criticisms but by immersing me, a pilot myself, in the challenges of normal operations.

Much of what he showed me was of the what-if variety, the essence not only of simulator work but also of the crew's real-world thinking. For instance, during the launch, as the shuttle rockets upward on autopilot, the pilots and flight controllers pass through a succession of mental gates, related to various combinations of main-engine failures, at various altitudes and speeds. The options and resulting maneuvers are complicated, ranging from a quick return to the launch site, to a series of tight arrivals at select runways up the eastern seaboard, to transatlantic glides, and finally even an "abort into orbit"—an escape route used by a Challenger crew in 1985 after a single main-engine failure. Such failures allow little time to make the right decision. As Bloomfield and I climbed away from Earth, tilted onto our backs, he occasionally asked the operators to freeze the simulation so that he could unfold his thoughts to me. Though the choices were clear, the relative risks were rarely so obvious. It was a deep view into the most intense sort of flying.

After we arrived in space, we continued to talk. One of the gates for engine failure during the climb to the Space Station stands at Mach 21.8 (14,900 mph), the last point allowed for a "high energy" arrival into Gander, Newfoundland, and the start of the emergency transatlantic track for Shannon, Ireland. An abort at that point provides no easy solution. The problem with Gander is how to bleed off excess energy before the landing (Bloomfield called this "a take-all-your-brain-cells type of flying"), whereas the problem with Shannon is just the opposite—how to stretch the glide. Bloomfield told me that immediately before his last space flight, in the spring of 2002, his crew and a Mission Control team had gone through a full-dress simulation during which the orbiter had lost all three engines by Mach 21.7 (less than 100 mph from the decision speed). Confident in his ability to fly the more difficult Canadian arrival, Bloomfield, from the cockpit of the simulator, radioed, "We're going high-energy into Gander."

Mission Control answered, "Negative," and called for Shannon instead.

Bloomfield looked over at his right-seat pilot and said, "I think we oughta go to Gander. What do you think?"

"Yeah."

Bloomfield radioed back: "No, we think we oughta go to Gander."

Mission Control was emphatic. "Negative. We see you having enough energy to make Shannon."

As commander, Bloomfield had formal authority for the decision, but Mission Control, with its expert teams and wealth of data, was expressing a strong opinion, so he acquiesced. Acquiescence is standard in such cases, and usually it works out for the best. Bloomfield had enormous respect for the expertise and competence of Mission Control. He was also well aware of errors he had made in the past, despite superior advice or instructions from the flight controllers. This time, however, it turned out that two of the flight controllers had not communicated correctly with each other, and that the judgment of Mission Control therefore was wrong. Lacking the energy to reach Shannon, the simulator went into the ocean well short of the airport. The incident caused a disturbance inside the Johnson Space Center, particularly because of the long-standing struggle for the possession of data (and ultimately control) between the pilots in flight and the engineers at their consoles. Nevertheless, the two groups worked together, hammered out the problems, and the next day flew the same simulator profile successfully. But that was not the point of Bloomfield's story. Rather, it was that these calls are hard to make, and that mistakes—whether his or the controllers'—may become obvious only after it is too late.

For all its realism, the simulator cannot duplicate the gravity load of the climb, or the lack of it at the top. The transition to weightlessness is abrupt, and all the more dramatic because it occurs at the end of the 3 G acceleration: when the main engines cut off, the crew gets the impression of going over an edge and suddenly dropping into a free fall. That impression is completely accurate. In fact the term zero gravity (0 G), which is loosely used to describe the orbital environment, refers to physical acceleration, and does not mean that Earth's gravitational pull has somehow gone away. Far from it: the diminution of gravitational pull that comes with distance is small at these low-orbit altitudes (perhaps 200 miles above the surface), and the shuttle is indeed now falling—about like a stone dropped off a cliff. The fall does not, of course, diminish the shuttle's mass (if it bumps the Space Station, it does so with tremendous force), but it does make the vehicle and everything inside it very nearly weightless. The orbital part of the trick is that though the shuttle is dropping like a stone, it is also progressing across Earth's surface so fast (17,500 mph) that its path matches (roughly) the curvature of the globe. In other words, as it plummets toward the ground, the ground keeps getting out of its way. Like the orbits of all other satellites, and of the Space Station, and of the Moon as well, its flight is nothing but an unrestricted free fall around and around the world.

To help the astronauts adapt to weightlessness, the quarters are designed with a conventional floor-down orientation. This isn't quite so obvious as it might seem, since the shuttle flies inverted in orbit. "Down" therefore is toward outer space—and the view from the cockpit windows just happens to be of Earth sliding by from behind and overhead. The crews are encouraged to live and work with their heads "up" nonetheless. It is even recommended that they use the ladder while passing through the hatch between the two levels, and that they "descend" from the cockpit to the mid-deck feet first. Those sorts of cautions rarely prevail against the temptations of weightlessness. After Bloomfield's last flight one of his crew commented that they had all been swimming around "like eels in a can." Or like superhumans, as the case may be. It's true that there are frustrations: if you try to throw a switch without first anchoring your body, the switch will throw you. On the other hand, once you are anchored, you can shift multi-ton masses with your fingertips. You can also fly without wings, perform unlimited flips, or simply float for a while, resting in midair. Weightlessness is bad for the bones, but good for the soul. I asked Bloomfield how it had felt to experience gravity again. He said he remembered the first time, after coming to a stop on the runway in Florida, when he picked up a small plastic checklist in the cockpit and thought, "Man, this is so heavy!" He looked at me and said, "Gravity sucks."

And orbital flight clearly does not. The ride is smooth. When the cabin ventilation is turned off, as it must be once a day to exchange the carbon dioxide scrubbers, the silence is absolute. The smell inside the shuttle is distinctly metallic, unless someone has just come in from a spacewalk, after which the quarters are permeated for a while with "the smell of space," a pungent burned odor that some compare to that of seared meat, and that Bloomfield describes as closer to the smell of a torch on steel. The dominant sensation, other than weightlessness, is of the speed across the ground. Bloomfield said, "From California to New York in ten minutes, around the world once in ninety minutes—I mean, we're moving." He told me that he took to loitering in the cockpit at the end of the workdays, just for the view. By floating forward above the instrument panel and wrapping his legs around one of the pilot seats, he could position his face so close to the front windshield that the structure of the shuttle would seem to disappear.

The view from there was etched into his memory as a continuous loop. In brief, he said: It's night and you're coming up on California, with that clearly defined coastline, and you can see all the lights all the way from Tijuana to San Francisco, and then it's behind you, and you spot Las Vegas and its neon-lit Strip, which you barely have time to identify before you move across the Rockies, with their helter-skelter of towns, and then across the Plains, with its monotony of look-alike wheels and spokes of light, until you come to Chicago and its lakefront, from which point you can see past Detroit and Cleveland all the way to New York. These are big cities, you think. And because you grew up on a farm in Michigan, played football there in high school, and still know it like a home, you pick out Ann Arbor and Flint, and the place where I-75 joins U.S. Highway 23, and you get down to within a couple of miles of your house before zip, you're gone. Zip goes Cleveland, and zip New York, and then you're out over the Atlantic beyond Maine, looking back down the eastern seaboard all the way past Washington, D.C. Ten minutes later you come up on Europe, and you hardly have time to think that London is a sprawl, France is an orderly display, the Alps are the Rockies again, and Italy is indeed a boot. Over Sicily you peer down into Etna's crater, into the glow of molten rock on Earth's inside, and then you are crossing Africa, where the few lights you see are not yellow but orange, like open flames. Past the Equator and beyond Madagascar you come to a zone of gray between the blackness of the night and the bright blue of the day. At the center of that zone is a narrow pink slice, which is the atmospheric dawn as seen from above. Daylight is for the oceans—first the Indian and then the Pacific, which is very, very large. Atolls appear with coral reefs and turquoise lagoons, but mostly what you see is cloud and open water. Then the pink slice of sunset passes below, and the night, and soon afterward you come again to California, though at another point on the coast, because ninety minutes have passed since you were last here, and during that time the world has revolved beneath you.

Ultimately the shuttle must return to Earth and land. The problem then is what to do with the vast amount of physical energy that has been invested in it—almost all the calories once contained in the nearly four million pounds of rocket fuel that was used to shove the shuttle into orbit. Some of that energy now resides in the vehicle's altitude, but most resides in its speed. The re-entry is a descent to a landing, yes, but primarily it is a giant deceleration, during which atmospheric resistance is used to convert velocity into heat, and to slow the shuttle by roughly 17,000 mph, so that it finally passes overhead the runway in Florida at airline speeds, and circles down to touch the ground at a well tamed 224 mph or less. Once the shuttle is on the runway, the drag chute and brakes take care of the rest.

The re-entry is a one-way ride that cannot be stopped once it has begun. The opening move occurs while the shuttle is still proceeding tail first and inverted, halfway around the world from the runway, high above the Indian Ocean. It is a simple thing, a brief burn by the twin orbital maneuvering rockets against the direction of flight, which slows the shuttle by perhaps 200 mph. That reduction is enough. The shuttle continues to free-fall as it has in orbit, but it now lacks the speed to match the curvature of Earth, so the ground no longer gets out of its way. By the time it reaches the start of the atmosphere, the "entry interface" at 400,000 feet, it has gently flipped itself around so that it is right-side up and pointed for Florida, but with its nose held 40 degrees higher than the angle of the descent path. The effect of this so-called angle of attack (which technically refers to the wings, not the nose) is to create drag, and to shield the shuttle's internal structures from the intense re-entry heat by cocking the vehicle up to greet the atmosphere with leading edges made of heat-resistant carbon-composite panels, and with 24,305 insulating surface tiles, each one unique, which are glued primarily to the vehicle's underside. To regulate the sink and drag (and to control the heating), the shuttle goes through a program of sweeping S-turns, banking as steeply as 80 degrees to one side and then the other, tilting its lift vector and digging into the atmosphere. The thinking is done by redundant computers, which use onboard inertial sensing systems to gauge the shuttle's position, altitude, descent rate, and speed. The flying is done by autopilot. The cockpit crews and mission controllers play the role of observers, albeit extremely interested ones who are ready to intervene should something go wrong. In a basic sense, therefore, the re-entry is a mirror image of the launch and climb, decompressed to forty-five minutes instead of eight, but with the added complication that it will finish with the need for a landing.

Bloomfield took me through it in simulation, the two of us sitting in the cockpit to watch while an experienced flight crew and full Mission Control team brought the shuttle in from the de-orbit burn to the touchdown, dealing with a complexity of cascading system failures. Of course, in reality the automation usually performs faultlessly, and the shuttle proceeds to Florida right on track, and down the center of the desired descent profile. Bloomfield expressed surprise at how well the magic had worked on his own flights. Because he had launched on high-inclination orbits to the Russian station Mir and the International Space Station, he had not flown a Columbia-style re-entry over the United States, but had descended across Central America instead. He said, "You look down over Central America, and you're so low that you can see the forests! You think, 'There's no way we're going to make it to Florida!' Then you cross the west coast of Florida, and you look inside, and you're still doing Mach 5, and you think, 'There's no way we're going to slow in time!'" But you do. Mach 5 is 3,500 mph. At that point the shuttle is at 117,000 feet, about 140 miles out. At Mach 2.5, or 1,650 mph, it is at 81,000 feet, about sixty miles out. At that point the crew activates the head-up displays, which project see-through flight guidance into the field of vision through the windshield. When the shuttle slows below the speed of sound, it shudders as the shock waves shift. By tradition if not necessity, the commander then takes over from the autopilot, and flies the rest of the arrival manually, using the control stick.

Bloomfield invited me to fly some simulated arrivals myself, and prompted me while I staggered around for a few landings—overhead the Kennedy Space Center at 30,000 feet with the runway and the coastal estuaries in sight below, banking left into a tight, plunging energy-management turn, rolling out onto final approach at 11,000 feet, following an extraordinarily steep, 18-degree glide slope at 345 mph, speed brakes on, pitching up through a "pre-flare" at 2,000 feet to flatten the descent, landing gear out at 300 feet, touching down on the main wheels with some skips and bumps, then drag chute out, nose gear gently down, and brakes on. My efforts were crude, and greatly assisted by Bloomfield, but they gave me an impression of the shuttle as a solid, beautifully balanced flying machine that in thick air, at the end, is responsive and not difficult to handle—if everything goes just right. Bloomfield agreed. Moreover, years have passed in which everything did go just right—leaving the pilots to work on the finesse of their touchdowns, whether they were two knots fast, or 100 feet long. Bloomfield said, "When you come back and you land, the engineers will pull out their charts and they'll say things like 'The boundary layer tripped on the left wing before the right one. Did you feel anything?' And the answer is always 'Well ... no. It was an incredibly smooth ride all the way down.'" But then, on the morning of February 1, something went really wrong—something too radical for simulation, that offered the pilots no chance to fly—and the Columbia lay scattered for 300 miles across the ground.

The foam did it. That much was suspected from the start, and all the evidence converged on it as the caib's investigation proceeded through the months that followed. The foam was dense and dry; it was the brownish-orange coating applied to the outside of the shuttle's large external tank to insulate the extreme cold of the rocket fuels inside from the warmth and moisture of the air. Eighty-two seconds after liftoff, as the Columbia was accelerating through 1,500 mph, a piece of that foam—about nineteen inches long by eleven inches wide, weighing about 1.7 pounds—broke off from the external tank and collided with the left wing at about 545 mph. Cameras near the launch site recorded the event—though the images when viewed the following day provided insufficient detail to know the exact impact point, or the consequences. The caib's investigation ultimately found that a gaping hole about ten inches across had been punched into the wing's leading edge, and that sixteen days later the hole allowed the hot gases of the re-entry to penetrate the wing and consume it from the inside. Through enormous effort this would be discovered and verified beyond doubt. It was important nonetheless to explore the alternatives. In an effort closely supervised by the caib, groups of NASA engineers created several thousand flow charts, one for each scenario that could conceivably have led to the re-entry breakup. The thinking was rigorous. For a scenario to be "closed," meaning set aside, absolute proof had to be found (usually physical or mathematical) that this particular explanation did not apply: there was no cockpit fire, no flight-control malfunction, no act of terrorism or sabotage that had taken the shuttle down. Unexpected vulnerabilities were found during this process, and even after the investigation was formally concluded, in late August, more than a hundred scenarios remained technically open, because they could not positively be closed. For lack of evidence to the contrary, for instance, neither bird strikes nor micrometeorite impacts could be completely ruled out.

But for all their willingness to explore less likely alternatives, many of NASA's managers remained stubbornly closed-minded on the subject of foam. From the earliest telemetric data it was known that intense heat inside the left wing had destroyed the Columbia, and that such heat could have gotten there only through a hole. The connection between the hole and the foam strike was loosely circumstantial at first, but it required serious consideration none-theless. NASA balked at going down that road. Its reasons were not rational and scientific but, rather, complex and cultural, and they turned out to be closely related to the errors that had led to the accident in the first place: simply put, it had become a matter of faith within NASA that foam strikes—which were a known problem—could not cause mortal damage to the shuttle. Sean O'Keefe, who was badly advised by his NASA lieutenants, made unwise public statements deriding the "foamologists"; and even Ron Dittemore, NASA's technically expert shuttle program manager, joined in with categorical denials.

At the caib, Gehman, who was not unsympathetic to NASA, watched these reactions with growing skepticism and a sense of déjà vu. Over his years in the Navy, and as a result of the Cole inquiry, he had become something of a student of large organizations under stress. To me he said, "It has been scorched into my mind that bureaucracies will do anything to defend themselves. It's not evil—it's just a natural reaction of bureaucracies, and since NASA is a bureaucracy, I expect the same out of them. As we go through the investigation, I've been looking for signs where the system is trying to defend itself." Of those signs the most obvious was this display of blind faith by an organization dependent on its engineering cool; NASA, in its absolute certainty, was unintentionally signaling the very problem that it had. Gehman had seen such certainty proved wrong too many times, and he told me that he was not about to get "rolled by the system," as he had been rolled before. He said, "Now when I hear NASA telling me things like 'Gotta be true!' or 'We know this to be true!' all my alarm bells go off ... Without hurting anybody's feelings, or squashing people's egos, we're having to say, 'We're sorry, but we're not accepting that answer.'"

That was the form that the physical investigation took on, with hundreds of NASA engineers and technicians doing most of the detailed work, and the caib watching closely and increasingly stepping in. Despite what Gehman said, it was inevitable that feelings got hurt and egos squashed—and indeed that serious damage to people's lives and careers was inflicted. At the NASA facilities dedicated to shuttle operations (Alabama for rockets, Florida for launch and landing, Texas for management and mission control) the caib investigators were seen as invaders of sorts, unwelcome strangers arriving to pass judgment on people's good-faith efforts. On the ground level, where the detailed analysis was being done, there was active resistance at first, with some NASA engineers openly refusing to cooperate, or to allow access to records and technical documents that had not been pre-approved for release. Gehman had to intervene. One of the toughest and most experienced of the caib investigators later told me he had a gut sense that NASA continued to hide relevant information, and that it does so to this day. But cooperation between the two groups gradually improved as friendships were made, and the intellectual challenges posed by the inquiry began to predominate over fears about what had happened or what might follow. As so often occurs, it was on an informal basis that information flowed best, and that much of the truth was discovered.

Board member Steven Wallace described the investigation not as a linear path but as a picture that gradually filled in. Or as a jigsaw puzzle. The search for debris began the first day, and soon swelled to include more than 25,000 people, at a cost of well over $300 million. NASA received 1,459 debris reports, including some from nearly every state in the union, and also from Canada, Jamaica, and the Bahamas. Discounting the geographic extremes, there was still a lot to follow up on. Though the amateur videos showed pieces separating from the shuttle along the entire path over the United States, and though search parties backtracked all the way to the Pacific coast in the hope of finding evidence of the breakup's triggering mechanism, the westernmost piece found on the ground was a left-wing tile that landed near a town called Littlefield, in the Texas Panhandle. Not surprisingly, the bulk of the wreckage lay under the main breakup, from south of Dallas eastward across the rugged, snake-infested brushland of East Texas and into Louisiana; and that is where most of the search took place. The best work was done on foot, by tough and dedicated crews who walked in tight lines across several thousand square miles. Their effort became something of a close sampling of the American landscape, turning up all sorts of odds and ends, including a few apparent murder victims, plenty of junked cars, and the occasional clandestine meth lab. More to the point, it also turned up crew remains and more than 84,000 pieces of the Columbia, which, at 84,900 pounds, accounted for 38 percent of the vehicle's dry weight. Certain pieces that had splashed into the murky waters of lakes and reservoirs were never found. It was presumed that most if not all the remaining pieces had been vaporized by the heat of re-entry, either before or after the breakup.

Some of the shuttle's contents survived intact. For instance, a vacuum cleaner still worked, as did some computers and printers and a Medtronic Tono-Pen, used to measure ocular pressure. A group of worms from one of the science experiments not only survived but continued to multiply. Most of the debris, however, was a twisted mess. The recovered pieces were meticulously plotted and tagged, and transported to a hangar at the Kennedy Space Center, where the wing remnants were laid out in correct position on the floor, and what had been found of the left wing's reinforced carbon-carbon (RCC) leading edge was reconstructed in a transparent Plexiglas mold—though with large gaps where pieces were missing. The hangar was a quiet, poignant, intensely focused place, with many of the same NASA technicians who had prepared the Columbia for flight now involved in the sad task of handling its ruins. The assembly and analysis went on through the spring. One of the principal caib agents there was an affable Air Force pilot named Patrick Goodman, an experienced accident investigator who had made both friends and enemies at NASA for the directness of his approach. When I first met him, outside the hangar on a typically warm and sunny Florida day, he explained some of the details that I had just seen on the inside—heat-eroded tiles, burned skin and structure, and aluminum slag that had emerged in molten form from inside the left wing, and had been deposited onto the aft rocket pods. The evidence was complicated because it resulted from combinations of heat, physical forces, and wildly varying airflows that had occurred before, during, and after the main-body breakup, but for Goodman it was beginning to read like a map. He had faith. He said, "We know what we have on the ground. It's the truth. The debris is the truth, if we can only figure out what it's saying. It's not a theoretical model. It exists." Equally important was the debris that did not exist, most significantly large parts of the left wing, including the lower part of a section of the RCC leading edge, a point known as Panel Eight, which was approximately where the launch cameras showed that the foam had hit. Goodman said, "We look at what we don't have. What we do have. What's on what we have. We start from there, and try to work backwards up the timeline, always trying to see the previous significant event." He called this "looking uphill." It was like a movie run in reverse, with the found pieces springing off the ground and flying upward to a point of reassembly above Dallas, and then the Columbia, looking nearly whole, flying tail-first toward California, picking up the Littlefield tile as it goes, and then higher again, through entry interface over the Pacific, through orbits flown in reverse, inverted but nose first, and then back down toward Earth, picking up the external tank and the solid rocket boosters during the descent, and settling tail-first with rockets roaring, until just before a vertical touchdown a spray of pulverized foam appears below, pulls together at the left-wing leading edge, and rises to lodge itself firmly on the side of the external tank.

The foam did it.

There was plenty of other evidence, too. After the accident the Air Force dug up routine radar surveillance tapes that upon close inspection showed a small object floating alongside the Columbia on the second day of its mission. The object slowly drifted away and disappeared from view. Subsequent testing of radar profiles and ballistic coefficients for a multitude of objects found a match for only one—a fragment of RCC panel of at least 140 square inches. The match never quite passed muster as proof, but investigators presumed that the object was a piece of the leading edge, that it had been shoved into the inside of the wing by the impact of the foam, and that during maneuvering in orbit it had floated free. The picture by now was rapidly filling in.

But the best evidence was numerical. It so happened that because the Columbia was the first of the operational shuttles, it was equipped with hundreds of additional engineering sensors that fed into an onboard data-collection device, a box known as a modular auxiliary data system, or mads recorder, that was normally used for postflight analysis of the vehicle's performance. During the initial debris search this box was not found, but such was its potential importance that after careful calculation of its likely ballistic path, another search was mounted, and on March 19 it was discovered—lying in full view on ground that had been gone over before. The really surprising thing was its condition. Though the recorder was not designed to be crash-proof, and used Mylar tape that was vulnerable to heat, it had survived the breakup and fall completely intact, as had the data that it contained, the most interesting of which pertained to heat rises and sequential sensor failures inside the left wing. When combined with the telemetric data that already existed, and with calculations of the size and location of the sort of hole that might have been punched through the leading edge by the foam, the new data allowed for a good fit with computational models of the theoretical airflow and heat propagation inside the left wing, and it steered the investigation to an inevitable conclusion that the breach must have been in the RCC at Panel Eight.

By early summer the picture was clear. Though strictly speaking the case was circumstantial, the evidence against the foam was so persuasive that there remained no reasonable doubt about the physical cause of the accident. As a result, Gehman gave serious consideration to NASA's request to call off a planned test of the launch incident, during which a piece of foam would be carefully fired at a fully rigged RCC Panel Eight. NASA's argument against the test had some merit: the leading-edge panels (forty-four per shuttle) are custom-made, $700,000 components, each one different from the others, and the testing would require the use of the last spare Panel Eight in the entire fleet. NASA said that it couldn't afford the waste, and Gehman was inclined to agree, precisely because he felt that breaking the panel would prove nothing that hadn't already been amply proved. By a twist of fate it was the sole NASA member of the caib, the quiet, cerebral, earnestly scientific Scott Hubbard, who insisted that the test proceed. Hubbard was one of the original seven board members. At the time of the accident he had just become the director of NASA's Ames Research Center, in California. Months later now, in the wake of Gehman's rebellion, and with the caib aggressively moving beyond the physical causes and into the organizational ones, he found himself in the tricky position of collaborating with a group that many of his own people at NASA saw as the enemy. Hubbard, however, had an almost childlike belief in doing the right thing, and having been given this unfortunate job, he was determined to see it through correctly. Owing to the closeness of his ties to NASA, he understood an aspect of the situation that others might have overlooked: despite overwhelming evidence to the contrary, many people at NASA continued stubbornly to believe that the foam strike on launch could not have caused the Columbia's destruction. Hubbard argued that if NASA was to have any chance of self-reform, these people would have to be confronted with reality, not in abstraction but in the most tangible way possible. Gehman found the argument convincing, and so the foam shot proceeded.

The work was done in San Antonio, using a compressed-nitrogen gun with a thirty-five-foot barrel, normally used to fire dead chickens—real and artificial—against aircraft structures in bird-strike certification tests. NASA approached the test kicking and screaming all the way, insisting, for instance, that the shot be used primarily to validate an earlier debris-strike model (the so-called Crater model of strikes against the underside tiles) that had been used for decision-making during the flight, and was now known to be irrelevant. Indeed, it was because of NASA obstructionism—and specifically the illogical insistence by some of the NASA rocket engineers that the chunk of foam that had hit the wing was significantly smaller (and therefore lighter) than the video and film record showed it to be—that the caib and Scott Hubbard finally took direct control of the testing. There was in fact a series of foam shots, increasingly realistic according to the evolving analysis of the actual strike, that raised the stakes from a glancing blow against the underside tiles to steeper-angle hits directly against leading-edge panels. The second to last shot was a 22-degree hit against the bottom of Panel Six: it produced some cracks and other damage deemed too small to explain the shuttle's loss. Afterward there was some smugness at NASA, and even Sean O'Keefe, who again was badly advised, weighed in on the matter, belittling the damage. But the shot against Panel Six was not yet the real thing. That was saved for the precious Panel Eight, in a test that was painstakingly designed to duplicate (conservatively) the actual impact against the Columbia's left wing, assuming a rotational "clocking angle" 30 degrees off vertical for the piece of foam. Among the engineers who gathered to watch were many of those still living in denial. The gun fired, and the foam hit the panel at a 25-degree relative angle at about 500 mph. Immediately afterward an audible gasp went through the crowd. The foam had knocked a hole in the RCC large enough to allow people to put their heads through. Hubbard told me that some of the NASA people were close to tears. Gehman had stayed away in order to avoid the appearance of gloating. He could not keep the satisfaction out of his voice, however, when later he said to me, "Their whole house of cards came falling down."

NASA's house was by then what this investigation was really all about. The caib discovered that on the morning of January 17, the day after the launch, the low-level engineers at the Kennedy Space Center whose job was to review the launch videos and film were immediately concerned by the size and speed of the foam that had struck the shuttle. As expected of them, they compiled the imagery and disseminated it by e-mail to various shuttle engineers and managers—most significantly those in charge of the shuttle program at the Johnson Space Center. Realizing that their blurred or otherwise inadequate pictures showed nothing of the damage that might have been inflicted, and anticipating the need for such information by others, the engineers at Kennedy then went outside normal channels and on their own initiative approached the Department of Defense with a request that secret military satellites or ground-based high-resolution cameras be used to photograph the shuttle in orbit. After a delay of several days for the back-channel request to get through, the Air Force proved glad to oblige, and made the first moves to honor the request. Such images would probably have shown a large hole in the left wing—but they were never taken.

When news of the foam strike arrived in Houston, it did not seem to be crucially important. Though foam was not supposed to shed from the external tank, and the shuttle was not designed to withstand its impacts, falling foam had plagued the shuttle from the start, and indeed had caused damage on most missions. The falling foam was usually popcorn sized, too small to cause more than superficial dents in the thermal protection tiles. The caib, however, discovered a history of more-serious cases. For example, in 1988 the shuttle Atlantis took a heavy hit, seen by the launch cameras eighty-five seconds into the climb, nearly the same point at which the Columbia strike occurred. On the second day of the Atlantis flight Houston asked the crew to inspect the vehicle's underside with a video camera on a robotic arm (which the Columbia did not have). The commander, Robert "Hoot" Gibson, told the caib that the belly looked as if it had been blasted with shotgun fire. The Atlantis returned safely anyway, but afterward was found to have lost an entire tile, exposing its bare metal belly to the re-entry heat. It was lucky that the damage had happened in a place where a heavy aluminum plate covered the skin, Gibson said, because otherwise the belly might have been burned through.

Nonetheless, over the years foam strikes had come to be seen within NASA as an "in-family" problem, so familiar that even the most serious episodes seemed unthreatening and mundane. Douglas Osheroff, a normally good-humored Stanford physicist and Nobel laureate who joined the caib late, went around for months in a state of incredulity and dismay at what he was learning about NASA's operational logic. He told me that the shuttle managers acted as if they thought the frequency of the foam strikes had somehow reduced the danger that the impacts posed. His point was not that the managers really believed this but that after more than a hundred successful flights they had come blithely to accept the risk. He said, "The excitement that only exists when there is danger was kind of gone—even though the danger was not gone." And frankly, organizational and bureaucratic concerns weighed more heavily on the managers' minds. The most pressing of those concerns were the new performance goals imposed by Sean O'Keefe, and a tight sequence of flights leading up to a drop-dead date of February 19, 2004, for the completion of the International Space Station's "core." O'Keefe had made it clear that meeting this deadline was a test, and that the very future of NASA's human space-flight program was on the line.

From Osheroff's scientific perspective, deadlines based on completion of the International Space Station were inherently absurd. To me he said, "And what would the next goal be after that? Maybe we should bring our pets up there! 'I wonder how a Saint Bernard urinates in zero gravity!' NASA sold the International Space Station to Congress as a great science center—but most scientists just don't agree with that. We're thirty years from being able to go to Mars. Meanwhile, the only reason to have man in space is to study man in space. You can do that stuff—okay—and there are also some biology experiments that are kind of fun. I think we are learning things. But I would question any statement that you can come up with better drugs in orbit than you can on the ground, or that sort of thing. The truth is, the International Space Station has become a huge liability for NASA"—expensive to build, expensive to fly, expensive to resupply. "Now members of Congress are talking about letting its orbit decay—just letting it fall into the ocean. And it does turn out that orbital decay is a very good thing, because it means that near space is a self-cleaning place. I mean, garbage does not stay up there forever."

In other words, completion of the Space Station could provide a measure of NASA's performance only in the most immediate and superficial manner, and it was therefore an inherently poor reason for shuttle managers to be ignoring the foam strikes and proceeding at full speed. It was here that you could see the limitations of leadership without vision, and the consequences of putting an executive like O'Keefe in charge of an organization that needed more than mere discipline. This, however, was hardly an argument that the managers could use, or even in private allow themselves to articulate. If the Space Station was unimportant —and perhaps even a mistake—then one had to question the reason for the shuttle's existence in the first place. Like O'Keefe and the astronauts and NASA itself, the managers were trapped by a circular space policy thirty years in the making, and they had no choice but to strive to meet the timelines directly ahead. As a result, after the most recent Atlantis launch, in October of 2002, during which a chunk of foam from a particularly troublesome part of the external tank, known as the "bipod ramp," had dented one of the solid rocket boosters, shuttle managers formally decided during the post-flight review not to classify the incident as an "in-flight anomaly." This was the first time that a serious bipod-ramp incident had escaped such a classification. The decision allowed the following two launches to proceed on schedule. The second of those launches was the Columbia's, on January 16.

The videos of the foam strike reached Houston the next day, January 17. They made it clear that again the offending material had come from the area of the bipod ramp, that this time the foam was larger than ever before, that the impact had occurred later in the climb (meaning at higher speed), and that the wing had been hit, though exactly where was not clear. The astronauts were happily in orbit now, and had apparently not felt the impact, or been able to distinguish it from the heavy vibrations of the solid rocket boosters. In other words, they were unaware of any trouble. Responsibility for disposing of the incident lay with engineers on the ground, and specifically with the Mission Management Team, or MMT, whose purpose was to make decisions about the problems and unscripted events that inevitably arose during any flight. The MMT was a high-level group. In the Houston hierarchy it operated above the flight controllers in the Mission Control room, and just below the shuttle program manager, Ron Dittemore. Dittemore was traveling at the time, and has since retired. The MMT meetings were chaired by his protégé, the once rising Linda Ham, who has come to embody NASA's arrogance and insularity in many observers' minds. Ham is the same hard-charging manager who, with a colleague, later had to be forcefully separated from the caib's investigation. Within the strangely neutered engineering world of the Johnson Space Center, she was an intimidating figure, a youngish, attractive woman given to wearing revealing clothes, yet also known for a tough and domineering management style. Among the lower ranks she had a reputation for brooking no nonsense and being a little hard to talk to. She was not smooth. She was a woman struggling upward in a man's world. She was said to have a difficult personality.

As the head of the MMT, Ham responded to news of the foam strike as if it were just another item to be efficiently handled and then checked off the list: a water leak in the science lab, a radio communication failure, a foam strike on the left wing, okay, no safety-of-flight issues here—right? What's next? There was a trace of vanity in the way she ran her shows. She seemed to revel in her own briskness, in her knowledge of the shuttle systems, in her use of acronyms and the strange, stilted syntax of aerospace engineers. She was decisive, and very sure of her sense for what was important and what was not. Her style got the best of her on day six of the mission, January 21, when at a recorded MMT meeting she spoke just a few words too many, much to her later regret.

It was at the end of a report given by a mid-ranking engineer named Don McCormack, who summarized the progress of an ad hoc engineering group, called the Debris Assessment Team, that had been formed at a still lower level to analyze the foam strike. The analysis was being done primarily by Boeing engineers, who had dusted off the soon to be notorious Crater model, primarily to predict damage to the underwing tile. McCormack reported that little was yet resolved, that the quality of the Crater as a predictor was being judged against the known damage on earlier flights, and that some work was being done to explore the options should the analysis conclude that the Columbia had been badly wounded. After a brief exchange Ham cut him short, saying, "And I'm really ... I don't think there is much we can do, so it's not really a factor during the flight, since there is not much we can do about it." She was making assumptions, of course, and they were later proved to be completely wrong, but primarily she was just being efficient, and moving the meeting along. After the accident, when the transcript and audiotapes emerged, those words were taken out of context, and used to portray Ham as a villainous and almost inhumanly callous person, which she certainly was not. In fact, she was married to an astronaut, and was as concerned as anyone about the safety of the shuttle crews. This was a dangerous business, and she knew it all too well. But like her boss, Ron Dittemore, with whom she discussed the Columbia foam strike several times, she was so immersed in the closed world of shuttle management that she simply did not elevate the event—this "in-family" thing—to the level of concerns requiring action. She was intellectually arrogant, perhaps, and as a manager she failed abysmally. But neither she nor the others of her rank had the slightest suspicion that the Columbia might actually go down.

The frustration is that some people on lower levels were actively worried about that possibility, and they understood clearly that not enough was known about the effects of the foam strike on the wing, but they expressed their concerns mostly to one another, and for good reason, because on the few occasions when they tried to alert the decision-makers, NASA's management system overwhelmed them and allowed none of them to be heard. The question now, of course, is why.

The caib's search for answers began long before the technical details were resolved, and it ultimately involved hundreds of interviews and 50,000 pages of transcripts. The manner in which those interviews were conducted became a contentious issue, and it was arguably Gehman's biggest mistake. As a military man, advised by military men on the board, he decided to conduct the interviews according to a military model of safety probes, in which individual fault is not formally assigned, and the interviews themselves are "privileged," meaning forever sealed off from public view. It was understood that identities and deeds would not be protected from view, only individual testimonies to the caib, but serious critics cried foul nonetheless, and pointed out correctly that Gehman was using loopholes to escape sunshine laws that otherwise would have applied. Gehman believed that treating the testimony as privileged was necessary to encourage witnesses to talk, and to get to the bottom of the story, but the long-term effect of the investigation will be diminished as a result (for instance, by lack of access to the raw material by outside analysts), and there was widespread consensus among the experienced (largely civilian) investigators actually conducting the interviews that the promise of privacy was having little effect on what people were willing to say. These were not criminals they were talking to, or careful lawyers. For the most part they were sincere engineering types who were concerned about what had gone wrong, and would have been willing even without privacy to speak their minds. The truth, in other words, would have come out even in the brightest of sunshine.

The story that emerged was a sad and unnecessary one, involving arrogance, insularity, and bad luck allowed to run unchecked. On the seventh day of the flight, January 22, just as the Air Force began to move on the Kennedy engineers' back-channel request for photographs, Linda Ham heard to her surprise that this approach (which according to front-channel procedures would have required her approval) had been made. She immediately telephoned other high-level managers in Houston to see if any of them wanted to issue a formal "requirement" for imagery, and when they informed her that they did not, rather than exploring the question with the Kennedy engineers she simply terminated their request with the Department of Defense. This appears to have been a purely bureaucratic reaction. A NASA liaison officer then e-mailed an apology to Air Force personnel, assuring them that the shuttle was in "excellent shape," and explaining that a foam strike was "something that has happened before and is not considered to be a major problem." The officer continued, "The one problem that this has identified is the need for some additional coordination within NASA to assure that when a request is made it is done through the official channels." Months later one of the caib investigators who had followed this trail was still seething with anger at what had occurred. He said, "Because the problem was not identified in the traditional way—'Houston, we have a problem!'—well, then, 'Houston, we don't have a problem!' Because Houston didn't identify the problem."

But another part of Houston was doing just that. Unbeknownst to Ham and the shuttle management, the low-level engineers of the Debris Assessment Team had concluded that the launch films were not clear enough to indicate where the foam had hit, and particularly whether it had hit the underside tile or a leading-edge RCC panel. Rather than trying to run their calculations in the blind, they had decided that they should do the simple thing and have someone take a look for damage. They had already e-mailed one query to the engineering department, about the possibility of getting the astronauts themselves to take a short spacewalk and inspect the wing. It later turned out that this would have been safe and easy to do. That e-mail, however, was never answered. This time the Debris Assessment engineers decided on a still simpler solution—to ask the Department of Defense to take some high-resolution pictures. Ignorant of the fact that the Kennedy group had already made such a request, and that it had just been peevishly canceled, they sent out two requests of their own, directed, appropriately, to Ron Dittemore and Linda Ham, but through channels that were a little off-center, and happened to fail. Those channels were ones they had used in their regular work as engineers, outside the formal shuttle-management structure. By unfortunate circumstance, the request that came closest to getting through was intercepted by a mid-level employee (the assistant to an intended recipient, who was on vacation) who responded by informing the Debris Assessment engineers, more or less correctly, that Linda Ham had decided against Air Force imagery.

The confusion was now total, yet also nearly invisible—and within the suppressive culture of the human space-flight program, it had very little chance of making itself known. At the top of the tangle, neither Ron Dittemore nor Linda Ham ever learned that the Debris Assessment Team wanted pictures; at the bottom, the Debris Assessment engineers heard the "no" without suspecting that it was not an answer to their request. They were told to go back to the Crater model and numerical analysis, and as earnest, hardworking engineers (hardly rebels, these), they dutifully complied, all the while regretting the blind assumptions that they would have to make. Given the obvious potential for a catastrophe, one might expect that they would have gone directly to Linda Ham, on foot if necessary, to make the argument in person for a spacewalk or high-resolution photos. However, such were the constraints within the Johnson Space Center that they never dared. They later said that had they made a fuss about the shuttle, they might have been singled out for ridicule. They feared for their standing, and their careers.

The caib investigator who asked the engineers what conclusion they had drawn at the time from management's refusal later said to me, "They all thought, 'Well, none of us have a security clearance high enough to view any of this imagery.' They talked about this openly among themselves, and they figured one of three things:

"'One: The "no" means that management's already got photos, and the damage isn't too bad. They can't show us the photos, because we don't have the security clearance, and they can't tell us they have the photos, or tell us the damage isn't bad, because that tells us how accurate the photos are—and we don't have the security clearance. But wait a minute, if that's the case, then what're we doing here? Why are we doing the analysis? So no, that can't be right.

"'Okay, then, two: They already took the photos, and the damage is so severe that there's no hope for recovery. Well ... that can't be right either, because in that case, why are we doing the analysis?

"'Okay, then, three: They took the photos. They can't tell us they took the photos, and the photos don't give us clear definition. So we need to do the analysis. That's gotta be it!'"

What the Debris Assessment engineers could not imagine is that no photos had been taken, or ever would be—and essentially for lack of curiosity by NASA's imperious, self-convinced managers. What those managers in turn could not imagine was that people in their own house might really be concerned. The communication gap had nothing to do with security clearances, and it was complete.

Gehman explained the underlying realities to me. He said, "They claim that the culture in Houston is a 'badgeless society,' meaning it doesn't matter what you have on your badge—you're concerned about shuttle safety together. Well, that's all nice, but the truth is that it does matter what badge you're wearing. Look, if you really do have an organization that has free communication and open doors and all that kind of stuff, it takes a special kind of management to make it work. And we just don't see that management here. Oh, they say all the right things. 'We have open doors and e-mails, and anybody who sees a problem can raise his hand, blow a whistle, and stop the whole process.' But then when you look at how it really works, it's an incestuous, hierarchical system, with invisible rankings and a very strict informal chain of command. They all know that. So even though they've got all the trappings of communication, you don't actually find communication. It's very complex. But if a person brings an issue up, what caste he's in makes all the difference. Now, again, NASA will deny this, but if you talk to people, if you really listen to people, all the time you hear 'Well, I was afraid to speak up.' Boy, it comes across loud and clear. You listen to the meetings: 'Anybody got anything to say?' There are thirty people in the room, and slam! There's nothing. We have plenty of witness statements saying, 'If I had spoken up, it would have been at the cost of my job.' And if you're in the engineering department, you're a nobody."

One of the caib investigators told me that he asked Linda Ham, "As a manager, how do you seek out dissenting opinions?"

According to him, she answered, "Well, when I hear about them ..."

He interrupted. "Linda, by their very nature you may not hear about them."

"Well, when somebody comes forward and tells me about them."

"But Linda, what techniques do you use to get them?"

He told me she had no answer.

This was certainly not the sort of risk-versus-risk decision-making that Michael Bloomfield had in mind when he described the thinking behind his own shuttle flights.

At 7:00 a.m. on the ninth day, January 24, which was one week before the Columbia's scheduled re-entry, the engineers from the Debris Assessment Team formally presented the results of their numerical analysis to Linda Ham's intermediary, Don McCormack. The room was so crowded with concerned observers that some people stood in the hall, peering in. The fundamental purpose of the meeting would have been better served had the engineers been able to project a photograph of a damaged wing onto the screen, but, tragically, that was not to be. Instead they projected a typically crude PowerPoint summary, based on the results from the Crater model, with which they attempted to explain a nuanced position: first, that if the tile had been damaged, it had probably endured well enough to allow the Columbia to come home; and second, that for lack of information they had needed to make assumptions to reach that conclusion, and that troubling unknowns therefore limited the meaning of the results. The latter message seems to have been lost. Indeed, this particular PowerPoint presentation became a case study for Edward Tufte, the brilliant communications specialist from Yale, who in a subsequent booklet, The Cognitive Style of PowerPoint, tore into it for its dampening effect on clear expression and thought. The caib later joined in, describing the widespread use of PowerPoint within NASA as one of the obstacles to internal communication, and criticizing the Debris Assessment presentation for mechanically underplaying the uncertainties that remained.

Had the uncertainties been more strongly expressed as the central factor in question, the need to inspect the wing by spacewalk or photograph might have become obvious even to the shuttle managers. Still, the Mission Management Team seemed unprepared to hear nuance. Fixated on potential tile damage as the relevant question, assuming without good evidence that the RCC panels were strong enough to withstand a foam strike, subtly skewing the discussion away from catastrophic burn-through and toward the potential effects on turnaround times on the ground and how that might affect the all-important launch schedule, the shuttle managers were convinced that they had the situation as they defined it firmly under control.

At a regularly scheduled MMT meeting later that morning McCormack summarized the PowerPoint presentation for Linda Ham. He said, "The analysis is not complete. There is one case yet that they wish to run, but kind of just jumping to the conclusion of all that, they do show that [there is], obviously, a potential for significant tile damage here, but thermal analysis does not indicate that there is potential for a burn-through. I mean, there could be localized heating damage. There is ... obviously there is a lot of uncertainty in all this in terms of the size of the debris and where it hit and the angle of incidence."

Ham answered, "No burn-through means no catastrophic damage. And the localized heating damage would mean a tile replacement?"

"Right, it would mean possible impacts to turnaround repairs and that sort of thing, but we do not see any kind of safety-of-flight issue here yet in anything that we've looked at."

This was all too accurate in itself. Ham said, "And no safety of flight, no issue for this mission, nothing that we're going to do different. There may be a turnaround [delay]."

McCormack said, "Right. It could potentially [have] hit the RCC ... We don't see any issue if it hit the RCC ..."

The discussion returned to the tiles. Ham consulted with a tile specialist named Calvin Schomburg, who for days had been energetically making a case independent of the Debris Assessment analysis that a damaged tile would endure re-entry—and thereby adding, unintentionally, to the distractions and false assumptions of the management team. After a brief exchange Ham cut off further discussion with a quick summary for some people participating in the meeting by conference call, who were having trouble hearing the speakerphone. She said, "So, no safety-of-flight kind of issue. It's more of a turnaround issue similar to what we've had on other flights. That's it? All right, any questions on that?"

And there were not.

For reasons unexplained, when the official minutes of the meeting were written up and distributed (having been signed off on by Ham), all mention of the foam strike was omitted. This was days before the Columbia's re-entry, and seems to indicate sheer lack of attention to this subject, rather than any sort of cover-up.

The truth is that Linda Ham was as much a victim of NASA as were Columbia's astronauts, who were still doing their science experiments then, and free-falling in splendor around the planet. Her predicament had roots that went way back, nearly to the time of Ham's birth, and it involved not only the culture of the human space-flight program but also the White House, Congress, and NASA leadership over the past thirty years. Gehman understood this fully, and as the investigation drew to a close, he vowed to avoid merely going after the people who had been standing close to the accident when it occurred. The person standing closest was, of course, Linda Ham, and she will bear a burden for her mismanagement. But by the time spring turned to summer, and the caib moved its operation from Houston to Washington, D.C., Gehman had taken to saying, "Complex systems fail in complex ways," and he was determined that the caib's report would document the full range of NASA's mistakes. It did, and in clean, frank prose, using linked sentences and no PowerPoint displays.

As the report was released, on August 26, Mars came closer to Earth than it had in 60,000 years. Gehman told me that he continued to believe in the importance of America's human space-flight effort, and even of the return of the shuttle to flight—at least until a replacement with a clearer mission can be built and put into service. It was a quiet day in Washington, with Congress in recess and the President on vacation. Aides were coming from Capitol Hill to pick up several hundred copies of the report and begin planning hearings for the fall. The White House was receiving the report too, though keeping a cautious distance, as had been expected; it was said that the President might read an executive summary. Down in Houston, board members were handing copies to the astronauts, the managers, and the families of the dead.

Gehman was dressed in a suit, as he had been at the start of all this, seven months before. It was up to him now to drive over to NASA headquarters, in the southwest corner of the city, and deliver the report personally to Sean O'Keefe. I went along for the ride, as did the board member Sheila Widnall, who was there to lend Gehman some moral support. The car was driven by a Navy officer in whites. At no point since the accident had anyone at NASA stepped forward to accept personal responsibility for contributing to this accident—not Linda Ham, not Ron Dittemore, and certainly not Sean O'Keefe. However, the report in Gehman's hands (248 pages, full color, well bound) made responsibility very clear. This was not going to be a social visit. Indeed, it turned out to be extraordinarily tense. Gehman and Widnall strode up the carpeted hallways in a phalanx of anxious, dark-suited NASA staffers, who swung open the doors in advance and followed close on their heels. O'Keefe's office suite was practically imperial in its expense and splendor. High officials stood in small, nervous groups, murmuring. After a short delay O'Keefe appeared—a tall, balding, gray-haired man with stooped shoulders. He shook hands and ushered Gehman and Widnall into the privacy of his inner office. Ten minutes later they emerged. There was a short ceremony for NASA cameras, during which O'Keefe thanked Gehman for his important contribution, and then it was time to leave. As we drove away, I asked Gehman how it had been in there with O'Keefe.

He said "Stiff. Very stiff."

We talked about the future. The report had made a series of recommendations for getting the shuttle back into flight, and beyond that for beginning NASA's long and necessary process of reform. I knew that Gehman, along with much of the board, had volunteered to Congress to return in a year, to peer in deeply again, and to try to judge if progress had been made. I asked him how genuine he thought such progress could be, and he managed somehow to express hope, though skeptically.

By January 23, the Columbia's eighth day in orbit, the crew had solved a couple of minor system problems, and after a half day off, during which no doubt some of the astronauts took the opportunity for some global sightseeing, they were proceeding on schedule with their laboratory duties, and were in good spirits and health. They had been told nothing of the foam strike. Down in Houston, the flight controllers at Mission Control were aware of it, and they knew that the previous day Linda Ham had canceled the request for Air Force photographs. Confident that the issue would be satisfactorily resolved by the shuttle managers, they decided nonetheless to inform the flight crew by e-mail—if only because certain reporters at the Florida launch site had heard of it, and might ask questions at an upcoming press conference, a Public Affairs Office, or PAO, event. The e-mail was written by one of the lead flight controllers, in the standard, overly upbeat style. It was addressed to the pilots, Rick Husband and William McCool.

Under the subject line "info: Possible PAO Event Question," it read,

> Rick and Willie,
>
> You guys are doing a fantastic job staying on the timeline and accomplishing great science. Keep up the good work and let us know if there is anything that we can do better from an MCC/POCC standpoint.
>
> There is one item that I would like to make you aware of for the upcoming PAO event ... This item is not even worth mentioning other than wanting to make sure that you are not surprised by it in a question from a reporter.

The e-mail then briefly explained what the launch pictures had shown—a hit from the bipod-ramp foam. A video clip was attached. The e-mail concluded,

> Experts have reviewed the high speed photography and there is no concern for RCC or tile damage. We have seen this same phenomenon on several other flights and there is absolutely no concern for entry. That is all for now. It's a pleasure working with you every day.

The e-mail's content honestly reflected what was believed on the ground, though in a repackaged and highly simplified form. There was no mention of the inadequate quality of the pictures, of the large size of the foam, of the ongoing analysis, or of Linda Ham's decision against Air Force imagery. This was typical for Mission Control communications, a small example of a long-standing pattern of something like information-hoarding that was instinctive and a matter as much of style as of intent: the astronauts had been told of the strike, but almost as if they were children who didn't need to be involved in the grown-up conversation. Two days later, when Rick Husband answered the e-mail, he wrote, "Thanks a million!" and "Thanks for the great work!" and after making a little joke, that "Main Wing" could sound like a Chinese name, he signed off with an e-mail smile—:). He made no mention of the foam strike at all. And with that, as we now know, the crew's last chance for survival faded away.

Linda Ham was wrong. Had the hole in the leading edge been seen, actions could have been taken to try to save the astronauts' lives. The first would have been simply to buy some time. Assuming a starting point on the fifth day of the flight, NASA engineers subsequently calculated that by requiring the crew to rest and sleep, the mission could have been extended to a full month, to February 15. During that time the Atlantis, which was already being prepared for a scheduled March 1 launch, could have been processed more quickly by ground crews working around the clock, and made ready to go by February 10. If all had proceeded perfectly, there would have been a five-day window in which to blast off, join up with the Columbia, and transfer the stranded astronauts one by one to safety, by means of tethered spacewalks. Such a rescue would not have been easy, and it would have involved the possibility of another fatal foam strike and the loss of two shuttles instead of one; but in the risk-versus-risk world of space flight, veterans like Mike Bloomfield would immediately have volunteered, and NASA would have bet the farm.

The fallback would have been a desperate measure—a jury-rigged repair performed by the Columbia astronauts themselves. It would have required two spacewalkers to fill the hole with a combination of heavy tools and metal scraps scavenged from the crew compartment, and to supplement that mass with an ice bag shaped to the wing's leading edge. In theory, if much of the payload had been jettisoned, and luck was with the crew, such a repair might perhaps have endured a modified re-entry and allowed the astronauts to bail out at the standard 30,000 feet. The engineers who came up with this plan realized that in reality it would have been extremely dangerous, and might well have led to a high-speed burn-through and the loss of the crew. But anything would have been better than attempting a normal re-entry as it was actually flown.

The blessing, if one can be found, is that the astronauts remained unaware until nearly the end. A home video shot on board and found in the wreckage documented the relaxed mood in the cockpit as the shuttle descended through the entry interface at 400,000 feet, at 7:44:09 Houston time, northwest of Hawaii. The astronauts were drinking water in anticipation of gravity's redistributive effect on their bodies. The Columbia was flying at the standard 40-degree nose-up angle, with its wings level, and still doing nearly 17,000 mph; outside, though the air was ultra-thin and dynamic pressures were very low, the aerodynamic surfaces were beginning to move in conjunction with the array of control jets, which were doing the main work of maintaining the shuttle's attitude, and would throughout the re-entry. The astronauts commented like sightseers as sheets of fiery plasma began to pass by the windows.

The pilot, McCool, said, "Do you see it over my shoulder now, Laurel?"

Sitting behind him, the mission specialist Laurel Clark said, "I was filming. It doesn't show up nearly as much as the back."

McCool said to the Israeli payload specialist, Ilan Ramon, "It's going pretty good now. Ilan, it's really neat—it's a bright orange-yellow out over the nose, all around the nose."

The commander, Husband, said, "Wait until you start seeing the swirl patterns out your left or right windows."

McCool said, "Wow."

Husband said, "Looks like a blast furnace."

A few seconds later they began to feel gravity. Husband said, "Let's see here ... look at that."

McCool answered, "Yup, we're getting some Gs." As if it were unusual, he said, "I let go of the card, and it falls." Their instruments showed that they were experiencing one hundredth of a G. McCool looked out the window again. He said, "This is amazing. It's really getting, uh, fairly bright out there."

Husband said, "Yup. Yeah, you definitely don't want to be outside now."

The flight engineer, Kalpana Chawla, answered sardonically, "What—like we did before?" The crew laughed.

Outside, the situation was worse than they imagined. Normally, as a shuttle streaks through the upper atmosphere it heats the air immediately around it to temperatures as high as 10,000¡, but largely because of the boundary layer—a sort of air cushion created by the leading edges—the actual surface temperatures are significantly lower, generally around 3,000¡, which the vehicle is designed to withstand, if barely. The hole in the Columbia's leading edge, however, had locally undermined the boundary layer, and was now letting in a plume of superheated air that was cutting through insulation and working its way toward the inner recesses of the left wing. It is estimated that the plume may have been as hot as 8,000¡ near the RCC breach. The aluminum support structures inside the wing had a melting point of 1,200¡, and they began to burn and give way.

The details of the left wing's failure are complex and technical, but the essentials are not difficult to understand. The wing was attacked by a snaking plume of hot gas, and eaten up from the inside. The consumption began when the shuttle was over the Pacific, and it grew worse over the United States. It included wire bundles leading from the sensors, which caused the data going into the MADS recorder and the telemetry going to Houston to fail in ways that only later made sense. At some point the plume blew right through the top of the left wing, and began to throw molten metal from the insides all over the aft rocket pods. At some point it burned its way into the left main gear well, but it did not explode the tires.

As drag increased on the left wing, the autopilot and combined flight-control systems at first easily compensated for the resulting tendency to roll and yaw to the left. By external appearance, therefore, the shuttle was doing its normal thing, banking first to the right and then to the left for the scheduled energy-management turns, and tracking perfectly down the descent profile for Florida. The speeds were good, the altitudes were good, and all systems were functioning correctly. From within the cockpit the ride appeared to be right.

By the time it got to Texas the Columbia had already proved itself a heroic flying machine, having endured for so long at hypersonic speeds with little left of the midsection inside its left wing, and the plume of hot gas still in there, alive, and eating it away. By now, however, the flight-control systems were nearing their limits. The breakup was associated with that. At 7:59:15 Mission Control noticed the sudden loss of tire pressure on the left gear as the damage rapidly progressed. This was followed by Houston's call "And Columbia, Houston, we see your tire-pressure messages, and we did not copy your last call," and at 7:59:32 by Columbia's final transmission, "Roger, ah, buh ..."

The Columbia was traveling at 12,738 mph, at 200,000 feet, and the dynamic pressures were building, with the wings "feeling" the air at about 170 mph. Now, suddenly, the bottom surface of the left wing began to cave upward into the interior void of melted and burned-through bracing and structure. As the curvature of the wing changed, the lift increased, causing the Columbia to want to roll violently to the right; at the same time, because of an increase in asymmetrical drag, it yawed violently to the left. The control systems went to their limits to maintain order, and all four right yaw jets on the tail fired simultaneously, but to no avail. At 8:00:19 the Columbia rolled over the top and went out of control.

The gyrations it followed were complex combinations of roll, yaw, and pitch, and looked something like an oscillating flat spin. They seem to have resulted in the vehicle's flying backwards. At one point the autopilot appears to have been switched off and then switched on again, as if Husband, an experienced test pilot, was trying to sort things out. The breakup lasted more than a minute. Not surprisingly, the left wing separated first. Afterward the tail, the right wing, and the main body came apart in what investigators later called a controlled sequence "right down the track." As had happened with the Challenger in 1986, the crew cabin broke off intact. It assumed a stable flying position, apparently nose high, and later disintegrated like a falling star across the East Texas sky.