

Knowing When to Stop: The Investigation of Flight 191

by

Mara E. Vatz

B.S. Electrical Engineering
Tufts University, 2003

B.A. Philosophy
Tufts University, 2003

SUBMITTED TO THE PROGRAM IN WRITING AND HUMANISTIC STUDIES IN
PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE IN SCIENCE WRITING
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

SEPTEMBER 2004

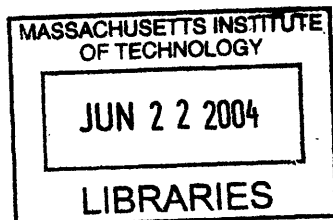
© 2004 Mara E. Vatz. All rights reserved.

The author hereby grants to MIT permission to reproduce
and to distribute publicly paper and electronic
copies of this thesis document in whole or in part.

Signature of Author: _____
Graduate Program in Science Writing
June 14, 2004

Certified by: _____
Marcia Bartusiak
Visiting Professor of Writing and Humanistic Studies
Thesis Advisor

Accepted by: _____
Robert Kanigel
Director, Graduate Program in Science Writing
Professor of Science Writing



ARCHIVES

Knowing When to Stop: The Investigation of Flight 191

by

Mara E. Vatz

Submitted to the Graduate Program in Science Writing
On June 14, 2004 in Partial Fulfillment of the
Requirements for the Degree of Master of Science in
Science Writing

ABSTRACT

On May 25, 1979, an American Airlines DC-10 crashed just after taking off from Chicago's O'Hare Airport. It was the worst crash in U.S. history at the time, having killed all 271 people on board and two people on the ground.

Arriving at the scene of a plane crash is akin to walking into a play during the third act: most of the story has already played itself out. The crash is the climax of a complex and nuanced plot with hundreds of characters and no clear beginning or end. Nevertheless, investigators from the National Transportation Safety Board are responsible for reconstructing the story from the evidence. They must study the characters and unearth the storyline and all of its twists and turns, and at the end determine the probable cause.

The NTSB spent six months investigating the crash of Flight 191. This is the story of how investigators pieced together the smoldering wreckage, wrestled with questions of personal error and accountability, dodged political and financial influences, and in the end put forth a list of safety recommendations based on the flaws they uncovered along the way.

The investigation of Flight 191 is one example of how investigators can take an otherwise hopeless situation and turn it into a platform for introspection and improvement.

Thesis Supervisor: Marcia Bartusiak

Title: Visiting Professor of Writing and Humanistic Studies

Knowing When To Stop: The Investigation of Flight 191

Just before midnight, in a field flooded with search lights, rescue workers and volunteers milled about. They sifted through wreckage and placed markers in the ground where bodies were found. Elwood Driver stood nearby, sipping coffee, taking in the disastrous scene before him. “I’m a pilot since I was 18,” he told *The Chicago Tribune*. “Forty years. This is the worst one I’ve seen.”

It was May 25, 1979, the Friday night of Memorial Day weekend. Fire trucks and ambulances lined the streets; helicopters circled above like hawks; two hundred and seventy-one people were dead. An American Airlines jumbo jet lay shattered in an abandoned airfield less than a mile from where it had taken off—its pieces still smoldering from the fire that erupted on impact. Driver, chairman of the National Transportation Safety Board (NTSB), was staring at the remains of what was, at that point, the worst plane crash in United States history.

Arriving at the scene of a plane crash is akin to walking into a play during the third act: most of the story has already played itself out. The crash is the climax of a complex and nuanced plot with hundreds of characters and no clear beginning or end. Nevertheless, NTSB investigators are responsible for reconstructing the story from the evidence. They must study the characters and unearth the storyline and all of its twists and turns. In short, for the next six months, Driver’s team of investigators would devote themselves to one question: What happened?

For the most part, society is willing to accept the risks of high-tech travel. The frequency of car accidents does little to discourage automobile travel. Bad drivers and poor driving conditions are an inescapable part of reality. But when hundreds of accidents are caused by faulty tires that peel apart at high speeds, people take notice. We are far less accepting of *preventable* risks.

As such, one of the critical questions an investigation seeks to answer is whether the crash was the result of a preventable risk. If so, investigators are faced with the more compelling task of determining how, exactly, the risk could have been averted: at what point in the chain of events leading up to the crash could someone, or something, have acted differently so as to eliminate the risk and avoid the crash? The answer is often unclear.

Peter Galison, a professor of history of science and physics at Harvard University, described how difficult it can be to separate human responsibility from technology in his article, “Accident of History.” He wrote, “It is *always* possible to trade human action for a technological one: failure to take notice can be swapped against a system failure to make noticeable. Conversely, every technological failure can be tracked back to the actions of those who designed, built, or used that piece of the material world...It is an unavoidable feature of our narratives about human technological systems that we are always faced with a contested ambiguity between human and material causation.”

This ambiguity is emblematic of any system that has levels of built-in checks and balances: when something does go wrong, it is often impossible to discern exactly who is deserving of the blame. When hundreds of people and decisions are involved, there often *isn’t* one person to blame.

And yet, we try not to let a little confusion stand in the way of reform. Because even if accountability isn’t clear—*especially* if accountability isn’t clear—then there is

likely a problem with the system that needs fixing. Whether that system is aircraft manufacturing and operation, failure testing of car tires, or national security, if it has inherent flaws that go unrecognized and unrepaired, then future failures are certain to arise.

We are in a race against time to understand and eliminate the risks that accompany new technologies before a disaster occurs. Tragically, it often takes an event to force the kind of honest introspection necessary for real improvement. In the aviation world, every crash mandates a certain level of introspection on the part of the airlines, the manufacturers, and the Federal Aviation Administration. Consequently, the industry has had to put into place a method, now well-tested, for managing its self-evaluation: an objective investigation conducted by the National Transportation Safety Board to determine the probable cause of the crash.

The NTSB does not assign blame. Its purpose during a crash investigation is to uncover the events that led to the tragedy and to do everything possible to prevent similar crashes from occurring down the line. The goal is to improve safety by improving the systems already in place. The investigation of Flight 191 is one example of how investigators can take an otherwise hopeless situation and turn it into a platform for introspection and improvement. We might do well, as a society preoccupied with high profile investigations like that of the shuttle Columbia tragedy or the post 9-11 hearings, to learn from the NTSB's example just how to handle the complexities of massive systematic failures and still come away from them with a better system in place.

American Airlines Flight 191 began its long-haul trip to Los Angeles without trouble, although delays at O'Hare had put it a few minutes behind schedule. It was a mild spring day, 63 degrees with clear skies. At 3:02:38 Chicago time, the control tower cleared American Airlines flight 191 for takeoff on runway 32R heading northwest. A few seconds later, Captain Lux confirmed, "Ah—American one ninety-one underway." That was the last communication Flight 191 had with the control tower.

As the plane accelerated down the runway, the cockpit voice recorder (CVR) picked up the voice of first officer James Dillard calling out the plane's speed as it passed through eighty knots. Everything sounded normal until just two seconds before lift-off, when the CVR recorded a thump, followed by the word "damn" one second later—the last recorded sound in the cockpit. A controller in the tower watched as the plane lifted off. What he saw was almost beyond words. He shouted to the other controllers in the tower, "Look at this—look at this—blew up an engine. Equipment—we need equipment. He blew an engine. Holy ____."

But the plane continued to gain altitude in what looked like a normal climb. The controller radioed to the captain, "American 191, you wanna come back and to what runway?" But there was no response. "He's not talking to me," the controller said. The plane began a shallow left turn. The turn got steeper and steeper—too steep. "He's gonna lose a wing," the controller said. "There he goes—there he goes." The plane, only 580 feet and 20 seconds into the air, began to dive and plunged to the ground.

The plane crashed into an old out-of-service airport field that had long since been overshadowed by O'Hare. The space was being used as K-9 training grounds and extended right up to the edge of a trailer park, where mobile homes lined a few loops of pre-planned streets. Just on the other side of the park stood several oil storage tanks—an

array of massive white cylinders with staircases winding around the outside that make the scale of the tanks look impossibly large. “If he’d kept going, he’d hit the oil tanks,” says Ken Miller, a man now in his fifties who has lived in the trailer park for over twenty-five years and today works in the park’s front office. “For miles around would’ve been devastated if he’d hit the oil tanks.”

Pieces of the shattered plane carved through some of the trailer homes and the fire on impact took the lives of two people on the ground. But the residents of the area still count themselves lucky. “He knew what he was doing,” says Miller. “Going down, he put it in the best place he could. We still credit that pilot.”

Miller was working in nearby Skokie at the time, and got a call from his boss who told him he’d better head home because there had been a plane crash. He says he could see the smoke from miles away. He rushed home to find that the streets were all blocked off. “There were nothing but fire trucks and hoses, everywhere,” he remembers. “The fuselage was out in the street over here,” he said, pointing through the window to the shady street that borders the old airfield.

The damage to the aircraft was extensive. “The air frame was, of course, severely broken up,” said investigator Henry C. Martinelli, a manager of aircraft systems engineering for American Airlines. Because the plane crashed with a full load of fuel, most of it was destroyed by the immense fire. The largest portions remaining were the engines, the landing gear and part of the tail. For weeks afterward, people sifted through the ashes, looking for parts and pieces of the airplane and for human remains. The whole area was under tight security, but even so, there were a few thefts. “There were some sick people,” Miller recalls. “One person parked on the toll way and walked over. He wanted to take something from one of the bodies, he wanted to take some lady’s ring. They caught some people trying to take pieces of the plane, but you know, they need every piece to put it all back together.”

The investigators didn’t have much to put back together; the damage to the plane was so complete. But they did have one major piece of the puzzle, a piece that hardly needed any putting together at all. Back on the runway, the left engine and pylon assembly (the structure that attaches the engine to the wing) was almost completely intact. And to many—though not to the NTSB—that was answer enough. Why did the plane crash? Because the engine fell off.

Of course, nothing is so simple. Like a child incessantly demanding to know “why?”, investigators are constantly searching for *causes*. In any investigation, answers along the way tend to open the door to more questions. The engine fell off, but why? Maybe it had pre-existing structural damage. If so, when, how, and why did the damage occur? It could have fallen off because of an explosion on board—terrorism or sabotage may have been involved. Again, who, when, why, and how?

Even these answers wouldn’t be enough. Understanding why the engine fell off was one thing, but figuring out why that caused the plane to crash was another. After all, DC-10s are designed to be flyable under catastrophic circumstances, even in the event of a complete engine loss. Why, then, couldn’t the pilots bring the plane back for an emergency landing? Maybe weather was a factor; or maybe the pilots were at fault. How experienced were they; were they well rested; what had they had to eat or drink the night before? All these questions and more needed to be addressed.

The investigation of Flight 191 very early on splintered into two clear but separate tracks. First, why did the engine fall off, and second, why did the loss of an engine cause the plane to crash? Behind every possible solution is at least one person—someone who caused, or more likely, failed to prevent a dangerous set of circumstances from arising. As Galison pointed out, it can be almost impossible to distinguish between human and technological actions. Investigators could go back and forth forever and trace the line of causation back through time ad nauseum. As it turned out, perhaps the most difficult part of conducting the investigation was knowing when to stop.

All major transportation systems—aviation, highway, railroad and marine—are under the scrutinizing eye of the National Transportation Safety Board. A relatively small government agency, the NTSB is called upon to investigate all major disasters and to make recommendations on how to improve overall safety. From its inception in 1967 (it is the successor of the Civil Aeronautic Authority), one of the driving philosophies has been to maintain independence from political and financial influences. For example, it is entirely independent from the Federal Aviation Administration (FAA), whose job it is to regulate and promote aviation. To an outsider, the distinction between the two agencies may seem subtle; but in the aviation world, they play very distinct roles. The NTSB makes all the recommendations; the FAA makes all the rules.

The culmination of an NTSB investigation is an accident report—a publication that can be hundreds of pages long—which states the pertinent facts, the probable cause, and the agency’s safety recommendations. “That’s really our payoff, and why we exist to begin with,” says Pamela Sullivan, a senior investigator for the North Central regional office in Chicago.

The NTSB is not responsible, or even interested, in assigning liability and blame. “Our purpose is to improve safety,” says Sullivan. “We look into these accidents to identify areas that can be changed or improved so the same kind of accident doesn’t occur twice.”

Assigning blame is left up to the courts. “We don’t make any money on the sale of the airplane. We don’t lose any money on the lawsuits after the crash,” says Robert MacIntosh, chief advisor of international safety affairs at the NTSB headquarters in Washington, DC. In fact, the NTSB’s accident report and probable cause are prohibited from being used as evidence in lawsuit, precisely so the investigation will not be influenced by financial pressure of multi-million dollar litigation.

The NTSB is among the first agencies to be notified of a crash. “We’re the first responders to the site,” says Sullivan. “We’ll get there whatever way we can,” she says, recalling that one of the investigators for Flight 191 had to ride to the site on the back of a fire engine because the traffic was so bad. “It’s an adventure.”

And time is of the essence. “With a major accident, you don’t want to lose any evidence,” she says. Even for smaller accidents, the arrival of the NTSB relieves local authorities of responsibility over a situation they often are not equipped to handle. “Especially in smaller communities, you’ll have some local sheriff who has *no* idea what to do with the airplane,” says Sullivan. “They’re very happy to see us arrive—someone who’s going to take control.”

The NTSB has ten regional offices around the country which handle the thousands of smaller incidents that arise each year. But for bigger crashes, the national

office steps in. It sends a “go team” of about fifteen people, who take over the reins from the regional investigators as soon as they arrive on the scene. The go team is always ready to rush to the site, “any way we can get there,” says Macintosh. “We bring assets and expertise that local groups don’t have.”

When investigators first arrive at the sight, the first concern is safety of the surrounding area. “The best way to describe it initially,” says Sullivan, “is *controlled chaos*. A lot of people trying to get organized, trying to do their jobs.” The NTSB is legally in charge of the site from the minute they arrive. “We give advice and instructions to the law enforcement as to how we’d like to handle things,” says Sullivan. “You do what you need to do to rescue the folks and don’t touch the rest. We always tell them to treat it like a crime scene, and they understand that.” Even after the fire is put out, the safety risks linger on. “There are some nasty things out there in the site,” says MacIntosh. “Dangerous things, from fuel and oil, biohazards from all that lavatory water and perhaps injured or deceased persons.”

As soon as possible, depending on the time of the accident, the investigators hold an organizational meeting to brief everyone on the rules of the investigation and to assign people to groups that will focus on particular areas of the investigation, such as the aircraft systems, human factors, or weather. “Not much happens until after that organizational meeting is conducted,” says Sullivan. The group members come from all disciplines within the aviation industry—air traffic control operators, pilots and engineers, to name a few. “The composition of the team is a unique thing that makes our investigation extremely thorough and rather broad in scope and that allows us to get deeply into each one of those areas,” says MacIntosh.

Investigators spend about a week’s worth of long, tiresome days out at the crash site. The schedule is grueling: wake up at 5 a.m., hold a meeting before breakfast, and be at the site by 7 a.m. Spend most of the day placing tags on identifiable parts of the plane and surveying the scene for anything unusual. “We try to get the Cockpit Voice Recorder and Flight Data Recorder”—the infamous black boxes—“and secure those and get them back to our lab at headquarters,” says Sullivan. There is a progress meeting every afternoon. “That’s where we gather and ask, ‘What more do we have to do? Where are we gonna take this thing?’” says MacIntosh. A separate informational meeting is held for the press and families of victims. The day doesn’t really end until 8 or 9 p.m., when the team sends a progress report back to headquarters.

“You don’t investigate the whole accident at the ‘hole’ or on the airfield,” says MacIntosh. More gets done back in the labs in Washington. That’s where the black boxes are analyzed, where investigators listen to the cockpit voice recorders, where the jagged pieces of metal are sent so metallurgists can determine which parts broke first. “Those people aren’t going to go to the site and tramp around in the wreckage, but they’re going to do their thing,” says MacIntosh.

Months of investigation culminate with a public hearing, open to visitors. Dozens of witnesses, from flight academy directors to metallurgists to mechanics who worked on the aircraft months earlier, are sworn in and questioned regarding the accident. The size of the public audience usually reflects the magnitude of the accident. Flight 191 was extremely high profile; the hearing, which took place over 10 days at a hotel near O’Hare later that summer, drew crowds.

Chairman Driver's opening statement reminded the attendees that the sole purpose of the hearing was to determine "the facts, conditions, and circumstances concerning this accident." He continued, "The inquiry is not being held for the purpose of determining the rights or liabilities of the private parties, and matters dealing with such rights will be excluded from these proceedings." Probable cause would be determined later, and so would the NTSB's recommendations. For now, Driver only wanted the facts.

The NTSB has no legal power to enforce their recommendations (that is FAA territory), but usually enforcement isn't necessary. Sullivan estimates that 80 percent of the recommendations are adopted voluntarily. "I think most are adopted because they are legitimate problems and reasonable solutions," she says. "People in the industry want to do the right thing. Nobody wants to design an airplane that fails... You don't want to be told, 'I told you so.'"

MacIntosh emphasizes that the product of the agency is to make transportation safer. "And if you look at the statistics over the past ten to fifteen years," he says, "it has improved, and a lot of its improvement is in engineering and training. We're flying more hours now, to more places, and have registered a lot less accidents," he notes. "We used to do fifteen to twenty major accidents a year. We used to have a transport plane smacking into a hill all the time. The advent of all the safety systems on the plane and safety maintenance procedures have really made the industry come a long way." The statistics prove his point. In 1984, there were over 3,000 accidents, resulting in more than 1,000 deaths. In 2003, those numbers had been cut almost in half.

"There is a great amount of satisfaction at the end of the day knowing that what you did made a difference," says Sullivan. It makes up for the trying lifestyle of the profession, both physically and emotionally. Sullivan speaks of the lack of stability that being an investigator leads to in her personal life, "Being on call and not having control over your life; not knowing where you're going or when you're coming back...It has gotten better now, but when you start missing holidays with your kids, and their birthdays...but then there's a lot of good sides of it that make you stay."

The investigators who arrived at the scene of Flight 191 had a long haul ahead of them. How could so many deaths and so much wreckage possibly lead to recommendations for safer travel? But before they could worry about how to prevent a repeat accident, before they could worry about when to stop asking questions, they had to figure out where to start. With no survivors and hardly any useful wreckage to work with, a natural starting point was to hear what the eye-witnesses had to say.

The witnesses told essentially the same story: the plane accelerated down the runway heading northwest, and everything seemed normal. But then, immediately after take-off, or maybe just before, (most likely during the plane's "rotation"—the few seconds of take-off when the nose lifts off the ground but the rear wheels are still rolling down the runway), the left engine broke free from the wing. It flipped up and over the wing and came to a skidding stop about three quarters of the way down the runway. The rest of the plane continued its take-off climb.

As eye-witness accounts are notoriously inaccurate, some of the details were inconsistent. One account said the engine burst into flames, but investigators later found no evidence of fire. What the witness probably saw was the engine "torching," an effect sometimes seen when an engine quickly burns off excess fuel but is not actually on fire.

Some reported seeing white smoke trailing from the wing, and one estimated that the airplane's takeoff speed was about 50 mph (which would have made it physically impossible for the plane to lift off the ground.) Some thought the plane rose to about 400 feet before beginning its fall, others thought only 200 feet.

But everyone agreed that within seconds of take off, the plane banked sharply to the left, more than 90 degrees, so the wings were practically perpendicular to the ground. Then the nose began to dive, almost as if the plane were entering a mid-air cartwheel. Being already so close to the ground, the plane crashed almost immediately. Some witnesses thought the pilots were struggling for control, others thought the pilots had control and miraculously avoided the adjacent trailer park, and still others described the plane as shaking—up and down, up and down—indicating no control at all.

Robert J. Graham, a supervisor of production control and aircraft maintenance for American Airlines, had perhaps the best vantage point. He was waiting to cross the runway in his van as Flight 191 accelerated towards him. He told the investigators what he saw: "As the aircraft got closer," he said, "I noticed what appeared to be vapor or smoke of some type coming from the leading edge of the wing and the No. 1 engine pylon. I noticed that the No. 1 engine was bouncing up and down quite a bit, and just about the time the aircraft got opposite my position and started rotation, the engine came off, went up over the top of the wing, and rolled back down onto the runway."

Before it went over the wing, he said, the engine went forward and up, "just as if it had lift and was actually climbing." It didn't strike the top of the wing on its way. Rather, it followed the clear path of the air flow of the wing, up and over the top of it, then down below the tail.

Graham continued to watch the plane as it climbed a "fairly normal climb, until it started a turn to the left. And at that point, I thought he was going to come back to the airport."

The most alarming aspect of the witness stories was that the engine fell off. An engine falling off was unsettling to everyone involved, to say the least. Driver told the *Chicago Tribune* that he had never heard of such a thing happening before. At the crash site, a reporter asked investigator Ed McAvoy, "Have you ever seen an engine fall off of a plane before?" McAvoy responded with a simple "No." "How long have you been doing this job?" the reporter asked. "Too long," said McAvoy.

"Engines don't drop off by themselves," says MacIntosh. Something had gone terribly wrong. The engine showed no evidence of fire damage, so an explosion was ruled out early on. The witnesses said that the engine breaking loose was the first sign of failure—that is, they didn't see anything hit the engine to make it fall off. Investigators searched the runway for other pieces of the plane that might have fallen off before the engine; they couldn't find anything. The failure must not have come from outside forces, but from within the pylon itself.

The fact that the engine fell off indicated a weakness somewhere in the pylon, says MacIntosh. Heads turned immediately to aircraft maintenance. Maybe a part was left out during a routine check-up, or maybe a piece had been manufactured incorrectly, "And that was their first thought," he says. The only time those areas are exposed is during maintenance; so maintenance quickly became a prime suspect.

The NTSB formed a separate committee to do a background check on the maintenance of Flight 191—hardly a simple task in a time when records were kept on paper, not computers. Investigators pored over thousands of pages of documentation that comprised Flight 191's nine-year maintenance history. They revisited every routine check-up, every filed complaint, and studied the DC-10's design and certification documents, looking for any signs of trouble or anything out of the ordinary. The group worked quickly and within a matter of days they found the smoking gun.

Two months before the crash, the accident aircraft had been at the American Airlines maintenance facility in Tulsa, Oklahoma for a routine check. During its two day stay, it also underwent a special procedure to replace spherical bearings, a procedure that involved removing the engine and pylon from the wing.

McDonnell Douglas had prescribed this operation a few years earlier in a Service Bulletin sent out to all DC-10 operators. Service bulletins are used to officially alert airlines of problems (big or small) with a plane and typically come with instructions on how to fix the problem. Unless the manufacturer specifies a time limit, airlines tend to wait until the airplane is in the shop for a maintenance overhaul to carry out a bulletin's procedure. As a result, it is not uncommon for non-critical bulletins to go unaddressed for months, or even years.

American Airlines began replacing spherical bearings on its planes in December of 1978. By that time, United and Continental Airlines had already completed their own replacements. The engineers at American Airlines had heard that the other airlines were removing the pylon and engine from the wing as a *single* unit, (instead of removing them one at a time, as McDonnell Douglas' instructions said to do), and decided to follow suit.

Removing the engine and pylon as a single unit seemed like a good idea at the time. For one thing, it saved almost 200 man hours of maintenance per aircraft. But more importantly, it seemed safer. Removing the two as a unit would reduce the number of disconnects (of hydraulic and fuel lines, or electrical cables, for example) from 79 to 27. The fewer the disconnects, the fewer the opportunities for damage or error.

But what the engineers at American Airlines who adopted and modified the new procedure didn't know was that Continental Airlines had, on two occasions, damaged a flange—an arched piece of metal that helps secure the rear part of the engine to the wing—while raising the engine and pylon as a unit back to the wing.

American wasn't alone in its ignorance. The FAA, which is supposed to be notified of major maintenance problems, didn't learn of Continental's damaged flanges until after the crash of Flight 191. It is up to the airlines to report major problems to the FAA; but it is also the airline's prerogative to decide what constitutes a major problem. As such, news of the damaged flanges slipped through the cracks.

The investigators were quick to pick it up. While the maintenance committee uncovered Continental's flange problem by searching through documents, a separate branch of investigators was homing in on the same story by searching through physical evidence.

The afternoon and morning following the crash, investigators combed the grass around the runway for bits and pieces of the airplane that fell off with the engine. They found just about every piece of the engine/pylon assembly, but it was a single bolt that got all the attention.

The bolt belonged to the thrust link assembly, the part of the pylon attachment that holds the engine in place under the enormous thrust forces experienced during takeoff. The bolt was cracked. This particular broken bolt, just one among hundreds of twisted, mangled shards of metal, was important to investigators because they thought that the way it was fractured showed signs of fatigue. They thought this bolt might have already been broken, or about to break, *before* the accident. It might even have been the first piece to break.

The notion of pre-existing damage sent waves of anxiety through the aviation community. Until the NTSB determined what had caused the damage, they had to assume the worst: that there was an inherent problem with the design of the airplane, and that this problem could be present on any or every DC-10 in service. They had to act fast.

The bolt was sent right away to a lab in Washington, D.C, where metallurgists would figure out how, when, and why it broke. In the meantime, the NTSB and FAA weren't taking any chances with the remaining 134 DC-10s in service in the United States. On Sunday night, the FAA issued the first of several Airworthiness Directives (legally binding orders, or commands). The Directive required every airline that operated DC-10s to inspect the thrust link assemblies, looking for evidence of damage similar to that on the accident aircraft. Until the inspections were completed and parts replaced as necessary, the planes were not allowed to fly.

On Monday, the stakes were raised when investigators found another piece of the Flight 191 aircraft that looked like it could have been damaged before the accident. The aft bulkhead flange had a 10-inch long fracture just below one of the points where the pylon attaches to the wing.

Now there were two pieces that could have triggered the massive structural failure: the bolt and the flange. Nobody could say for sure if the bolt had gone first, causing the flange to break, or if the flange broke first and in turn damaged the bolt. "We don't know which came first, the chicken or the egg," one investigator told the *Chicago Tribune*.

Either way, the FAA had to revise its inspection orders to take into account the latest findings. That night it issued the next Airworthiness Directive, this time asking inspectors to look for damage to the flanges as well as the bolt in the thrust link assembly. This Airworthiness Directive came with a stringent time limit: any plane that hadn't been inspected by Tuesday at 2 a.m. (Chicago time) would be grounded until further notice.

As of late Monday night, things were looking promising for the airlines. The results of the first inspections were rolling in and so far no problems had been found. "It appeared...that most of the inspections would be completed by that deadline and no major air service disruptions were expected," the *Tribune* wrote.

Everyone was in for a big surprise.

By Tuesday, news began to spread that some of the inspections had turned up problems on Northwest and United Airlines DC-10s. Once the airlines knew what to look for and where to look for it, cracks started showing up everywhere. By the end of the inspections, eight aircraft had been found to have overload cracks in the same area of the pylon that was damaged on the accident aircraft.

And two United Airlines mechanics had found a "wobbly" engine—an engine they could rock back and forth, fairly easily, by hand. "We removed the access panels and found cracks so big you could trip over them," one of the mechanics said at the time.

“Rivets were broken, fasteners were sheared. It gives you a funny feeling in the pit of your stomach to see the extent of that damage.” On the whole, though, broken parts were replaced and aircraft were returned to service in no time. The FAA approved the inspections and added a stipulation that the planes had to undergo rigorous inspections every 100 hours of flight or every 10 days (whichever came first). By Friday, one week after the crash, all but a handful of DC-10s were back in full service.

But not for long. The metallurgist’s report was in: the bolt cracked under extreme and sudden stress, not because of built up fatigue. The flange broke first. Then, on Monday, June 4, new cracks were found on two airplanes—airplanes that had passed inspections just a week earlier. This finding coincided with the maintenance committee’s discovery that several airlines could have caused damage to the flanges during maintenance by removing the engine and pylon as a single unit. There was a simple and obvious correlation: some of the planes that turned up with cracks during the inspections a week before had also had their engines and pylons removed as a single unit during maintenance, months earlier. Investigators thought for a while the two new cracks were caused by maintenance, and had simply been overlooked in the first round of inspections. But by Tuesday night, investigators weren’t certain. They suspected that the latest cracks might have developed in the 100 hours since the last inspection—not during maintenance. Simply put, everyone was confused.

“At a certain point in time, we felt confident that we knew what was causing the cracks,” FAA official Melvin Beard recalled at the hearing later that summer. “We had seen some of them, looked at some of them in detail, and we felt confident that we could find any crack, or that we were going to find any crack,” he continued. “It was when two additional cracks were found on aircraft that reportedly had been inspected previously that our certitude...waned.”

“I honestly felt at 6 p.m. Tuesday that we had it firmly under control for the first time,” Charles Foster, associate administrator for aviation standards, told the *Washington Post*. But five hours later, with a little more information, he was a lot less certain. Langhorne Bond, administrator of the FAA, spoke to Foster later that night on the phone. Bond’s spokesman told the *Washington Post* about the conversations: “Foster was saying, ‘Jesus Christ, we can’t go into court now and say we have this under control. It would be perjury.’”

Bond didn’t sit by idly. In the interest of public safety, drastic measures had to be taken—measures the NTSB didn’t have the authority to take. Langhorne Bond stepped up to the plate and hit one out of the park: on Wednesday, June 6, the FAA grounded all U.S.-operated DC-10s indefinitely.

The FAA suspended the DC-10’s type certificate, the equivalent of having your driver’s license, passport, and birth certificate invalidated, thereby making it illegal to fly the aircraft under any circumstances. Grounding a fleet of airplanes is a last resort for the FAA. The agency’s mission is to promote and encourage aviation; so by taking dozens of aircraft out of service, Bond was jeopardizing the very industry his job was meant to protect. That conflict of interest had weighed heavily on his decision, but until investigators could get a handle on the situation, he hardly had a choice.

In the following weeks of early summer, the country’s DC-10s stood with their wheels planted firmly on the ground; airlines scrambled to rearrange flight schedules

around the immobilized fleet; and investigators took a closer look at American Airlines maintenance.

The practice of removing the pylon and engine as a unit was immediately prohibited, and investigators closed in on the Tulsa maintenance facility for a discriminating look at the rest of the steps in the procedure. As it turned out, removing the engine and pylon as a unit was only the beginning of the problems.

Back in 1978, when mechanics were carrying out the service bulletin on the first planes, they ran into some trouble while removing the engine and pylon. When they removed the bolts and bearings in the order that the manufacturer's manual instructed them to, the last few were really difficult to get out. The simple solution—to change the order in which they removed the bolts and bearings—was put into effect without consulting McDonnell Douglas or the FAA. The maintenance engineers at American Airlines didn't think changing the order of the steps was a significant deviation.

In fact, it was not uncommon to deviate slightly from the manufacturer's manual. At the hearing, American Airlines vice president of engineering William P. Hannan explained that, "In many of the cases you can't really do it the way the manufacturer has written a procedure. They are required at the beginning to write literally thousands of procedures based on the knowledge they have at that time. So if you get into a part of the airplane, deep into the airplane fairly early, a procedure may not cover that, or it may be based on how the airplane is put together, not what you do in service."

The investigators didn't share the mechanics' nonchalant approach to procedural changes. They studied the metal stress that could arise from removing the bolts and bearings in the wrong order, and found that under some circumstances, removing the connections the way American Airlines did could cause the flange to bear some of the weight of the engine and pylon assembly that it wasn't designed to bear. The result could be a fatigue crack similar to that found on Flight 191.

The investigators didn't stop there. They stayed in Tulsa, looking at every step of the procedure, and found more deviations. "I recall talking to some of the investigation team after I joined the Safety Board in 1988 about the procedural things that they pursued in the process of the investigation," says MacIntosh, who was the Investigator In Charge of the famous 1989 DC-10 crash in Sioux City, in which the pilots miraculously landed the plane after all three hydraulic systems had been destroyed in flight—at about 30,000 feet. "We discussed how they visited the American Airlines maintenance facility and went through step by step the engine change procedures that were being used and how they were, let me find the right word here, they were 'surprised' with the use of an industrial fork lift in the process rather than the traditional engine change cradle or lifting devices." The investigators didn't think the forklift was adequate for the job. Some of the mechanics agreed that that the forklift was difficult to operate. "The down movement wasn't correct on [the forklift]," one of the mechanics testified at the hearing. "When you would move the lever to the down position, there seemed to be a spot or an area in there where the forklift would come down and it wasn't smooth when it would first start."

Not only was it hard to operate, but the particular forklift used for Flight 191 happened to have run out of gas in the middle of the procedure, and that particular model forklift, when it runs out of gas, has the tendency to drift downward a matter of inches every hour. An unintended downward drift like that could have caused the flange to bear

some of the weight of the engine and pylon assembly that it was not meant to bear, and so could have been responsible for the crack in the flange.

Investigators could not determine for sure what had caused the crack in the flange—whether it was removing the engine and pylon as a unit, or changing the order in which the bolts and bearings were removed, or if it was using the forklift instead of the engine cradle to support the assembly. But what they did determine, more importantly, was that communications among maintenance crews, manufacturers and the FAA were unsound.

The mentality of the maintenance workers' culture baffled the safety board. What appeared to investigators as a flagrant deviation from procedure was, to the maintenance workers, a somewhat casual decision. The idea that crew workers were making changes to manufacturer's instructions concerned investigators, while maintenance crews shrugged it off as just part of the job. "We use a lot of common sense in this industry," one of them said at the hearing.

But it was more than just the mechanics' attitudes that troubled investigators; it was that the system of keeping maintenance records allowed major and minor errors to go unnoticed. Also, the way the crews signed the work cards made it almost impossible to determine exactly who had completed what job. Jobs that required only one person to do them had three signatures on the card. "The crew just normally signs together," one maintenance worker said at the hearing.

The crash investigation, while revealing flaws in the mechanics of the aircraft, also opened the doors to criticism of the FAA's organization and policies and cast a shadow over McDonnell Douglas. People started to wonder why the manufacturer and the FAA hadn't known about the faulty maintenance procedures. The FAA began to fall out of favor across the board. Passengers and airlines were concerned that the FAA wasn't giving airline maintenance enough attention, while McDonnell Douglas, on the other hand, felt that the FAA was overreacting, or over compensating, by grounding the DC-10 fleet. The European equivalent of the FAA, which had followed suit in grounding its DC-10s, decided a few weeks later to un-ground its planes, challenging the unspoken authority of the FAA and further adding to public's distrust of the agency.

McDonnell Douglas suffered from similar public distrust. The DC-10 already had a tarnished safety record—in 1974, a plane crashed near Paris after a rear cargo door blew off the plane. The immediate loss of pressure caused the cabin floor to collapse, which in turn severed the control lines running to the tail. The crash killed all 345 people on board. Just one year earlier, in a similar accident, a cargo door came off of an American Airlines flight over Windsor, Ontario, but the pilots managed to land that plane. After the investigations determined the cargo door design was inadequate, McDonnell Douglas redesigned the doors and issued a Service Bulletin requiring airlines to adopt the changes. But the FAA did not issue even a single Airworthiness Directive—which always draws negative media attention to the manufacturer—in response to these two incidents.

Flight 191, on the other hand, resulted in three Airworthiness Directives and a 38-day grounding of the fleet. Passengers became wary of DC-10s, and airlines slowed or canceled their orders for new planes. In time, passenger skepticism subsided, but the damage was already done. Two years after the crash, *The New York Times* reported that the repercussions of Flight 191 had "stopped the sales momentum of the DC-10 and, in

part, prevented McDonnell Douglas from aggressively developing a new generation of planes,” which some argue was one of the main reasons the company fell behind its competitors in the 1980s. Throughout the 1990s, McDonnell Douglas designed aircraft for the military and upgraded the DC-9 and DC-10, but still did not develop any newly conceived commercial aircraft. In 1998, the company merged with its long-time competitor, Boeing.

Just two months after the crash of Flight 191, investigators had narrowed the search down to three main maintenance flaws and had opened the floodgates to countless procedural deficiencies. But even then, the investigation was far from over. The question of why the plane couldn't fly without an engine remained to be answered.

At approximately 3 p.m. on May 25, Flight 191 rounded the corner onto the runway and laid on the throttle. The leading edge slats were extended for takeoff, giving the wings a little extra curvature, which in turn gives them a little extra lift. As air flows over and under the plane's wings, it travels faster over the top of the wing than the bottom—because the top is curved more than the bottom, and so the distance over it is farther. The faster traveling air has a lower pressure than the slower air underneath the wing. As a result, there is a net force upwards on the wings. This phenomenon is called “lift.”

Pilots prefer to take off “into the wind”—that is, going against the wind. The faster the plane is going relative to the air around it, the more lift it will have. Take-off speeds are typically measured in “knots of indicated airspeed” (KIAS)—that is, how fast the plane is moving relative to the air around it, because the amount of lift a plane has depends on its speed relative to the air, not the ground. Taking-off into the wind allows the air to travel fast over the wing without the plane having to build up as much ground speed.

From the outside, the trip down the runway looks simple: Go fast enough, get enough lift, and the plane will take off. But inside the cockpit there's a lot more going on. Before the plane even begins to taxi out to the runway, the pilots must calculate the take-off speed based on the weight of the aircraft, runway length and wind speed and direction. There are a few different “take-off speeds.” First, there is the speed at which a plane *can* become airborne, if all the engines have power and if the pilots choose to lift off. That is what pilots call “V-1.” If an engine fails before the plane gets to V-1, the pilots can theoretically abort the take-off and bring the plane to a safe and controlled landing before reaching the end of the runway. In fact, in this situation, pilot manuals require that he do so.

But if an engine fails after the plane reaches V-1, there won't be enough room left on the runway to safely stop the plane, so the pilot is required to continue with the take-off. But, if this happens, he will most likely circle around and return for an emergency landing.

Even though a plane is capable of becoming airborne after it passes through V-1, there is another speed marker which must be met before the pilots are allowed to initiate takeoff: V-2. If an engine fails some time after V-1 but before V-2, not only does the plane not have enough room to stop on the runway, but it doesn't have enough speed to render the control surfaces (the rudder, the ailerons, for example) strong enough to control the yawing motion, or twisting of the plane, that would occur because of the

sudden loss of power in one engine. So, the pilots must wait until the plane reaches V-2 before leaving the ground. And typically, they won't take-off until the plane passes through a third speed, "V-R" (R for rotation), that allows for some margin of error.

Flight 191 made it to V-R without any trouble. But as the plane began its rotation, the flange in the left wing finally gave way, and then a bolt cracked, leaving the engine and pylon hanging onto the wing as if by a thread at only two other attachment points. Under the extreme force of the engine's take-off thrust, the remaining attachments didn't have a chance of holding on.

Bolts began breaking, and the engine and pylon separated completely from the wing, flew up and over it and destroyed a portion of the leading edge of the wing, severing the hydraulic lines, electrical wires and slat followup cables along the way.

Having already long passed V-1, the pilots were committed to taking off, even though they had literally lost an engine. To complicate matters, the pilots probably had no idea that the engine had fallen off. There is no clear view from the cockpit to the part of the wings from which the engines hang. In fact, most of the fuselage and wings are in a massive blind spot.

But that shouldn't have mattered. The DC-10 was designed to be flyable even in the event that an engine falls off a wing. But when the engine fell off of Flight 191, it also damaged a number of critical systems along the way.

One of those systems was the hydraulics. Hydraulic systems in airplanes, like power steering in a car, make it easy to move very large components of the plane from a joystick, or yoke, in the cockpit. Whereas older planes use a system of cables and pulleys to translate the movement of a yoke, newer planes use hydraulics. The important control surfaces are all hydraulically powered: the rudder, which is on the tail and controls the heading angle; the elevators, which also reside on the tail and can force the nose of the plane to point up or down; the ailerons, or flaps that reside on top of the wing surface and control the bank angle by stopping the airflow over a wing and forcing it down; and the slats, the wing extensions that give the wings more curvature and therefore more lift, for takeoff and landing.

A DC-10 has three hydraulic systems. If any one hydraulic system fails, the other two are strong enough to manage the controls themselves. And in many cases, when one system fails, the other two can isolate the failure and share hydraulic pressure with the rest of the failed system. Ideally, critical redundant systems (systems that are essential for flight, like electric or hydraulic lines) are not placed right next to each other. Instead, they are separated by some amount of space within the aircraft. The idea is that a single catastrophic event should not be able to damage a primary system *and* its backups in one fell swoop.

But when the engine separated from Flight 191, it destroyed more than one hydraulic line in the wing—lines that ran practically alongside each other due to space constraints. There was no way to regain hydraulic pressure. The No. 1 hydraulic lines began to bleed like severed veins. And as hydraulic pressure was lost, the leading edge slats on the left wing slowly began to retract, because now there was less and less pressure holding them extended and the force of the oncoming air pressure was pushing them back in.

Meanwhile, the rest of the plane still had its hydraulic pressure. The slats on the right wing remained extended and caused a dangerous asymmetry. The right wing, with

its slats extended, had plenty of lift; the left wing did not. Without its slats extended, the left wing didn't have enough lift to keep flying, and it stalled. Consequently, the plane entered a left turn, just as a car would if the brakes were suddenly applied to the wheels on only the driver's side. As the plane turned, it stopped climbing and began its descent, only twenty seconds after takeoff.

In most cases, entering a stall should not cause a plane to crash. After all, paper airplanes stall and recover on their own all the time. The familiar flight pattern of swooping up to a dead stop then entering a sharp dive that is so distinctive of paper airplanes is nothing more than a series of stalls and recoveries. Commercial jets will perform much the same way—although a little guidance from the pilots always helps. The procedure for recovering from a stall is second nature to any commercial pilot: increase engine power and point the nose down. Get going fast enough and you'll be flying again.

Amateur pilots commonly and sometimes fatally err by pulling back on the yoke when the plane stalls and enters its natural dive, as planes are designed to do. A plane's natural tendency to enter a dive during a stall is intentionally enhanced by the manufacturers who make sure that a plane's center of gravity is slightly forward of the middle of the plane. But by pulling back on the yoke, an amateur pilot trying in vain to counter the dive would actually just be slowing the plane down. If the plane slows down, it won't regain enough speed to regain lift and start flying again, and as such, won't ever recover from the stall. The correct response to a stall, counterintuitive though it may seem, is to push forward on the yoke and encourage the plane to dive at its top speed until it can be brought under control again.

Another trick to recovering from a stall is to make sure that it doesn't happen in the first place. According to Walter Estridge, the Director of American Airlines flight academy at the time of the Flight 191 crash, "Our primary methodology and training on stall recover is to, number one, avoid the condition, recognize a situation which may lead to a stall situation, and avoid getting there. That is the first and most primary. The next thing would be the next recognition cue that one gets indicating a stall. Then the stall recover procedure would be executed."

If it does happen that a pilot finds himself entering a stall, it helps if he is already at a high enough altitude that pointing the nose down won't immediately drive the plane into the ground. A few thousand feet above ground level would make most pilots nervous. When Flight 191 stalled, it was only 400 feet off the ground. If the pilots had tried to recover from the stall by entering a dive to gain speed, the result would have been the same: immediate impact with the ground. The only option the pilots had to recover from the stall was to increase the power in the remaining engines and hope that that would get the plane flying fast enough to regain lift on the left wing.

But the pilots didn't increase the power in the other engines. They *decreased* power and pitched the plane up. They were following the procedure for an engine loss—that is, the loss of power in an engine, not the *physical* loss of an engine. Power loss in an engine is hardly a rare event. "Engine failures happen on a regular (but unscheduled) basis," says MacIntosh. "But aircraft are brought to the ground by skilled airmen. If you've ever had a car engine go out while you're driving, and you have to steer it back to the curb, it's about three times heavier when the power steering goes out. But people don't just lose control of the vehicle when that happens." Said NTSB investigator

McAvoy at the time of the crash, “He could have flown the thing all the way to LA. The problem was not the engines; it was a low altitude. He was at such a low altitude that he did not have time to take corrective action.”

When an engine does lose power, a series of automatic events occur. First, the other engine or engines kick into overdrive. Normally, for take-off, the power settings of the engines (N1) is about 80 percent of their full capability. But when one engine loses power, the others compensate and reach levels above 100 percent—the equivalent of a car’s tachometer venturing into that forbidden red zone. In the cockpit, the pilot or first officer will see the power meter for one engine drop to zero while the others flare up. He’ll also hear a chirping sound and see a warning light indicated the loss of power in an engine. Whichever person is not handling the controls at the moment calls “engine out” and names the engine which has lost power. The pilot handling the controls is supposed to slow the plane down, and, if the plane is still climbing in altitude right after take-off, he is supposed to level out the climb angle. If the pilot were to keep flying at top speed, the other engines would be quickly overworked and damaged. So the pilots of Flight 191, knowing for sure that they had lost power in the No. 1 engine, but not knowing for sure much else, slowed the plane down.

In a bizarre and unfortunate twist of fate, the damage caused by the engine/pylon separation disabled some, but not all, of the cockpit warnings and indicators. The “engine out” warning light worked just fine. But the stall warning didn’t work at all. Neither did the slat disagreement warning. So, while the plane was slowing down and entering an asymmetric-stall induced left turn, the only information the pilots had access to told them they were dealing with an engine failure and a little turbulence.

Estridge described the situation in the cockpit as “extremely difficult, if not impossible,” to assess in the time period that the crew of Flight 191 were faced with. At the hearing, when asked whether under those chaotic conditions the pilots acted as they were trained to do, he answered simply: “I was extremely proud.”

It was difficult to figure out exactly what the pilots knew and didn’t know in the 31 seconds of flight. It was impossible from the wreckage to tell whether they had tried to move the ailerons to counter the left turn, or moved the elevator to keep the nose from diving into the ground. The flight simulator tests at least showed investigators what *could* have been done. When pilots were thoroughly briefed on the details of Flight 191, they were able to bring the plane under control in the simulators. But when they went into the simulation with no background information, they acted exactly as the pilots of Flight 191 did, and the simulation ended in a nearly identical crash. As far as finding out what really happened in the cockpit, investigators had to tap into the next source of evidence: the black box.

The black box always gets a lot of media attention. It is the one piece of the plane that is designed to hold all the information concerning what went on in the plane’s final moments. Actually, there are two black boxes, and they aren’t black at all—they are painted fluorescent orange to make them easy to find and recover amidst wreckage. One of the boxes is the cockpit voice recorder (CVR), which records everything heard in the cockpit, and the other is the digital flight data recorder (DFDR) which, in 1979, recorded only a handful of flight parameters such as engine thrust, pitch angle, and attitude. It also recorded the pilot’s actions (for instance, whether he tried to move the ailerons) and it

records how much the ailerons actually moved as a result. In some cases, the black boxes are never recovered, or are too damaged to be of any use to the investigation. But in the case of Flight 191, the boxes were recovered, and with the help of corroborating evidence, investigators were able to glean a fairly accurate profile of the flight.

The CVR had almost no information on the tape. The box itself wasn't terribly damaged, but when the engine and pylon tore through some of the plane's electric lines, the CVR lost power and stopped recording. The last sound was a thump, followed by the word "damn," just one second before takeoff. Investigators were never able to hear what the pilots said during the next 31 seconds of flight; they were never able to figure out how much the pilots knew as the plane was going down.

Nevertheless, the CVR was of some use to the investigation. The fact that it lost power clued investigators in to the electrical situation in the cockpit. If the CVR lost power, then everything else on that circuit must have also lost power. That bit of information was the starting point to figuring out exactly what was and was not working in the cockpit during the flight.

First, investigators had to learn all about the DC-10s wiring. The complexity of the drawings and descriptions of the electrical system is magnificent. "It's not like a DC-3 wiring system," said Serge Clayton, the principal staff engineer in electrical design at McDonnell Douglas, during the hearing. "It is a little more involved...I think I could line up those books on the table for you, but you would need a pretty good-sized table."

Very simply put, there are three electrical systems on a DC-10, each powered by one of the three engines. There are also some back-up and air powered generators, one of which is a 30-minute power supply for the captain's instruments, essential communication instruments, and navigation equipment. But the backup power source doesn't automatically kick in. It must be manually activated by the flick of a switch on the pilot's overhead panel.

The redundancy in the electrical system is impressive. In addition to having three separately powered systems, there are layers of protective circuitry that automatically isolate problems so they don't spread and damage the rest of the system. The isolation mechanism works just like a circuit breaker in the basement of a house: when one circuit in the house gets overloaded (maybe because someone is using the toaster and the hairdryer at the same time), the circuit breaker cuts off the current supply to that part of the house. That ensures that the wires running through the walls don't get overheated and overloaded with current; it ensures that they don't catch fire.

In an airplane, it is essential to protect the electrical components from being damaged. If a current surge is detected in a generator, for example, the electrical system will engage a "lockout mechanism"—one of the layers of protective circuitry—to protect the rest of the airplane's wiring from damage. The lockout mechanism isolates the faulty generator and all of its wiring from the rest of the system. Any components that were supposed to be powered by the generator lose power as a result, but the rest of the electrical system continues to function as if nothing went wrong.

When the engine fell off Flight 191, the electrical system went haywire. "When the separation took place, of course the wiring just literally massively failed," said Clayton. First, the loss of the engine meant the loss of the generator that the engine had powered. In addition, when the engine tore free, it ripped through electrical wires in the wing. "The way those generator feeders had been cut...it appeared as though someone

had taken a big ax and just cut them in two,” said Clayton. The result was disastrous. The lockout mechanism went into effect, as it was designed to do, to protect the rest of the airplane’s wiring. But because it isolated the No. 1 system, a number of the aircraft’s systems and instruments immediately lost power. Among these systems were the captain’s flight instruments, the left stall warning computer, the stickshaker motor (which causes the yoke to physically shake when the plane is entering a stall, so the pilot, whose hands are always on the yoke, cannot help but notice the warning), and the slat disagree warning light system. Portions of the DFDR sensors and the CVR were also disabled.

The lockout mechanism on Flight 191 could have been unlocked. Power could have been restored to some of the cockpit instruments. But the pilots, in their urgency to regain control of the plane, were most likely too preoccupied to take that action fast enough. If the pilots had unlocked the mechanism, they would have restored power to the captain’s flight instruments as well as some of the engine instruments—and perhaps had enough information to understand the problem and recover from the stall. There was a flight engineer in the cockpit who would have had his hands free and could have flicked the switch to restore power, but in take-off position, the flight engineer cannot reach the panel. According to the accident report, “He must reposition his seat to face his panel, release his safety belt, and get out of his seat to reach the switches.”

Investigators were able to learn more about what happened in the cockpit from the DFDR, which was slightly damaged, but contained substantial information. It recorded 50 seconds of data during the take-off and roll and 31 seconds of airborne data before the recording ended on impact. Two seconds before take-off, just before the word “damn” was heard in the cockpit, the DFDR recorded the last stable thrust reading for the No. 1 engine. Two seconds later, as the engine separated, it stopped recording the positions of the left inboard aileron, left inboard elevator, lower rudder and two of the leading edge slats—all of which had been powered by the now defunct No. 1 electric power generator.

The plane climbed normally for the first 9 seconds of flight. It got up to a speed of 172 knots relative to the air (KIAS). But then it began to slow down. Eleven seconds later the plane began its roll to the left. It had slowed down to 159 KIAS, the stall speed for a wing without extended flaps. The pilots tried to counter the turn by using the ailerons to force the right wing down, which would have leveled the plane out. The DFDR recorded this input and also recorded that the ailerons on the right wing did actually move (which told investigators that the ailerons had been working), but the force just wasn’t strong enough to get the plane level again.

Three seconds before impact, the plane was banked 90 degrees to the left—perpendicular to the ground. By the time it crashed, it had rolled over onto its back and was diving nose-first at 21 degrees. According to the DFDR readings of the ailerons, rudder and elevators, the pilots were doing everything they could to level the plane out.

But even the black boxes couldn’t tell the investigators everything they needed to know. For instance, while the DFDR recorded the settings of the right wing ailerons and slats, it said nothing about the left wing ailerons. That information was gleaned from the photographs taken by witnesses.

The photographs were taken from far away; they were blurry and dark and didn’t look promising at first glance. But with a little digital enhancement performed by a lab in Palo Alto, California, the plane and another segment of its story came into focus. The lab spent days doing what would only take a few seconds and very little expertise using

modern computers. In the late 1970s, at the brink of the digital age, the enhancement was a highly technical undertaking, but it boils down to one process: the image on the film was converted into a digital image by placing a grid with thousands of squares over the picture, shining light through it and measuring the amount of light that passed through each square. The intensity of the light in each square was assigned a corresponding number. This array of numbers thus became a “digital” version of the photograph.

Looking at the wings of the plane in the original pictures, the gradations of gray were so similar that it was impossible to tell the difference between the leading edge slats and the rest of the wing, let alone whether or not the slats were extended. But with the digital image, the contrast was easily adjusted. Consider the wing area, which was made up of very similar shades of gray, and therefore a small range of numbers. By stretching out the range of numbers (assigning the low end to zero and the high end to 100), the light grays can become lighter and the dark grays darker. All of a sudden, it was very clear just where the wing ended and the leading edge slats began.

The enhancement answered a few questions. First, investigators saw that the tail of the airplane had not been damaged by the engine separation. They also saw that the nose gear was down during the initial climb, before the roll—a fact that had been difficult to determine from contradictory witness statements. They saw that the ailerons on the right wing were extended, which confirmed that the pilots were trying to force the right wing down to counter the steep left turn they had entered.

It was now clear to investigators why the plane crashed after the engine fell off. The plane was going too fast to abort the take-off, so the pilots had no choice but to try to fly the plane. They knew they had lost power in the left engine, and take-off procedures mandated that they slow the plane down. They probably wouldn't have followed those procedures if they had known the left slat was retracting. The cockpit instrumentation should have alerted them to the slat retraction, but didn't. It, too, was faulty because it had no electrical power. By the time the plane stalled and entered its leftward roll, the pilots were entirely too uninformed and ill-equipped to handle the situation. From the moment the engine separated, Flight 191 was doomed.

The story investigators pieced together from the evidence is complicated. But even more complicated was parsing out exactly which events could have been prevented—or could be prevented in the future—and how. The ambiguities that the Flight 191 investigators faced were typical of any investigation. As Galison said, finding the evidence is only part of the story. Determining the facts and the probable cause is in a sense just the fuel of the NTSB's fire. The real impact comes with the safety recommendations.

Sometimes the recommendations can be as simple as telling the airlines to adhere to the aircraft maintenance manual. Early on in the investigation the NTSB released a few straightforward recommendations. The first was to put an immediate halt on the practice of removing the engine and pylon as a unit. The next one concerned the take-off procedure that required pilots to slow down in the event of an engine loss. When investigators realized that Flight 191 wouldn't have stalled if the pilots hadn't slowed down, they recommended altering the take-off procedure. The NTSB also recommended stronger redundancy to be built into the stall warning system.

At the same time, they required that all manufacturers provide some kind of protection against unintended slat retraction during critical phases of flight. As a result, slat locking devices (which were already present on some models of aircraft) were universally adopted. Once the slats are extended, they'll stay that way until the pilot voluntarily brings them back in. MacIntosh described the device as similar to the one that keeps the trunk of a car open. "Once you open the trunk and let go, it doesn't just come slamming down. It requires a separate, deliberate action to close it again."

Some of the recommendations were a little less obvious. There is no straightforward way to address massive hydraulic and electric failures. The systems are already designed to withstand a certain amount of damage, but clearly nobody imagined the kind of tragedy that took hold of Flight 191. As Charles Dundore, chief program engineer of the DC-10, said at the hearing, "it would be unreasonable to try to design hydraulic piping installations to survive any mode of major structural failure." In fact, if combined failures were taken into account in the design of the airplane, "from a realistic, practical point of view," Dundore said, "there would be no aircraft industry. But it isn't limited to that. The entire industrial world, wherever we are building things for people to use, the whole science of engineering is based on assessing some acceptable level of risk."

Nevertheless, the engine did fall off of Flight 191, and therefore the possibility of it happening again could not be ignored. The recommendations addressing this issue were understandably vague. Most of them boiled down to a general plea to the airlines and manufacturers to "do better next time": Implement better maintenance surveillance and quality control; pay more attention to hazard analysis before you change a maintenance procedure; improve communication among the airlines, manufacturer and the FAA. Even the aircraft's type certificate was scrutinized. One of the more nebulous recommendations suggested that during the design, manufacturers should take into account more of the possible failure combinations, as well as difficulties that might arise during maintenance. The NTSB doesn't offer any specific advice as to how these recommendations should be implemented. Interpretation is left up to the manufacturers and airlines at which the recommendations are aimed.

There is no escaping risk, much less a prescribed formula for eliminating it. The least we can do is put up the good fight. If we let politics, corruption, or ignorance prevent us from understanding what went wrong and ultimately fixing it, then, as Harvard historian of science, Peter Galison, says, "the world is a disordered and dangerous place." These investigations, he continues, "struggle, incompletely and unstably, to hold that nightmare at bay."

We cannot expect to win the race to eliminate all risk before tragedy crops up; but perhaps as long as we have a method in place to discover our mistakes, we won't be quite as likely to fall behind.

Acknowledgements

This thesis was inspired by my longtime fear and fascination of airplanes, as well as the sage advice to “write about something you can stay obsessed with for a year.” I would like to thank the investigators at the NTSB who shared their stories with me; George Smith and Rosalind Williams for being such willing and reliable resources; and the faculty and my classmates in the MIT Graduate Program of Science Writing, whose guidance, talent, and friendship made this year so valuable. I am especially grateful to my thesis advisor, Marcia Bartusiak, for her ability to make me more excited about writing with every new edit, and for being so cheerful and enthusiastic, even during the busiest times. Finally, I would like to thank my family for their endless support and encouragement; John for keeping me on track; and of course, my cat Josie, for always trying to convince me that life is really just about food, sleep, and companionship, and for never letting me work too long without taking a break to play string.

About the Author

Mara E. Vatz grew up in Winnetka, Illinois, where summers days meant playing tennis and swimming in Lake Michigan, and summer evenings belonged to the Ravinia Festival. In May, 2003, she graduated from Tufts University with a Bachelor of Science in electrical engineering and a Bachelor of Arts in philosophy, but admittedly spent most of her time in Curtis Hall, home of *The Tufts Observer*. She enjoys writing about science and history, and there will always be ink in her pen reserved for old technology--especially old technology that plays music and games.

Knowing When To Stop: The Investigation of Flight 191

Bibliography

Books

Adair, Bill. *The Mystery of Flight 427: Inside a Crash Investigation*. Washington, DC: Smithsonian Institution Press, 2002.

Eddy, P.; Potter, E.; Page, B. *Destination Disaster: From the Tri-Motor to the DC-10: The Risk of Flying*. New York: Quadrangle/The New York Times Book Co., 1976.

Ellis, Glenn. *Air Crash Investigation of General Aviation Aircraft*. Greybull, Wyoming: Capstan Publications, 1984.

International Civil Aviation Organization. "Manual of Aircraft Accident Investigation." 4th edition, 1970.

Smith, Hubert C. *Illustrated Guide to Aerodynamics*. New York: McGraw-Hill Professional, 2nd edition, 1991.

Stitch, Rodney. *The Real Unfriendly Skies: Saga of Corruption*. Alamo, CA: Diablo Western Press, 1990.

Interviews and Discussions

Dinwiddie, Car. Director, North Central Regional NTSB Office. Interview with author. NTSB North Central Regional Office, DuPage Airport, West Chicago, Illinois, March 22, 2004.

MacIntosh, Robert. Chief Advisor for International Safety Affairs. Interview with author. National Transportation Safety Board Office of Aviation Safety, Washington, D.C., January 30, 2004.

Miller, Ken. Interview with author. Oasis Mobile Home Park, Des Plaines, Illinois, December 23, 2003.

Smith, George. Director, Dibner Institute. Discussion with author. Dibner Institute, Cambridge, Massachusetts, October, 2003.

Suiter, Ron. Director of Subsystems, McDonnell Douglas (retired). Interview with author. Massachusetts Institute of Technology, October 10, 2003.

Sullivan, Pamela. Senior Investigator, NTSB, North Central Region. Interview with author. NTSB North Central Regional Office, DuPage Airport, West Chicago, Illinois, March 22, 2004.

Williams, James H. Professor of Mechanical Engineering, Massachusetts Institute of Technology. Interview with author. Massachusetts Institute of Technology, October 2, 2003.

Williams, Rosalind. Director of Program in Science, Technology, and Society, Massachusetts Institute of Technology. Discussion with author. Massachusetts Institute of Technology, April 9, 2004.

National Transportation Safety Board Documents

National Transportation Board Aircraft Accident Report: "American Airlines, Inc., DC-10-10, N110AA, Chicago-O'Hare International Airport, Chicago, Illinois, May 25, 1979." NTSB-AAR-79-17.

Transcript: *National Transportation Safety Board Public Hearing for American Airlines Flight 191*, Rosemont, Illinois, July 31 – August 10, 1979.

Newspaper Articles

"Airlines to inspect DC-10 engine bolts; foreign firms also order tests." *The Chicago Tribune*, May 29, 1979.

Andreson, Monroe; Toolan, Sean. "Too hot for anything but last rites." *The Chicago Tribune*, May 26, 1979.

Bianchi, Laura W. "Worst disaster puzzles federal aviation official." *Daily Herald, Arlington Heights*, May 26, 1979.

Carnes, Terry. "Plane was 'a tremendous ball of fire.'" *Daily Herald, Arlington Heights*, May 26, 1979.

Cohen, Edie. "Hospitals mobilize emergency services." *Daily Herald, Arlington Heights*, May 26, 1979.

Cohen, Rena W. "Airport life goes on, but others wait." *Daily Herald, Arlington Heights*, May 26, 1979.

Crawford, William Jr. et al. *The Chicago Tribune*, May 30, 1979.

- “DC-10 safety has stirred controversy since 1971.” *The Chicago Tribune*, June 3, 1979.
- De Lama, George. “A survivor’s story: He always feared one would fall.” *The Chicago Tribune*, May 27, 1979.
- Estep, George. “No panic when tower hits button.” *The Chicago Tribune*, June 3, 1979.
- Feaver, Douglas B. “‘Possible design problem’ grounds all U.S. DC-10s.” *Washington Post*, June 7, 1979.
- Feaver, Douglas B. “Airline charge on manufacture of DC-10s gains credence.” *Washington Post*, August 1, 1979.
- Feaver, Douglas B. “American changes emergency routine for piloting DC-10s.” *Washington Post*, August 2, 1979.
- Feaver, Douglas B. “DC-10 bolt broke after other failure.” *Washington Post*, June 1, 1979.
- Feaver, Douglas B. “DC-10 firm foresaw crash as one in billion chance.” *Washington Post*, July 31, 1979.
- Feaver, Douglas B. “DC-10 gets green light from FAA.” *Washington Post*, July 14, 1979.
- Feaver, Douglas B. “DC-10s may fly again in week.” *Washington Post*, June 3, 1979.
- Feaver, Douglas B. “Engineer balks at changes in critical DC-10 systems.” *Washington Post*, August 3, 1979.
- Feaver, Douglas B. “FAA Hopes to lift flight ban on DC-10 jets today or Tuesday.” *Washington Post*, July 9, 1979.
- Feaver, Douglas B. “Installation of bolts under study in pylon damage to some DC-10s.” June 29, 1979.
- Feaver, Douglas B. “McDonnell Douglas officials tell hill DC-10 is safe, urge return to flight.” *Washington Post*, June 21, 1979.
- Feaver, Douglas B. “Missing bolt is first clue in probe of jet crash.” *Washington Post*, May 26, 1979.
- Feaver, Douglas B. “New DC-10 flaws.” *Washington Post*, July 11, 1979.

- Feaver, Douglas B. "Pilot helpless in O'Hare DC-10, simulator finds." *Washington Post*, July 1, 1979.
- Feaver, Douglas B. "Probers shift focus from crashed DC-10." *Washington Post*, June 27, 1979.
- Feaver, Douglas B. "Rare checks made of DC-10 engine flange." *Washington Post*, June 10, 1979.
- Feaver, Douglas B. "Still more DC-10 cracks found." *Washington Post*, July 12, 1979.
- Feaver, Douglas B.; Barbash, Fred. "DC-10 lacks wing slats lock system." *Washington Post*, June 24, 1979.
- Feaver, Douglas B.; Barbash, Fred. "U.S. airlines often violate maintenance standards." *Washington Post*, July 29, 1979.
- Feaver, Douglas B.; Bredemeier, Kenneth. "Judge stays his writ grounding all DC-10s." *Washington Post*, June 6, 1979.
- Feaver, Douglas B.; Graham, Bradley. "FAA rules let airlines change DC-10 procedures." *Washington Post*, June 20, 1979.
- Feaver, Douglas B.; Warden, Rob. "270 killed in Chicago jet crash." *Washington Post*, May 26, 1979.
- "Feud over DC-10 maintenance." *Washington Post*, August 10, 1979.
- Gelman, David et al. "The Super-Sleuths of the Skies." *Newsweek*, June 11, 1979.
- Ginnetti, Toni; Montgomery, Diana. "274 die in worst U.S. aviation disaster." *Daily Herald, Arlington Heights*, May 26, 1979.
- Graham, Bill. "Crash worst air disaster in US." *Daily Herald, Arlington Heights*, May 26, 1979.
- Graham, Bradley; Kramer, Larry. "FAA's credibility is diminishing, both in U.S. and in Europe." *Washington Post*, June 24, 1979.
- Hansen, Jerry. "Fire all around: trailer residents." *Daily Herald, Arlington Heights*, May 26, 1979.
- "The horror at O'Hare." Editorial. *The Chicago Tribune*, May 27, 1979.
- Janet, Key. "DC-10 crash left insurer nightmare." *The Chicago Tribune*, June 3, 1979.

“Judge impounds broken jet parts.” *The Chicago Tribune*, May 30, 1979.

“Jumbo DC-10 considered advanced.” *The Chicago Tribune*, May 26, 1979.

Juneau, William; Koziol, Ronald. “Dozens of US dental experts fly here to aid in identifying victims.” *The Chicago Tribune*, May 27, 1979.

Lyon, Jeff. “In pilot’s forty years, ‘this is the worst one I’ve ever seen.’” *The Chicago Tribune*, May 27, 1979.

Marcotte, Paul; Carnes, Terry. “Rain of fire spurs rescue of those on the ground.” *Daily Herald, Arlington Heights*, May 26, 1979.

O'Brien, John; Axelrod, David. “‘It went up in flame, swish, just like napalm.’” *The Chicago Tribune*, May 26, 1979.

“O’Hare tragedy: last moments of flight 191.” *The Chicago Tribune*, May 27, 1979.

“Previous DC-10 problems noted.” *Daily Herald, Arlington Heights*, May 26, 1979.

“Problems are found on 59 DC-10s.” *The Chicago Tribune*, June 2, 1979.

Rodeghier, Katherine. “DC-10 considered one of the safest.” *Daily Herald, Arlington Heights*, May 26, 1979.

Sheils, Merrill et al. “How Safe?” *Newsweek*, June 11, 1979.

Sjostrom, Joseph. *The Chicago Tribune*, May 27, 1979.

“This side of caution.” Editorial. *The Chicago Tribune*, May 31, 1979.

“Toll tops previous high; 1978 crash in San Diego killed 144.” *Washington Post*, May 26, 1979.

Unger, Robert; Powers, Thomas. “Inspection shows 37 DC-10s flawed—2 called ‘serious.’” *The Chicago Tribune*, June 1, 1979.

Wiener, Leonard. “DC-10 viable, claim experts.” *The Chicago Tribune*, May 30, 1979.

Williams, Dennis A, et al. “It Just Disintegrated.” *Newsweek*, June 4, 1979.

Young, David. “...191, do you want to come back?” *The Chicago Tribune*, May 31, 1979.

Young, David. "2d broken jet part found: US to airlines: Inspect DC-10s or face grounding." *The Chicago Tribune*, May 29, 1979.

Young, David. "DC-10 flaws are serious: Douglas outlines problems in pylon." *The Chicago Tribune*, May 31, 1979.

Young, David. "DC-10 has history of problems." *The Chicago Tribune*, May 27, 1979.

Young, David. "Hint 2d jet engine failed: Broken bolt is found; FAA to probe DC-10s." *The Chicago Tribune*, May 28, 1979.

Young, David. "Jet tape can't reveal why, "damn"—last word from 191's cockpit." *The Chicago Tribune*, May 27, 1979.

Young, David. "New flaw grounds DC-10s: Find crack in engine mounts." *The Chicago Tribune*, May 30, 1979.

Young, David. "Pilot says DC-10 can take off minus engine." *The Chicago Tribune*, May 27, 1979.

Zyda, Joan. "Horror of matching pieces of bodies." *The Chicago Tribune*, May 26, 1979.

Websites

National Transportation Safety Board home page, <http://www.nts.gov>.

Aviation discussion forum, http://airliners.net/discussions/tech_ops/.

Airplane crash information site, <http://www.airdisaster.com/special/special-aa191.shtml>.

Boeing Corporation home page, <http://www.boeing.com/history/mdc/index.htm>.