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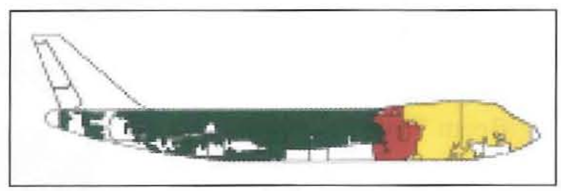
Learning from a Tragedy: Explosions and Flight 800

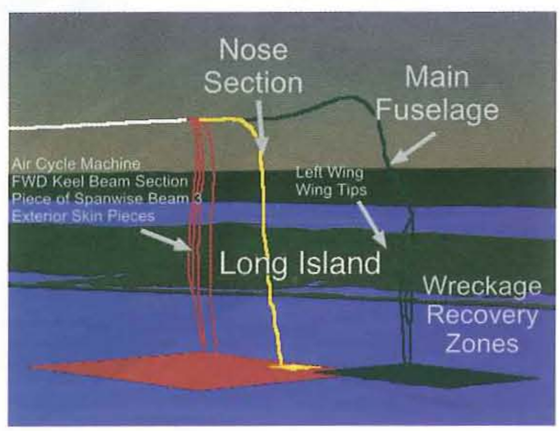
by Joe Shepherd

On the evening of July 17, 1996, a Boeing 747-131 operated by Trans World Airlines as flight 800 from New York to Paris crashed just off the coast of Long Island. All 230 persons aboard perished. Thousands more have been affected in some way—including the people in my lab here at Caltech, which has been involved in the crash investigation since November 1996. The mystery of flight 800 has not been solved. The investigation continues—we're still carrying out experiments, and the National Transportation Safety Board (NTSB) probably will not close the case for some time. The NTSB is an independent federal agency whose mission is to investigate accidents in all transportation modes—airplanes, pipelines, railways, highways, ships, and so on. They probe the circumstances surrounding an accident, try to find its probable cause, and, most importantly, make recommendations to prevent a recurrence—recommendations that have greatly affected aviation over the years. (The Safety Board has no regulatory authority.) The agency is a small one—only about 400 people total—so it has to call on outside help in its investigations. Thus a typical investigation, which is headed up by a senior Safety Board investigator, includes many parties. For example, in an aviation accident, the Federal Aviation Administration (FAA) is a party by law, and the other parties include the airframe and power plant manufacturers, the unions, and the operators, all of whom have expertise in various fields relating to the accident. In this case, the investigators were divided up into 19 teams—the biggest air-crash investigation in U.S. history.

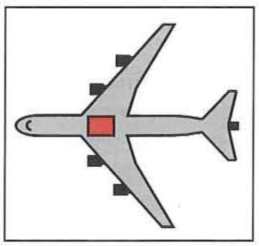
The wreckage of flight 800 was cataloged and spread out on the floor of an empty hangar in Calverton, about 30 miles from the crash site. In an attempt to reconstruct what happened, 94 feet of the fuselage was reassembled into a structure dubbed "jetosaurus rex."

Flight 800 started off routinely, but when it was about 14 minutes out of JFK Airport and at about 13,800 feet, the airplane exploded, scattering debris over some 150 square miles of ocean. It took about nine months for the NTSB, the FBI, the Navy, the Coast Guard, and other agencies to recover and catalog the wreckage. Divers spent 1,773 hours on the bottom, 120 feet deep, and 13,000 trawl lines scoured 40 square miles of ocean floor. Ultimately, about 95 percent of the airplane and its contents were retrieved—more than 20,000 items, some as small as a quarter. The wreckage was found in three zones, shown in red, yellow, and green on the map below. The parts in and around the center of the aircraft were found in the red zone. The portion of the fuselage ahead of the wings was found in the yellow zone, and the remainder of the plane was in the green zone, which lies somewhat to the east. (Remember, the aircraft was traveling from west to east.)

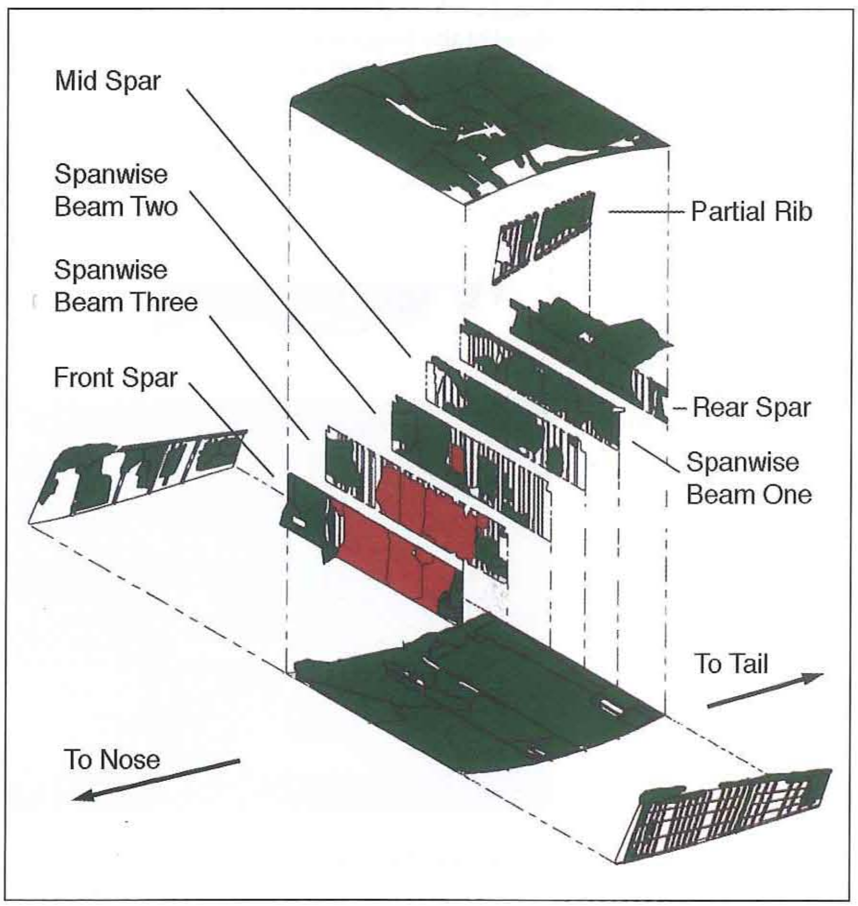




This view of the crash site looks northwest toward Long Island. (New York City is out of view to the left, and the airplane was traveling in the direction shown.) The red, yellow, and green regions show where wreckage from various parts of the aircraft were found.



Left: In addition to fuel tanks in the wings, a 747 has a so-called center wing tank (shown here in red) in the fuselage under the passenger cabin. Below: The center wing tank is spanned by several structural members that divide it into seven bays, numbered zero through six from fore to aft. Bay zero, between the front spar and spanwise beam three, is a dry bay. Later 747s carry fuel in bay zero, but in the 100 series it's open to the air, so spanwise beam three is effectively the fuel tank's front wall. Again, the colors refer to where the wreckage was found.



The wreckage was brought to an abandoned hangar complex at Calverton, Long Island, where it was spread out on the floor and painstakingly examined. As pieces were identified, they were fit together and the fuselage was laid out skin side down, like a filleted fish. The wings were laid out in another part of the hangar, as were the seats, which were set out in their proper order. It became apparent that something catastrophic had happened in the so-called center wing tank, which I'm going to spend a lot of time talking about. This relatively small section of the airplane was found in more than 700 pieces. To try to find out what happened, the NTSB team members reconstructed 94 feet of the fuselage, starting just behind (and including) the center wing tank and running forward—some 1,600 pieces of wreckage, all told. They built a steel skeleton, dubbed "jetosaurus rex," to which they wired fuselage pieces and interior components so that they could climb around inside and look at the relative locations of deformed metal, cracks, and so-called "witness marks" made where pieces of the aircraft hit each other as it came apart. (The reconstruction, not counting the skeleton, weighed about 60,000 pounds.) After intensive examination, including exhaustive computer simulations—finite-element structural analyses by Boeing engineers—they concluded that the only way to explain all the observations was if there had been an explosion in the center tank. The Safety Board reconstructed a detailed sequence of how the aircraft broke up, and it believes that the explosion was one of the first events in the accident.

Almost all of the tank's pieces were found in the green zone, except for a few very significant components—the front spar, spanwise beam three, the manufacturing panel from spanwise beam two (don't worry about the names; I'll explain them momentarily), and the machinery under the tank—which were found in the red zone. The center wing tank is actually in the fuselage, under the passenger cabin, and runs from wing to wing—if you're sitting in the plane looking out over the wing, you're sitting on top of the tank. It's about 20 feet long, 20 feet wide, $6^1/_2$ feet high in front, 4 feet high in back, and contains a series of floor-to-ceiling partitions that run from one side to the other. These partitions contain access holes that Boeing's workers use while they're assembling the aircraft. Before the plane leaves the plant, these holes are covered by the so-called manufacturing panels and sealed shut, never to be opened again. In addition, each partition has at least one access hole with a removable cover, called a maintenance panel, that allows workers to clamber from bay to bay within the tank later on. And, finally, the bottom and top corners of the partitions are notched, allowing fuel to flow between bays.

Now, the folks who build airplanes are divided into structures people and propulsion people, and

It became apparent that something catastrophic had happened in the so-called center wing tank, which I'm going to spend a lot of time talking about. This relatively small section of the airplane was found in more than 700 pieces.

Left: A peek inside the center wing tank, specifically bay one, showing two fuel probes (white arrow), a vent tube (black arrow), a fuel fill tube (green arrow), and a wiring bundle and terminal block (red arrows).
Below: The front portion of air conditioning unit number three, which lives under the center wing tank.

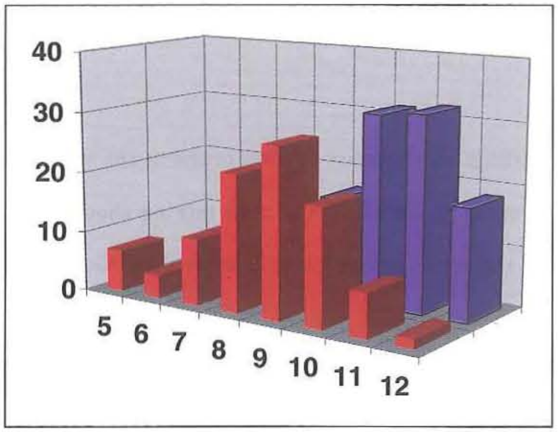
the two look at their airplane quite differently. The structural guys see it as an exquisite monocoque construction that has to have a few engines hung off it in order to fly. The propulsion folks think of it as four beautiful engines with a bit of wing for lift. The structural guys built this tank, and the partitions are actually structural members that run to very nearly each wing tip and carry the wing's bending moment through the fuselage. In order, the partitions are the front spar (which is also the front wall of the tank), spanwise beam three, spanwise beam two, the mid spar, spanwise beam one, and the rear spar, which doubles as the tank's rear wall. The NTSB believes that the explosion blew spanwise beam three into the front spar, causing both to fail. The center section of the airplane disintegrated, breaking the plane in two just ahead of the front spar. The nose plunged into the ocean, while the rear half of the fuselage, which remained attached to the wings and engines, continued on for some distance. This is why, if you follow the flight path, you come to the wreckage of the center section first, then the nose, and finally the rear section.

This is where Caltech came in. Since fuel-tank explosions are, thankfully, an extremely rare occurrence, this conclusion caused puzzlement and concern in the aircraft industry. So Merritt Birky, the Safety Board's senior investigator in charge of the fire and explosion team, asked Caltech's explosion-dynamics lab to assist him in investigating the explosion. We study such things as fuel properties, flames, and the detonation process (an explosion is really just a very fast-moving flame), and a lot of our work is connected with hazard evaluations for nuclear power plants, nuclear storage facilities, rocket sites, and so on. Our laboratory is part of GALCIT, (the Graduate Aeronautical Laboratory at the California Institute of Technology), which was founded in 1926 under Theodore von Kármán and has had a long-standing connection with aircraft design and aviation safety.

Now, in order to have a flame, you've got to have three things. One, you need fuel—in this case, the little bit of aviation-grade kerosene, called Jet A, that was left over when the flight arrived at JFK from Athens. The 747 is a marvelous airplane that can fly all the way from New York to Paris with just the fuel in its wings. Airlines don't like to carry around extra fuel, which is weight that could be used for more passengers, so they didn't refill the center tank when they refueled at JFK. Two, you've got to have air. Well, the tank was full of air, except for about 50 gallons of kerosene lying on the floor of this 13,000-gallon tank—a layer maybe three-sixteenths of an inch deep. And three, you need some source of ignition.

But to get an explosion, you need fuel vapor. If you set liquid fuel on fire, you'll just get a puddle of burning fuel. This is not something you *want* in an aircraft, but it's not going to cause an explosion. So how do we get vaporized fuel? Well, July 17 was a hot day, and there's a set of air-conditioning units that sit underneath the tank. As the air conditioners run, the heat from the machinery could have seeped upward and heated the fuel, causing some of it to evaporate. So now we have fuel vapor and air, and if we have ignition, we can possibly have an explosion.

So we had to answer three questions. Would an explosion have taken place on that particular day? Well, that depends on the exact mixture of liquid fuel, vapor, and air in the tank. Assuming there



The composition of Jet A's vapor (red) versus its liquid (blue) at 50° C in a half-full tank. The horizontal scale indicates the number of carbon atoms per molecule, and the vertical scale is the percentage of molecules with that number of carbon atoms.

was an explosion, could it have ruptured the tank? Well, that depends on how strong the pressure wave was. And the toughest question, which the chairman of the Safety Board always likes to remind me of whenever I see him, is: Where was the ignition source? Sometimes just a spark can start an explosion, and whatever started this one left no visible trace in the wreckage. To answer that, you have to know how the explosion actually propagated from bay to bay through the tank. What that meant for the combustion was not clear when we started, so we've learned some things about how flames propagate inside multi-compartment tanks.

We started with the flammability question—was there the right proportion of vapor and oxygen in order to burn? If we start out with air and slowly begin adding fuel vapor, it won't burn—the fuel molecules are too widely dispersed to propagate the reaction. But as we add more vapor, we reach the lower limit of flammability (or, in this case, of explosion). And soon, as we keep adding more vapor, there won't be enough oxygen to go around—we've hit the upper limit of flammability, and again, it won't burn. So there's a narrow region within which the mixture is explosive; outside of that, it's safe. The lower limit, which is what we're interested in, is about 0.7 percent of Jet A vapor in air. This number has been known for years—it's fundamental to jet-engine design.

Now Jet A is a very complicated mixture of a whole bunch of different kinds of molecules. It's not a simple thing like natural gas—I wish it were. And how much vapor you have depends on how willing the molecules are to evaporate, which in turn depends on their exact chemical structures, the liquid's temperature, and how much liquid there is. (It turns out that a very thin layer behaves differently than Jet A does in bulk, as you'll see.) So the Safety Board hired Jim Woodrow of the University of Nevada at Reno to analyze the chemical makeup of Jet A. Notice that what's in the liquid (blue) is very different from what's in the vapor (red), because the big, heavy molecules—the ones with 10 or more carbon atoms—are a lot more sluggish at a given temperature and don't escape into the vapor so readily.

So we need to know the temperature, which is not an easy measurement in this complicated tank. The beams and spars radiate and conduct heat, but the most important thing is the heat source—those three air conditioning units and their associated duct work. These aren't simply overgrown versions of the air conditioner in your bedroom window—they're heat exchangers that actually run off hot air from the engines (or from a small gas turbine in the rear of the airplane that generates electricity when the main engines aren't running). These "Environmental Control Units" (that's Boeing-speak) take in air at over 230° C and 60 pounds per square inch (psi) and convert it to −1° C and 15 psi to pressurize the cabin. That's what you breathe, and it also keeps you comfortable and civil to your neighbor while you're sitting at the gate for several hours, which is what happened in this case. Each air conditioner puts out a different amount of heat, and a lot more heat comes from the ducts, creating hot spots on the tank floor where the liquid fuel can evaporate. So last summer, we worked with the Safety Board, Boeing, and the FAA on a series of tests in which we flew a 747-100 that had thermocouples mounted throughout the tank. (Our role was primarily to point and say, "Hey—why don't you put a thermocouple over here?") The graph on the opposite page shows the temperatures recorded while the plane sat, air conditioners running, for the length of time that TWA 800's did. Dan Bower of the Safety Board and then-postdoc Raza Akbar [BS '89] analyzed the data and found that the air-conditioner compartment got hot enough to boil water—over 100° C—and the air in the tank's interior got as hot as 60° C in places. The temperature usually falls fairly quickly after takeoff—once the plane begins climbing, the outside air pressure drops and air bleeds out of the tank through vents, while the remaining air expands and cools. The outside air temperature drops as well, cooling off the air conditioners, which are just under the airplane's skin. But for a while at the beginning of the flight, the temperatures can run pretty high. The coolest temperature we saw at the time when the explosion occurred was about 40° C.

Knowing the temperature, it's pretty straightforward to find the number of fuel molecules one can have in a given volume of air. This is called the vapor pressure, and it rises with the temperature. A simple way to think about it is, how much water do you have in the air if you have 100 percent humidity? We all know that it can be much more humid on a hot day than a cold one. Vapor pressure is measured in millibars—

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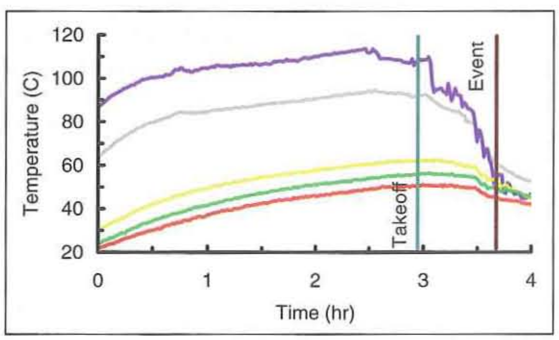
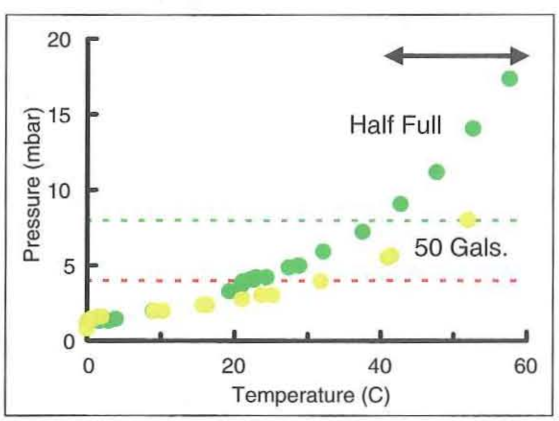
a bar is the pressure of the atmosphere at sea level at 0° C, and a millibar is one thousandth of that. On a hot, muggy day with a thunderstorm approaching, the vapor pressure might be 40 millibars. So postdoc Julian Lee measured the vapor pressure of Jet A and found that it's five millibars or higher at the temperatures we encountered in the flight test. Remember that number. You'll note that although we know that flight 800's tank only had about 50 gallons of fuel, we also did a set of studies simulating a half-full tank. This is because all the previous work in this area had been done using a half- or quarter-full tank, so in order to show that the 50-gallon case behaves quite differently—as you will see shortly—we needed to include the fuller tank as a reference point.

The amount of air is important, too, because the flammability limit is measured by the amount of fuel vapor relative to the amount of air, and the air gets thinner as you go up in altitude. At 13,800 feet, which was where the explosion occurred, the air pressure is only about 0.6 bars. But the fuel is hot enough that the air in the tank remains saturated with fuel vapor, even though the vents are sucking the vapor-air mixture out of the tank. So the vapor pressure remains constant while the air pressure drops, raising the relative percentage of vapor. Remember that at sea level, the lower limit of flammability is about 0.7 percent—7 millibars—of vapor, which corresponds to the vapor pressure of 50 gallons of fuel heated to 50° C. That's in the range of the air temperatures we saw in the flight test, which is bad enough. But it gets worse: at 13,800 feet the lower flammable limit is just under four millibars. (This has been known since studies by the FAA and the Air Force in the late '60s, and Julian's experiments confirmed it.) Julian found that 50 gallons of fuel will give us five millibars at temperatures as low as 30° C; and John Sagebiel of the Desert Research Institute took air samples from the tank during the flight test and verified that more than five millibars of fuel vapor were present. So we're well over the lower flammable limit.

But would it really explode? Julian put some Jet A in a coffee-can-sized pressure vessel, heated it up, and zapped a little spark between a pair of electrodes. (A spark is convenient because you know how much energy you're putting into it, but we've also done this experiment with things such as hot filaments.) The vaporized portion of the fuel was completely consumed in less than half a second. That's certainly fast enough to qualify as explosive, so we've answered the first of our three questions.

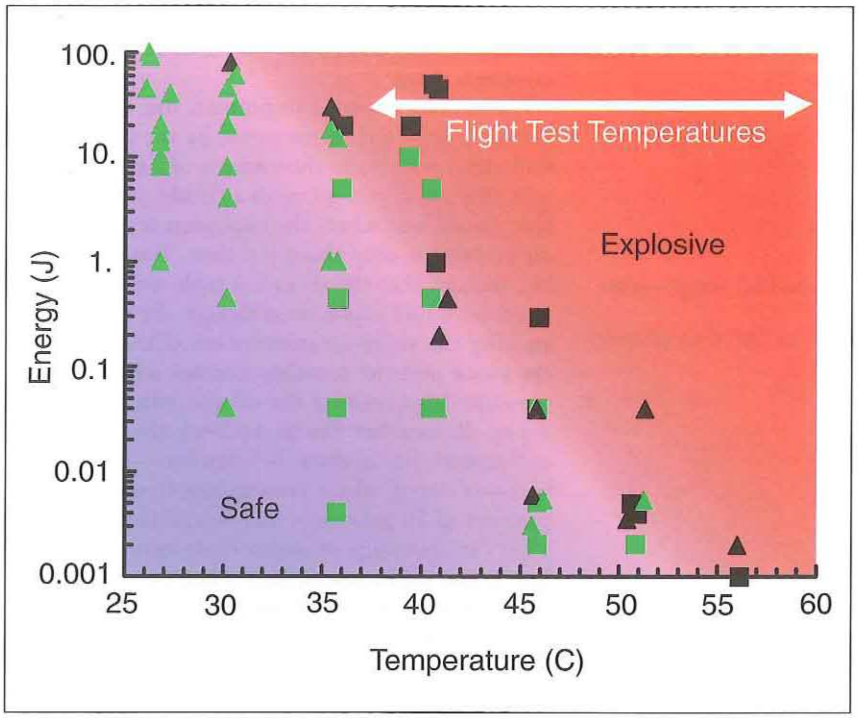
He did this over and over again with different amounts of fuel at different temperatures, and discovered that as the temperature increases from about 30 to 60° C, the minimum ignition energy drops enormously—nearly 100,000-fold. That's a very significant finding, and it's another reason why we feel it's very important to keep the temperature down inside these tanks. It turns out that the heat capacity of the fuel itself is what keeps the tank's temperature within safe limits. Even a tank that's only one-eighth full—1,625 gallons, or 10,563 pounds of fuel—will soak up a lot of heat before it warms to a temperature where you'll get significant evaporation. But a nearly empty tank has nowhere to store all that heat except in the air, which has a much lower heat capacity, so everything gets much hotter much faster. That factor of 100,000 is actually the ignition-energy difference between the partly full tank and the tank with 50 gallons in it—because

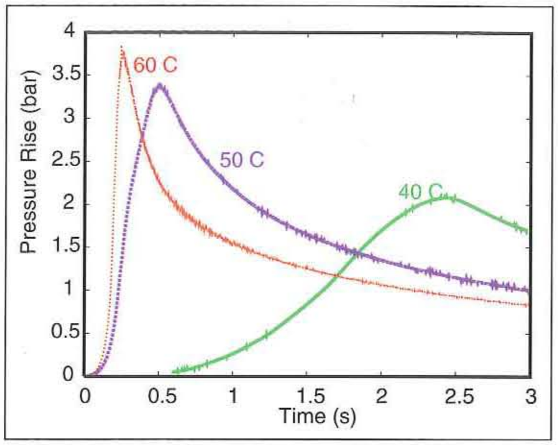




Top: When you sit at the gate for hours, the passengers aren't the only things that get hot. The blue line shows the temperature in the compartment beneath the center wing tank that holds the air conditioners. The gray line is the temperature of the tank floor, and the yellow, green, and red lines are air temperatures from various points in bay three.

Bottom: Jet A's vapor pressure increases with temperature. The dotted lines are the lower flammable limit at sea level (green) and 13,800 feet (red). The arrow shows the temperature range seen in the flight test.





Above: The amount of energy it takes to ignite a sample of Jet A drops by a factor of nearly 100,000 over a surprisingly narrow temperature range. The green data points represent samples that did not ignite; the black ones exploded. The squares are tests simulating 50 gallons of fuel and the triangles represent a quarter-full tank.

Above, right: The height and sharpness of the pressure peak measures the explosion's punch. As the temperature goes down, the explosion gets progressively weaker until eventually the vapor doesn't even ignite.

the fuller tank stays cooler, there's so little vapor in it that you need one heck of a jolt to ignite it. All this is shown in the plot above. The vertical axis is logarithmic, meaning that each increment on the vertical scale is 10 times larger than the previous one. We measure energy in joules, and a joule is one watt for one second. In other words, if you turned on a 100-watt bulb for one second, that's 100 joules. You can get that type of energy from 110 volts AC—household wiring. And 0.01 joule is what you get from a typical static-electricity shock when you shuffle your feet across the carpet.

There are seven fuel gauges in the tank that run on 24-volt wiring with a system to limit the current to less than one-tenth of the minimum ignition energy. But other systems draw more juice—for example, the fuel pumps run on 110 volts AC, as do the cabin lights. These wires are bundled together elsewhere in the plane, and the possibility exists that some insulation degraded, resulting in arcing between the 110-volt wiring and the fuel-quantity instrumentation system wiring. The Safety Board and the FAA are looking at the wiring issues.

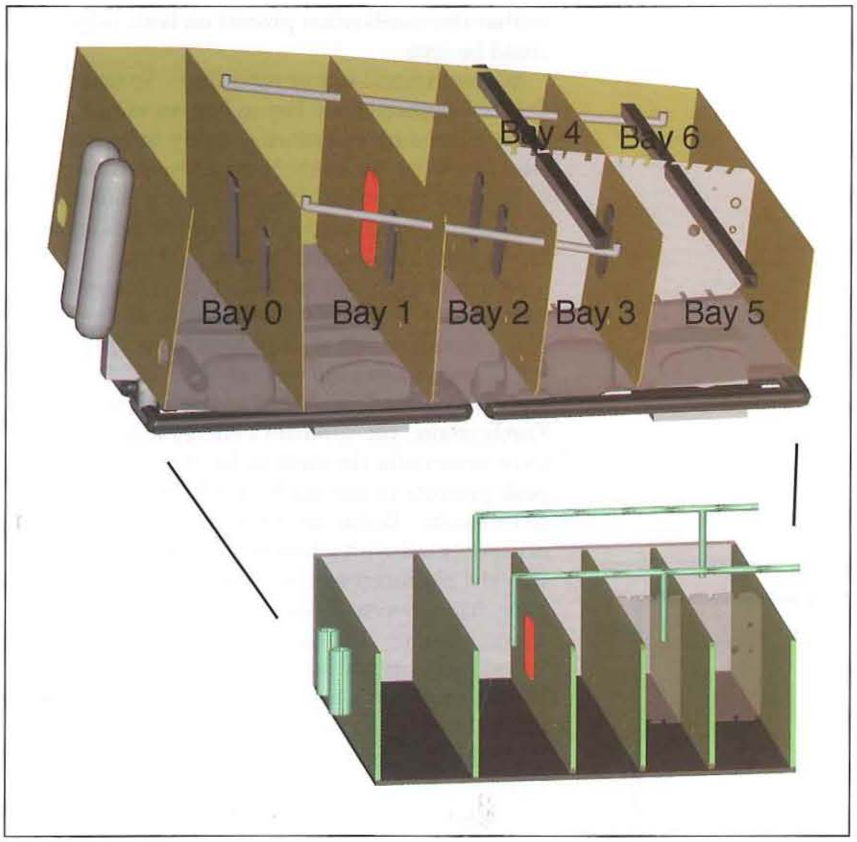
So now we know that the mixture was explosive and that a smallish spark would suffice to ignite it, but could it have damaged the tank? Yes, it could have. Julian found that the explosion's force increased rapidly with the the mixture's increasing temperature, a result confirmed by Chris Krok [PhD '97] in a much larger, 1,180-liter tank. At 60° C, the pressure jumped three and a half bars in a tenth of a second. Even at 40° C we got a peak pressure of almost two bars. It only takes on the order of 20 psi, or one and a half bars, to rupture the front of the tank, so we have enough pressure to cause tank failure. Well gee, you say, that doesn't seem like much—I put more than 20 psi in my tires. But this pressure is being applied over an enormous area. Spanwise beam three is 20 feet wide and 6 feet high, and you're pushing on every square inch of it with 20 pounds. That's more than 500,000 pounds of force—more than the weight of the aircraft itself—all on one structural member, and pushing horizontally on a member that's designed to resist vertical loads. It's just not up to it.

This brings us to the question that's really driving our investigation—where was the ignition source? Knowing *where* the source was would tell us *what* it was.

Backtracking to the source meant we had to deal with the very sticky issue of what the explosion did as it went through the tank, which meant we needed a replica of the tank that was big enough to incorporate the details, such as the vent pipes and the holes in the partitions, that determined how the explosion propagated. The model also had to be sturdy enough to withstand a large explosion over and over again. An explosion in our lab isn't very exciting, because we don't want it to get away from us—it's a little tiny noise in a thick steel vessel. When we give visitors a tour, they look around and say, "Is that it? That little pop? That's *all?*" If you want to make a lot of noise, you've got to go outdoors. So we built a quarter-scale model of the tank to use outdoors—at an abandoned Titan missile base near Denver, as it turned out. Denver is the home of Applied Research Associates (ARA), a firm that specializes in explosive tests and that was our partner on this project. ARA has a lease on the base for just this kind of work, and one of the first things they had to do was weld the doors to the launch-control bunker shut—it had become a popular hangout for local teenagers.

Chris designed the model; Accurate Manufactur-

Left: The tests that included a layer of Jet A in addition to the simulant produced some spectacular fireballs.

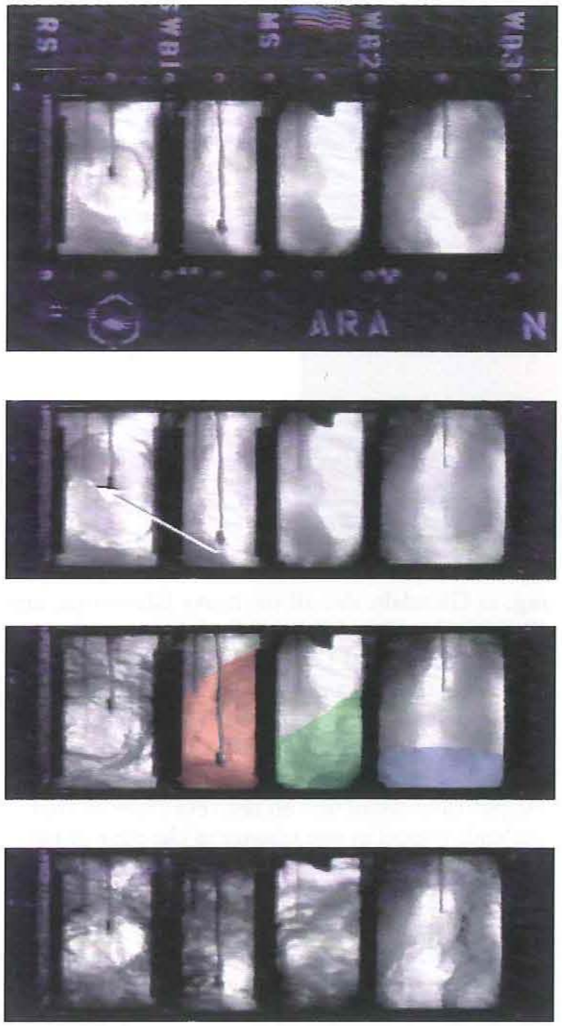


Above: The model (bottom) includes several key features of the real tank (top). Although the corner notches are hard to see in this rendering, other holes, including the manufacturing panel in spanwise beam two (red), are clearly visible. The two fore-and-aft pipes are the vent tubes that connect bays one and six, and bays one and three, to the vent stringers (the dark, transverse, rectangular tubes) that lead out to the wing tips and the outside air. The two cylinders on the front spar are potable-water tanks.

ing, in Glendale, did all the heavy fabrication; and Chris, Julian, Pavel Svitek (the support engineer for our group), and I did the final assembly. Chris's design was a quarter-scale model not only spatially—where the tank was 6 feet high, our model was 18 inches high; 20 feet long became 5 feet long; and so on—but temporally as well. He put flow restrictors on the vent pipes so that the tank vented in one quarter of the time of the full-size tank, and he sized the corner notches and the other holes in the partitions so that flows between the bays were also to scale. Whatever we saw in the model would happen in one-quarter of the time of whatever happened in full-scale.

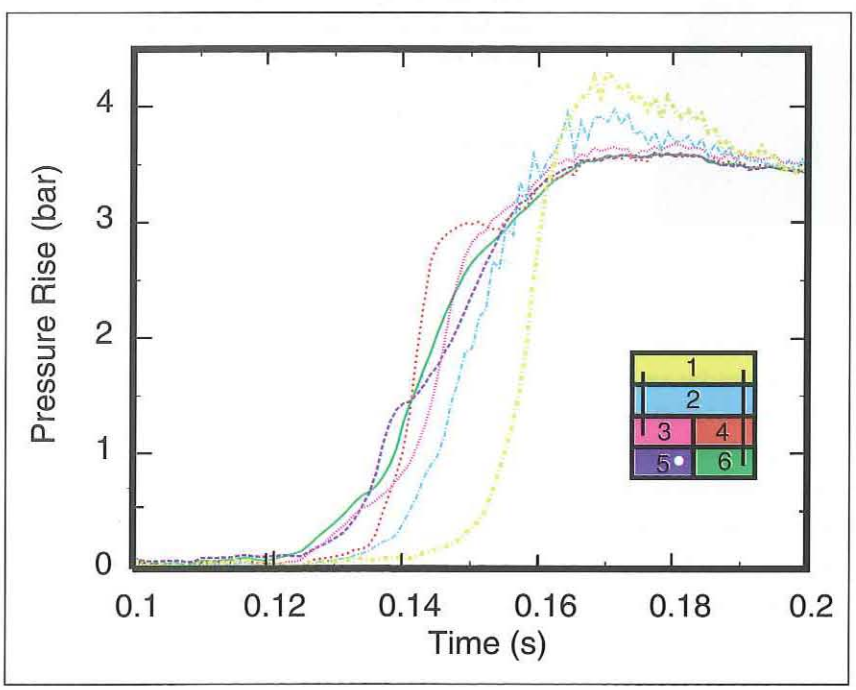
The model had three-quarter-inch steel top and bottom plates, reinforced with I-beams, and a three-quarter-inch fixed rear spar. The other partitions were removable. The top plate contained our sensors, as well as plumbing connections for the vents and the gas-handling system. (Julian and Chris spent two months building all the instruments.) High-speed pressure transducers recorded the passage of shock waves, while slow-speed pressure transducers recorded the slower pressure changes due to combustion and venting. Thermocouples measured the temperature, and photodiodes detected infrared and visible radiation. Motion detectors in the top and bottom plates indicated when the beams and spars broke free. Finally, electrical feed-throughs allowed igniters to be placed anywhere in the tank to simulate suspected ignition locations, such as the fuel probes or the terminal blocks where various electrical connections are made.

The sides were one-and-a-quarter-inch-thick sheets of a polycarbonate plastic called Lexan—the same stuff that bulletproof windows are made out of—allowing us to follow the combustion with high-speed cameras. (We also videotaped all the tests.) The partial rib, which runs fore-and-aft from the rear spar to the mid spar and which contains numerous holes, was also made of Lexan,



Left: In the tests, each bay had its own high-speed camera, running at roughly 400 frames per second, trained on it, so that these pictures are actually composites overlaid on a photo of the model. Note the labels across the top—"RS" is rear spar, "SWB1" is spanwise beam one, and so on. The silhouettes that look like hanging microphones are the igniter and the backup igniter; the thinner silhouettes are thermocouples. These photos are from test number four, in which the partitions were firmly secured to see how the explosion moved from bay to bay. The circles in the first two frames and the ripples in the other frames are shadows cast by the flame front. The colors in the third frame have been added for emphasis.

Below: Pressure data from the same test. The inset in the lower right corner is a schematic of the model, with each bay color-coded to match the pressure traces. The red dot in bay 5 marks the ignition point. The sudden pressure rises mark where each bay exploded. Bays six and three both feed into bay four, giving it the sharpest pressure rise of all—the "shoulder" on the graph. The pressure in each bay exceeded the failure pressure, but what actually does the damage is the pressure differential on opposite sides of a partition.



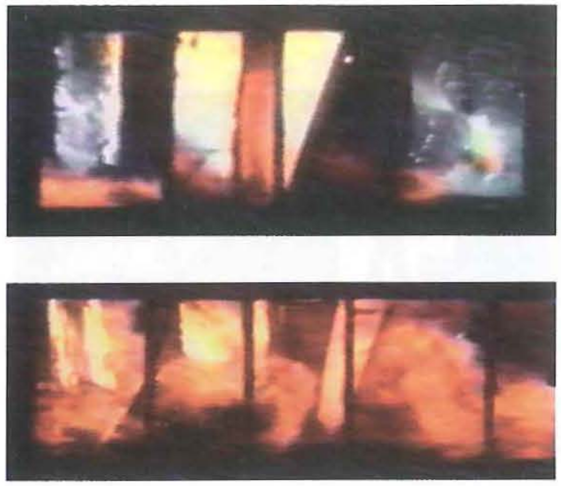
so that the combustion process on both sides of it could be seen.

We had several sets of partitions. To study how the flame moved from bay to bay, we used $^3/_4$-inch-thick aluminum partitions securely bolted into steel brackets. To study how partition failure influenced the process, we used much thinner aluminum sheets, secured by just enough screws so that they'd break free at about 20 psi.

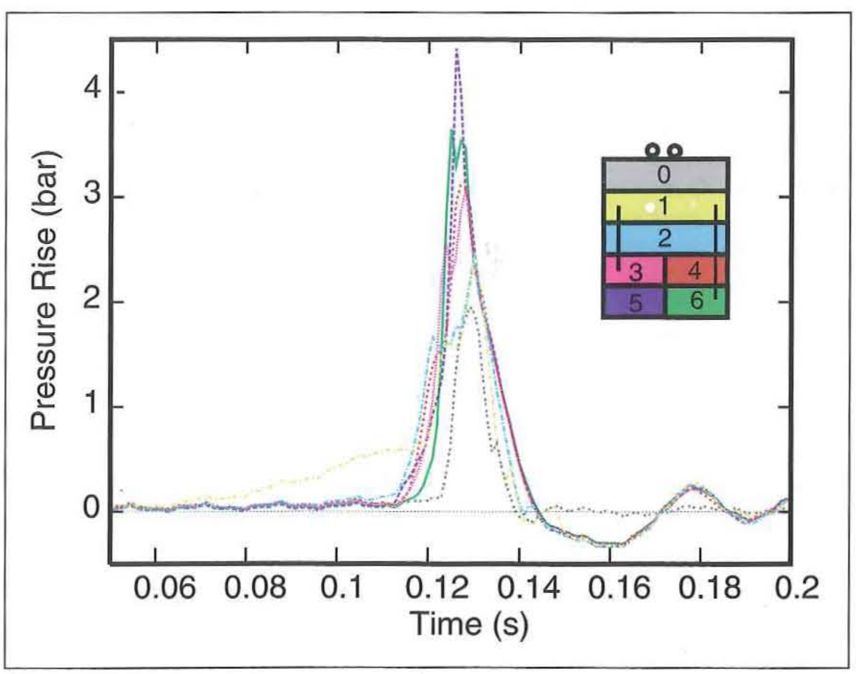
Denver may be the mile-high city, but it's still well short of flight 800's altitude, so we had to find a simulant fuel vapor whose flame speed at 0.82 bar (Denver's air pressure) and 25° C was equal to Jet A's flame speed at 0.6 bar and 50° C. Furthermore, the simulant's energy content had to be essentially the same as Jet A, so that the peak pressure in our model would be the same as in full-scale. Before we went up there, Chris had experimented with a bunch of fuels and discovered that the hydrocarbons, such as methane or propane, had too slow a flame speed but too much energy content. On the other hand, hydrogen burned too quickly and wasn't energetic enough. He finally hit on a mixture of 7 percent hydrogen and 1.45 percent propane in air that, like Baby Bear's bowl of porridge, was just right. So to start each test, we'd suck 8.45 percent of the air out of the model and refill it to ambient pressure with premixed hydrogen and propane. (It's pretty astonishing that we could still seal our model after all those explosions—we used a third of a tube of silicone caulking compound per test, and lots of double-sided foam-core tape.) We then stirred the tank with a bellows pump. In the actual aircraft, of course, convection from the hot spots in the tank did the mixing in the three hours it sat on the runway.

Chris, Julian, Pavel, and the ARA guys did 30 explosions from October through December. I went up there twice, but my main contribution was to sit back here in Pasadena and worry a lot. They'd send me the data every day, and I'd process

The second test was number 21 in the series. The photo below, from the high-speed camera in bay two, shows that spanwise beam two was actually bowed backward from the force of the explosion in bay one (to the right) before being ejected forward by subsequent explosions. You can also see the cloud of liquid Jet A (arrowed) being kicked up by the jet from the corner notch.



Above: These stills were lifted from the videotape. In the top photo, the bottom side of spanwise beam two has broken loose, and flames are beginning to engulf the rear bays. In the bottom photo, the rear bays have exploded, and all the partitions have come loose. (The front spar and spanwise beams two and three were ejected out the front of the tank. The mid spar and spanwise beam one remained in the tank, although the mid spar was blown forward. Spanwise beam one was shoved toward the rear.) Below: Since this test was done with weak partitions, pressure data was taken in bay zero (the dry bay) as well. The pressure rises were more closely bunched together, and the pressure dropped sharply when the panels blew out, rather than slowly venting away as in the strong-partition test.



it and post it on the Web so that the other team members at Sandia, at NTSB headquarters, in Norway, and in Canada could get daily updates. It was easier than faxing umpteen people, and the folks doing computer simulations of the explosion could download our data directly. We provided some very nice results for the simulations, which in turn takes us closer toward our goal of finding the ignition source. In order to give you a better feel for the very complex sequences of events we recorded, let's look at some pictures and pressure data from two of the tests.

The first test I'll show you used the strong partitions. The ignition source was in bay five, which is to the left in the pictures on the opposite page. In the first frame, the nice, regular bubble surrounding the igniter is the flame front. You can see it's very even. We also know that it's growing relatively slowly, because you don't see any pressure rise until 0.12 seconds, and even then it's very gentle for the next hundredth of a second. At the same time, the advancing flame front pushed unburned gas ahead of itself through the holes into bays three and six, causing similar pressure rises. Although you can't see it, these jets of unburned gas roiled the air in bays three and six, priming them to explode—turbulent air will carry a flame front very rapidly, producing a very fast explosion. In the second frame, the flame is passing into bay six through a hole in the partial rib (arrow). Bay six was immediately engulfed in flame, as seen in the third frame, and this explosion caused the pressure in the bay to skyrocket, squirting a tongue of fire (red) through the corner notch into bay four. Similar jets of flame are visible in bays two (green) and one (blue). It's a cascade—the jet in bay four drives compression in bay two, which in turn spills over into bay one. The bays also ignite in that order, as mirrored in the pressure data. Because bay two is roughly twice as big as the preceding bays, it takes longer to burn and thus bay one ignites relatively slow-

A set of still photos from the videotape of test 21. In the first frame, you can see the front spar beginning to tear loose. In the second frame, at least one panel can be seen near the front of the fireball. In the third and fourth frames, the remaining Jet A in the bottom of the tank burns off. The fireball, although visually impressive, does very little damage to the tank.

ly—a whopping hundredth of a second later.

The second test used weak partitions, and included a thin layer of Jet A on the floor in addition to our simulant fuel vapor. The ignition source was in bay one. The pressure data shows that bay one began to get pressurized in about six hundredths of a second, but it's so large that it continued to burn for another six hundredths of a second—an eternity on this time scale—before anything else happened. But this sent jets of gas through the notches into bay two, creating turbulence in advance of the flame's arrival. As we saw before, this set up a cascade effect, so that when the flame did arrive at bay two, it moved like lightning and engulfed the remaining bays in a hundredth of a second or so. And, finally, the cycles of negative and positive pressure that began at about 0.14 seconds were due to partition failures—the flying panels created partial vacuums in their wakes, and the combustion products vented toward the front of the tank.

We've been spending a great deal of time analyzing our data over the last several months. We're examining the details of how the pressure differentials vary across components, and when each differential reaches failure pressure. Our Canadian collaborators are comparing the results to the breakup sequence the Safety Board deduced from the wreckage analysis, which indicated that certain parts of the center wing tank stayed intact longer than others. It's what we call an inverse problem—we have the results, and our task is to figure out what we started with. We hope to find a signature that will allow us to draw some conclusions about where the ignition source might have been. We do see that the ignition location influences the pattern, but we don't have any kind of a smoking gun.

There are several complicating factors. For example, the fuel vapor probably wasn't evenly distributed throughout the bays. The liquid fuel certainly wasn't—it was sloshing around in the bottom of the tank, which is covered with a whole bunch of stiffeners. (The tank's floor and ceiling are actually extensions of the lower and upper skins of the wings, and help carry the wing's bending moment through the fuselage.) Since the aircraft was still climbing, the fuselage was tilted up by about five or six degrees. Fuel would puddle up behind each stiffener, spilling over from stiffener to stiffener en route to the notches that drain back to the next bay. There's a lot of uncertainty about the fuel distribution, and that's an important point we're considering.

The real explosion happened with Jet A vapor rather than our simulant, so this summer we're going back to Denver to do quarter-scale tests using Jet A. (We'll have to pump the tank down to simulate the explosion altitude.) Furthermore, our structural-failure scenario is extremely simplified—the center wing tank's upper and lower skins came apart at the same time that the beams and spars moved. And unfortunately, size matters. There are some aspects of explosions that simply don't scale well, so the Sandian and Norwegian groups are modeling our quarter-scale flame to determine how our results relate to the full-scale situation.

So then, what does all our work have to do with the real world? Three months after the crash, the NTSB recommended that the FAA pursue ways to make the center fuel tank less flammable. The accumulated weight of our results, coupled with others' studies and pressure from the Safety Board and the public, has since caused the FAA to take up the recommendation. A committee of industry/FAA committees called the Fuel Tank Harmonization Working Group, which is not a barbershop quartet, looked at such things as a further reduction in ignition sources, cooling the tank, using fuels with lower flash points, and possibly installing inerting systems. (An inerting system introduces an inert gas, such as nitrogen, into the tank to drive out some air and hence oxygen mole-

cules, reducing their number to below the lower limit of flammability.) A draft of the results of that study are now undergoing review. In addition, there have been several airworthiness directives—legally binding orders from the FAA to the airlines—about possible sources of ignition associated with the fuel-quantity instrumentation system wiring inside the center wing tank. The FAA has also mandated a tank-inspection program on both the 737s and 747s, so the next time one of these planes goes in the shop for what they call heavy maintenance (or within two years, whichever comes first), there'll be a whole list of things to look at. (People don't go into these tanks very often, and for good reason—it's a very tough environment. You have to use a breathing apparatus, and crawl through small holes into confined spaces that just give me the heebie-jeebies. And once you open all those access panels, you've disturbed the tank's integrity, so that it all has to be resealed afterward.) And because a cooler tank is safer than a hot one, the NTSB has suggested that additional fuel be put into the tanks during extended gate holds or other long periods on the ground. But the NTSB and the FAA are still debating the specifics, which would depend on how long the aircraft had been sitting, and what it had been doing earlier.

Finally, let me put all this talk of explosions into perspective. Air travel is extraordinarily safe, particularly in the United States. On average, there's an accident resulting in fatalities—from all causes, not just fuel-tank explosions—roughly once in every two million departures. Last year, U.S. airlines made 10 million departures, and there have been something like 317 million departures worldwide since the start of jet travel in 1959. In all that time there have been about a dozen fuel-tank explosions. Some of those involved JP-4, which is very similar in volatility and vapor pressure to gasoline (and thus much more hazardous than Jet A!), and is now rarely used in commercial aviation. There are only three known explosions of center wing tanks, of which TWA 800 is one. One of the other two was connected with a bomb—a 727 flown by Avianca Airlines in 1989. Someone in Colombia was getting rid of an enemy, and unfortunately brought down the entire plane. The remaining one happened in 1991, on a runway in Manila, to a 737 belonging to Philippine Air Lines—the closest parallel we can find to Flight 800. This aircraft had been modified after it left the factory, and it is believed that this modification, or a faulty fuel float switch, caused the explosion. (In 1976, an Iranian Air Force 747 that had been converted into a tanker exploded. That was a wing tank proper, however, and lightning is believed to be involved; furthermore there was mixed loading with JP-4.) However tragic, explosions of center wing tanks are extremely rare. Even so, measures are being taken to drive the probability down even further. □

Joe Shepherd has been an associate professor of aeronautics at Caltech since 1993—his second career here; he got his PhD in applied physics from Caltech in 1980. (He earned his BS in physics from the University of South Florida in 1976.) Before returning to Pasadena, he was on the faculty at Rensselaer Polytechnic Institute and a staff member at Sandia National Laboratory. He has been studying explosions for the past 20 years and has worked the whole spectrum of such events, from tiny droplets evaporating in tabletop experiments all the way up to nuclear explosions in the Nevada desert. Over the last five years, he has led the research group that developed the Explosion Dynamics Laboratory and put Caltech in the position to make a unique contribution to this investigation.

This article is adapted from a recent Watson Lecture.