PETER GALISON

AN ACCIDENT OF HISTORY

We regularly ask after the limits of historical inquiry; we agonize over the right combination of psychological, sociological, and technical explanations. We struggle over how to combine the behavior of machines and practices of their users. Imagine, for a moment, that there was a nearly punctiform scientific-technological event that took place in the very recent past for which an historical understanding was so important that the full resources of the American government bore down upon it. Picture further that every private and public word spoken by the principal actors had been recorded, and that their every significant physical movement had been inscribed on tape. Count on the fact that lives were lost or jeopardized in the hundreds, and that thousands of others might be in the not so distant future. Expect that the solvency of some of the largest industries in the United States was on the line through a billion dollars in liability coverage that would ride, to no small extent, on the causal account given in that history. What form, we can ask, would this high-stakes history take? And what might an inquiry into such histories tell us about the project of – and limits to – historical inquiry more generally, as it is directed to the sphere of science and technology?

There are such events and such histories – the unimaginably violent, destructive, and costly crash of a major passenger-carrying airplane. We can ask: What is the concept of history embedded in the accident investigation that begins while crushed aluminum is still smoldering? Beginning with the Civil Aeronautics Act of 1938, the Civil Aeronautics Authority (a portion of which became today's National Transportation Safety Board) and its successors have been assigned the task of reporting on each accident, determining what happened, producing a "probable cause" and arriving at recommendations to what is now the Federal Aviation Authority (and through them to industry and government) that would avoid repetition. Quite deliberately, the NTSB report conclusions were disqualified from being used in court: the investigative process was designed to have some freedom both from the FAA and from the courts. Since its establishment, the system of inquiry has evolved in ways I will discuss, but over the last half century there are certain elements that remain basically constant. From these consistencies, and from the training program and manuals of investigation, I believe we can understand the guiding historiographical principles that underlie these extraordinary inquiries. What they say – and do not say – can tell us about the broad system of aviation, its interconnectedness and vulnerabilities, but also, perhaps, something larger about the reconstruction of the intertwined human and machinic world as it slips into the past.

P. Galison and A. Roland (eds.), Atmospheric Flight in the Twentieth Century, 3–43

There is a wide literature that aims to re-explain aviation accidents. Such efforts are not my interest here. Instead, I want to explore the form of historical explanation realized in the accident reports. In particular, I will focus on a cluster of closely related instabilities, by which I mean unresolvable tensions between competing norms of explanation. Above all, the reports are pulled at one and the same time towards *localizing* accounts (causal chains that end at particular sites with a critical action) and towards *diffusing* accounts (causal chains that spread out to human interactions and organizational cultures). Along the way, two other instabilities will emerge: first, a sharp tension between an insistence on the necessity of following protocol and a simultaneous commitment to the necessary exercise of protocol-defying judgment. Second, there is a recurrent strain between a drive to ascribe final causation to human factors and an equally powerful, countervailing drive to assign agency to technological factors. To approach these and related questions, one needs sources beyond the reports alone. And here an old legislative stricture proves of enormous importance: for each case the NTSB investigates, it is possible to see the background documentation, sometimes amounting to many thousands of pages. From this "docket" emerge transcripts of the background material used to assemble the reports themselves: recordings and data from the flight, metallurgical studies, interviews, psychological analyses. But enough preliminaries. Our first narrative begins in Washington, DC, on a cold Wednesday afternoon, January 13, 1982.

The accident report opened its account at Washington National Airport. Snow was falling so hard that, by 1338, the airport had to shut down for 15 minutes of clearing. At 1359, Air Florida Flight 90, a Boeing 737-222 carrying 5 crewmembers and 74 passengers, requested and received their Instrument Flight Rules clearance. Twenty minutes later, a tug began de-icing the left side of the plane, then halted because of further departure delays. With the left side of the aircraft cleared, a relief operator replaced the initial one, and resumed the spraying of heated glycol-water mixture on the right side. By 1510, the relief operator finished with a final coat of glycol, inspected the plane's engine intakes and landing gear, and found all surfaces clear of snow and ice. Stuck in the snow, the Captain blasted the engines in reverse for about a minute in a vain effort to free the plane from its deepening prison of water, glycol, ice, and snow. With a new tug in place, the ground crew successfully pulled flight 90 out of the gate at 1535. Planes were backed up in holding patterns up and down the East Coast as they waited for landing clearance. Taxiways jammed: flight 90 was seventeenth in line for takeoff.

When accident investigators dissected the water-soaked, fuel-encrusted cockpit voice recorder (cvr), here is what they transcribed from time code 1538:06 forward. We are in the midst of their "after start" checklist. Captain Larry Michael Wheaton, a 34 year-old captain for Air Florida, speaks first on CAM-1. The first officer is Roger Alan Pettit, a 31 year-old ex-fighter pilot for the Air Force; he is on CAM-2.

1538:06 Wheaton/CAM-1 {my insertions in curly brackets} After start

Pettit/CAM-2 Electrical

Wheaton/CAM-1 Generators

Pettit/CAM-2 Pitot heat {heater for the ram air intake that measures airspeed}

Wheaton/CAM-1 On

Pettit/CAM-2 Anti-ice

Wheaton/CAM-1 {here, because some of the listeners heard "on" and the majority "off", the tape was sent to FBI Technical Services Division where the word was judged to be "off".} Off.

Pettit/CAM-2 Air conditioning pressurization

Wheaton/CAM-1 Packs on flight

Pettit/CAM-2 APU {Auxiliary Power Unit}

Wheaton/CAM-1 Running

Pettit/CAM-2 Start levers

Wheaton/CAM-1 Idle […]

Preparation for flight includes these and many other checklist items, each conducted in a format in which the first officer Pettit "challenges" captain Wheaton, who then responds. Throughout this routine, however, the severe weather commanded the flightcrew's attention more than once as they sat on the taxiway. In the reportorial language of the investigators' descriptive sections, the following excerpt illustrates the flight crew's continuing concern about the accumulating ice, snow and slush, as they followed close behind another jet:

> At 1540:42, the first officer continued to say, "It's been a while since we've been deiced." At 1546:21, the captain said, "Tell you what, my windshield will be deiced, don't know about my wings." The first officer then commented, "well – all we need is the inside of the wings anyway, the wingtips are gonna speed up on eighty anyway, they'll shuck all that other stuff." At 1547:32, the captain commented, "(Gonna) get your wing now." Five seconds later, the first officer asked, "D'they get yours? Did they get your wingtip over 'er'?" The captain replied, "I got a little on mine." The first officer then said, "A little, this one's got about a quarter to half an inch on it all the way."[1]

Then, just a little later, the report on voice recordings indicates:

> At 1548:59, the first officer asked, "See this difference in that left engine and right one?" The captain replied, "Yeah." The first officer then commented, "I don't know why that's different – less it's hot air going into that right one, that must be it – from his exhaust – it was doing that at the chocks awhile ago but, ah."

Which instrument exactly the first officer had in mind is not clear; the NTSB (for reasons that will become apparent shortly) later argued that he was attentive to the fact that, despite similar Engine Pressure Ratios (the ratio of pressure at the intake and exhaust of the jet and therefore a primary measure of thrust), there was a difference in the readout of the other engine instruments. These others are the N1 and N2 gauges – displaying the percent of maximum rpm of low and high pressure compressors respectively – , the Exhaust Gas Temperature gauge (EGT), and the fuel flow gauge that reads in pounds per minute. Apparently satisfied with the first officer's explanation that there was hot air entering the right engine from the preceding plane, and that somehow this was responsible for the left-right discrepancy, the captain and first officer dropped the topic. But ice and snow continued to accumulate on the wings, as was evident from the cockpit voice recorder tape recorded four minutes later. To understand the first officer's intervention at 1558:12, you need to know that the "bugs" are hand-set indicators on the airspeed gauge; the first corresponds to V1, the "decision speed" above which the plane has enough speed to accelerate safely to flight on one engine and below which the plane can (theoretically) be stopped on the runway. The second speed is VR, rotation speed at which the nosewheel is pulled off the ground, and the third, V2, is the optimal climbout speed during the initial ascent, a speed set by pitching the plane to a pre-set angle (here 18°).

1553:21 Pettit/CAM-2 Boy, this is a losing battle here on trying to deice those things, it (gives) you a false sense of security that's all that does

Wheaton/CAM-1 That, ah, satisfied the Feds

Pettit/CAM-2 Yeah

1558:10 Pettit/CAM-2 EPR all the way two oh four {Engine Pressure Ratio, explained below}

1558:12 Pettit/CAM-2 Indicated airspeed bugs are a thirty-eight, forty, forty four

Wheaton/CAM-1 Set

1558:21 Pettit/CAM-2 Cockpit door

1558:22 Wheaton/CAM-1 Locked

1558:23 Pettit/CAM-2 Takeoff briefing

1558:25 Wheaton/CAM-1 Air Florida standard

1558:26 Pettit/CAM-2 Slushy runway, do you want me to do anything special for this or just go for it?

1558:31 Wheaton/CAM-1 Unless you got anything special you'd like to do

1558:33 Pettit/CAM-2 Unless just takeoff the nose well early like a soft field takeoff or something

1558:37 Pettit/CAM-2 I'll take the nose wheel off and then we'll let it fly off

1558:39 Pettit/CAM-2 Be out of three two six, climbing to five, I'll pull it back to about one point five five supposed to be about one six depending on how scared we are.

1558:45 (Laughter)

As in most flights, the captain and first officer were alternating as "pilot flying"; on this leg the first officer had the airplane. For most purposes, and there are significant exceptions, the two essentially switch roles when the captain is the pilot not flying. In the above remarks, the first officer was verifying that he would treat the slushy runway as one typically does any "soft field" – the control wheel is pulled back to keep weight off the front wheel and as soon as the plane produces enough lift to keep the nosewheel off the runway, it is allowed to do so. His next remark re-stated that the departure plan calls for a heading of 326-degrees magnetic, that their first altitude assignment was for 5,000 feet, and that he expected to throttle back from thrust (EPR) takeoff setting of 2.04 to a climb setting of between 1.55 and 1.6. Takeoff clearance came forty seconds later, with the urgent injunction "no delay." There was another incoming jet two and a half miles out heading for the same runway. Flight 90's engines spooled up, and the 737 began its ground roll down runway 36. Note that the curly brackets indicate text I have added to the transcript.

1559:54 {Voice identification unclear} CAM-? Real cold here

1559:55 Pettit/CAM-2 Got 'em?

1559:56 Wheaton/CAM-1 Real cold

1559:57 Wheaton/CAM-1 Real cold

1559:58 Pettit/CAM-2 God, look at that thing

1600:02 Pettit/CAM-2 That doesn't seem right does it?

1600:05 Pettit/CAM-2 Ah, that's not right

1600:07 Pettit/CAM-2 (Well) –

1600:09 Wheaton/CAM-1 Yes it is, there's eighty {knots indicated airspeed}

1600:10 Pettit/CAM-2 Naw, I don't think that's right

1600:19 Pettit/CAM-2 Ah, maybe it is

1600:21 Wheaton/CAM-1 Hundred and twenty

1600:23 Pettit/CAM-2 I don't know

1600:31 Wheaton/CAM-1 Vee one

1600:33 Wheaton/CAM-1 Easy

1600:37 Wheaton/CAM-1 Vee two

1600:39 CAM (Sound of stickshaker starts and continues to impact)

1600:45 Wheaton/CAM-1 Forward, forward {presumably the plane is over-rotating to too high a pitch attitude}

1600:47 CAM-? Easy

1600:48 Wheaton/CAM-1 We only want five hundred {feet per minute climb}

1600:50 Wheaton/CAM-1 Come on, forward

1600:53 Wheaton/CAM-1 Forward

1600:55 Wheaton/CAM-1 Just barely climb

1600:59 Pettit/CAM-2 (Stalling) we're (falling)

1601:00 Pettit/CAM-2 Larry we're going down, Larry

1601:01 Wheaton/CAM-1 I know it

1601:01 ((Sound of impact))

The aircraft struck rush-hour traffic on the Fourteenth Street Bridge, hitting six occupied automobiles and a boom truck, ripping a 41-foot section of the bridge wall along with 97 feet of railings. The tail section pitched up, throwing the cockpit down towards the river. Torn to pieces by the impact, the airplane ripped and buckled, sending seats into each other amidst the collapsing structure. According to pathologists cited in the NTSB report, seventy passengers, among whom were three infants and four crewmembers, were fatally injured; seventeen passengers were incapacitated by the crash and could not escape.[2] Four people in vehicles died immediately of impact-induced injuries as cars were spun across the bridge. Only the tail section of the plane remained relatively intact, and from it six people were plunged into the 34-degree ice-covered Potomac. The one surviving flight attendant, her hands immobilized by the cold, managed to chew open a plastic bag containing a flotation device and give it to the most seriously injured passenger. Twenty minutes later, a Parks Department helicopter arrived at the scene and rescued four of the five survivors; a bystander swam out to rescue the fifth.[3]

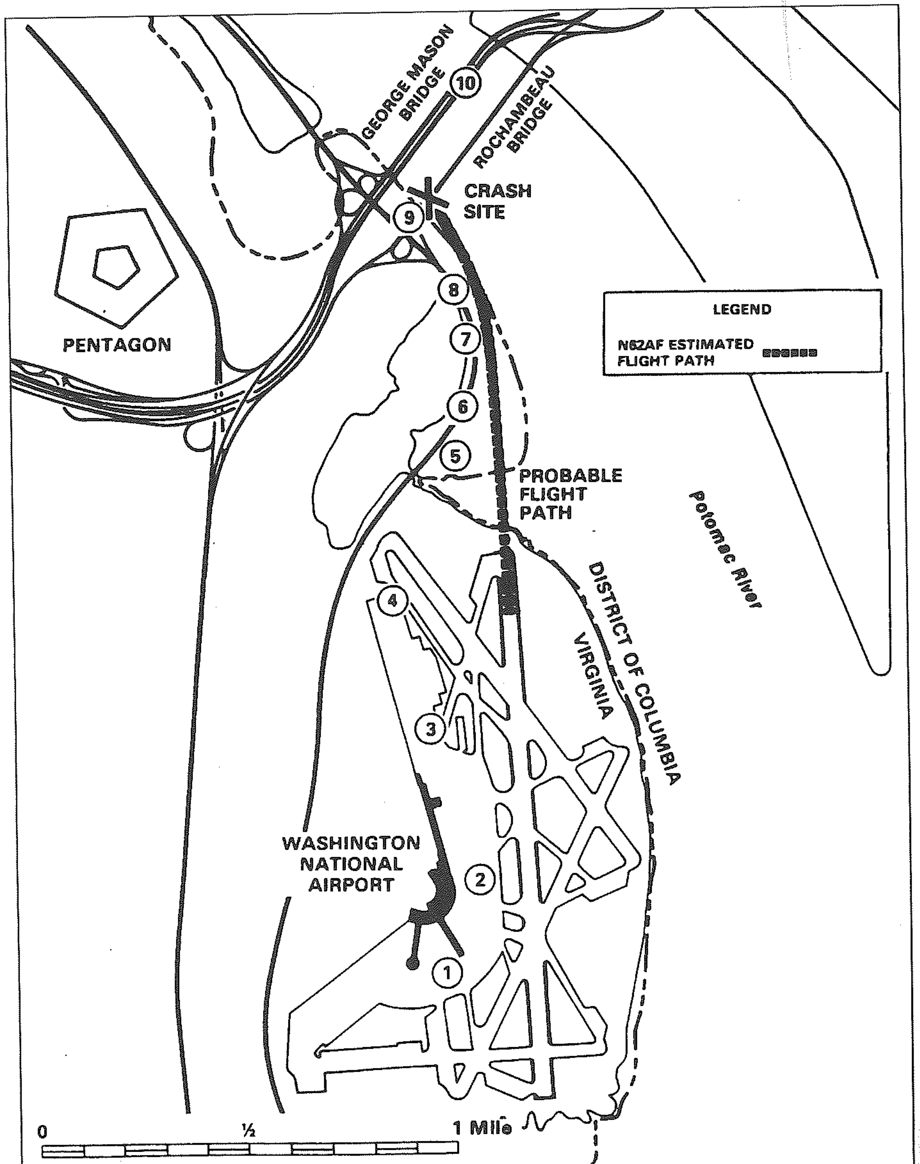

Figure 1. Flightpath. Sources: National Transportation Safety Board, Aircraft Accident Report, Air Florida, Inc. Boeing 737-222, N62AF, Collision with 14th Street Bridge, near Washington National Airport Washington, D.C., January 13, 1982, p. 7, figure 1. Hereafter, NTSB-90.

2. THE PHYSICS OF FAILURE

Why did flight 90 crash? At a technical level (and as we will see the technical never is purely technical) the NTSB concluded that the answer was twofold: not enough thrust and contaminated wings. Easily said, less easily demonstrated. The crash team mounted three basic arguments. First, from the cockpit voice recorder, investigators could extract and frequency analyze the background noise, noise that was demonstrably dominated by the rotation of the low-pressure compressor. This frequency, which corresponds to the number of blades passing per second (BPF), is closely related to the instrument panel gauge N1 (percentage of maximum rpm for the low pressure compressor) by the following formula:

BPF (blades per second) = (rotations per minute (rpm) x number of blades)/60

or

Percent max rpm (N1) = (rpm x 60 x BPF x 100)/(maximum rpm x number of blades)

Applying this formula, the frequency analyzer showed that until 1600:55 – about six seconds before the crash – N1 remained between 80 and 84 percent of maximum. Normal N1 during standard takeoff thrust was about 90 percent. It appeared that only during these last seconds was the power pushed all the way. So why was N1 so low, so discordant with the relatively high setting of the EPR at 2.04? After all, we heard a moment ago on the CVR that the engines had been set at 2.04, maximum takeoff thrust. How could this be? The report then takes us back to the gauges.

The primary instrument for takeoff thrust was the Engine Pressure Ratio gauge, the EPR. In the 737 this gauge was read off of an electronically divided signal in which the inlet engine nose probe pressure given by Pt2 was divided by the engine exhaust pressure probe Pt7. Normally the Pt2 probe was deiced by the anti-ice bleed air from the engine's eighth stage compressor. If, however, ice were allowed to form in and block the probe Pt2, the EPR gauge would become completely unreliable. For with Pt2 frozen, pressure measurement took place at the vent (see figure 2) – and the pressure at that vent was significantly lower than the compressed air in the midst of the compressor, making

apparent EPR = Pt7/(Pt2-vent) > real EPR = Pt7/Pt2.

Since takeoff procedure was governed by throttling up to a fixed EPR reading of 2.04, a falsely high reading of the EPR meant that the "real" EPR could have been much less, and that meant less engine power.

To test the hypothesis of a frozen low pressure probe, the Boeing Company engineers took a similarly configured 737-200 aircraft with JT8D engines resembling those on the accident flight, and blocked with tape the Pt2 probe on the number one engine (simulating the probe being frozen shut). They left the number two engine probe unblocked (normal). The testers then set the Engine Pressure Ratio

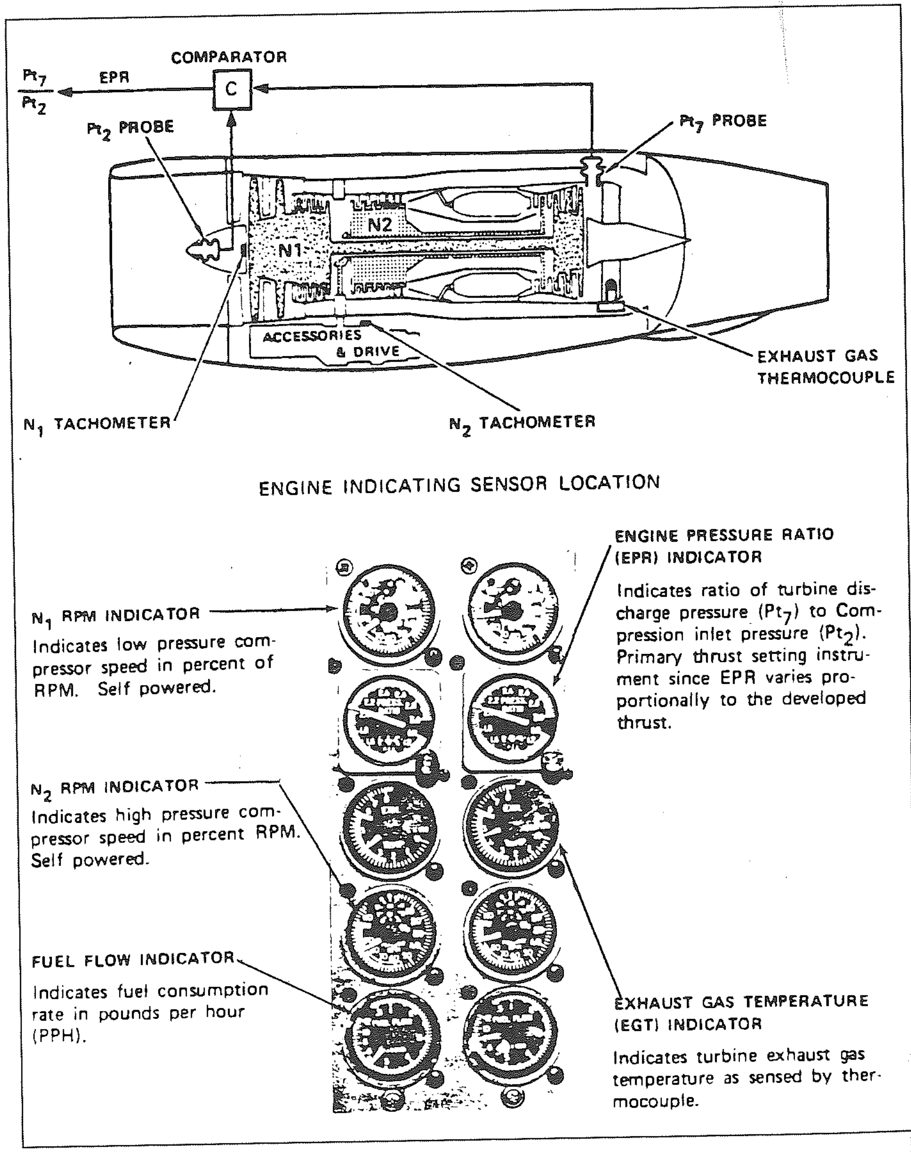

Figure 2. Pt2 and Pt7. Source: NTSB-90, p. 25, figure 5.

indicator for both engines at takeoff power (2.04), and observed the resulting readings on the other instruments for both "frozen" and "normal" cases. This experiment made it clear that the EPR reading for the blocked engine was deceptive – as soon as the tape was removed from Pt2, the EPR revealed not the 2.04 to which it had been set, but a mere 1.70. Strikingly, all the other number one engine gauges

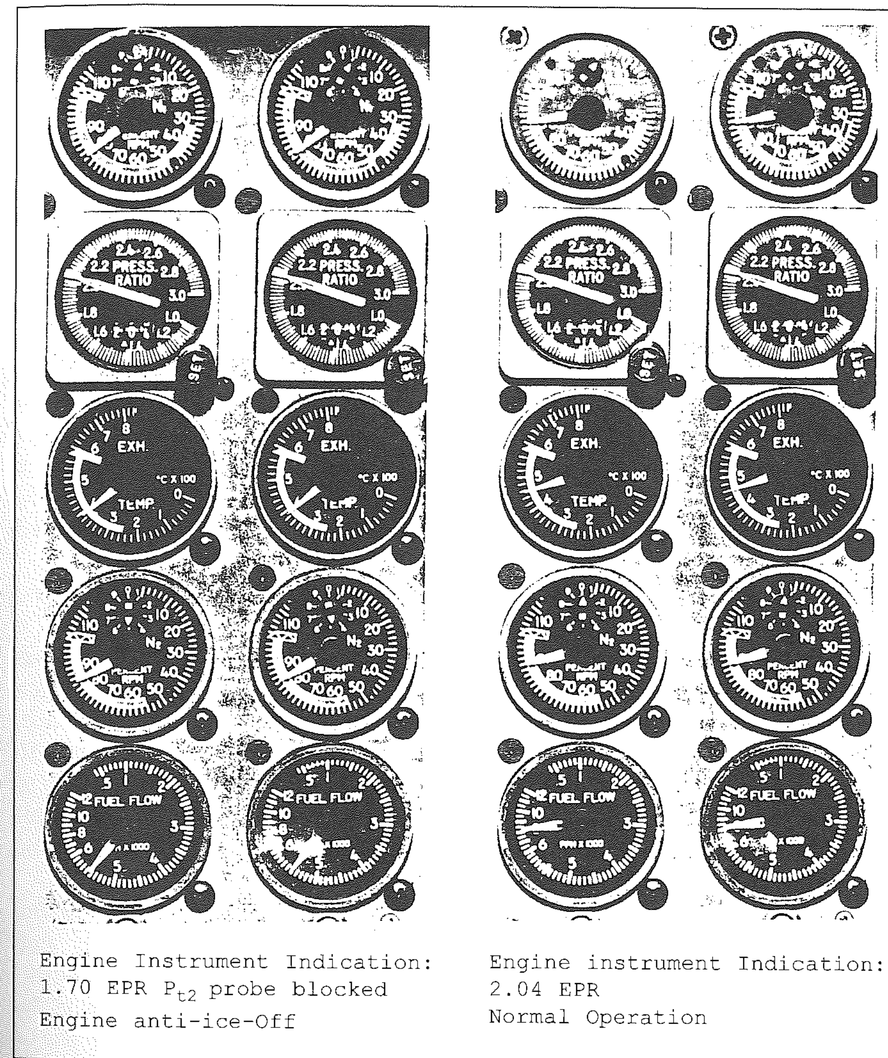

Figure 3. Instruments for Normal/Blocked Pt2. Source: NTSB-90, p. 26, figure 6.

– N1, N2, EGT, and Fuel Flow – remained at the level expected for an EPR of 1.70. One thing was now clear: instead of two engines operating at an EPR of 2.04 or 14,500 lbs of thrust each, flight 90 had taken off, hobbled into a stall, and begun falling towards the 14th Street Bridge with two engines delivering an EPR of 1.70, a mere 10,750 lbs of thrust apiece. At that power, the plane was only marginally able to climb under perfect conditions. And with wings covered with ice and snow, flight 90 was not, on January 13, flying under otherwise perfect conditions.

Finally, in Boeing's Flight Simulator Center in Renton, Washington, staff unfolded a third stage of inquiry into the power problem. With some custom programming the computer center designed visuals to reproduce the runway at Washington National Airport, the 14th Street Bridge and the railroad bridge. Pilots flying the simulator under "normal" (no-ice configuration) concurred that the simulation resembled the 737s they flew. With normalcy defined by this consensus, the simulator was then set to replicate the 737-200 with wing surface contamination – specifically the coefficient of lift was degraded and that of drag augmented. Now using the results of the engine test and noise spectrum analysis, engineers set the EPR at 1.70 instead of the usual takeoff value of 2.04. While alone the low power was not "fatal" and alone the altered lift and drag were not catastrophic, together the two delivered five flights that did reproduce the flight profile, timing and position of impact of the ill-starred flight 90. Under these flight conditions the last possible time in which recovery appeared possible by application of full power (full EPR = 2.23) was about 15 seconds after takeoff. Beyond that point, no addition of power rescued the plane.[4]

Up to now the story is as logically straightforward as it is humanly tragic: wing contamination and low thrust resulting from a power setting fixed on the basis of a frozen, malfunctioning gauge drove the 737 into a low-altitude stall. But from this point on in the story that limpid quality clouds. Causal lines radiated every which way like the wires of an old, discarded computer – some terminated, some crossed, some led to regulations, others to hardware; some to training, and others to individual or group psychology. At the same time, this report, like others, began to focus the causal inquiry upon an individual element, or even on an individual person. This dilemma between causal diffusion and causal localization lay at the heart of this and other inquiries. But let us return to the specifics.

The NTSB followed, inter alia, the deicing trucks. Why, the NTSB asked, was the left side of the plane treated without a final overspray of glycol while the right side received it? Why was the glycol mixture wrongly reckoned for the temperature? Why were the engine inlets not properly covered during the spraying? Typical of the ramified causal paths was the one that led to a non-regulation nozzle used by one of the trucks, such that its miscalibration left less glycol in the mixture (18%) than there should have been (30%).[5] What does one conclude? That the replacement nozzle killed these men, women and children? That the purchase order clerk who bought it was responsible? That the absence of a "mix monitor" directly registering the glycol-to-water ratio was the seed of destruction?[6] And the list of circumstances without which the accident would not have occurred goes on – including the possibility that wing de-icing could have been used on the ground, that better gate holding procedures would have kept flight 90 from waiting so long between de-icing and takeoff, to name but two others.[7]

There is within the accident report's expanding net of counterfactual conditionals a fundamental instability that, I believe, registers in the very conception of these

accident investigations. For these reports in general – and this one in particular – systematically turn in two conflicting directions. On one side the reports identify a wide net of *necessary* causes of the crash, and there are arbitrarily many of these – after all the number of ways in which the accident might *not* have happened is legion. Human responsibility in such an account disperses over many individuals. On the other side, the reports zero in on *sufficient, localizable* causes, often the actions of one or two people, a bad part or faulty procedure. Out of the complex net of interactions considered in this particular accident, the condensation was dramatic: the report lodged immediate, local responsibility squarely with the captain.

Fundamentally, there were two charges: that the captain did not reject the takeoff when the first officer pointed out the instrument anomalies, and that, once in the air, the captain did not demand a full-throttle response to the impending stall. Consider the "rejection" issue first. Here it is worth distinguishing between dispersed and individuated causal agency (*causal instability*), and individual and multiple responsibility (*agency instability*). There is also a third instability that enters, this one rooted between the view that flight competence stems from *craft* knowledge and the view that it comes from *procedural* knowledge (*protocol instability*).

The NTSB began its discussion of the captain's decision not to reject by citing the Air Florida Training and Operations Manual:

> Under adverse conditions on takeoff, recognition of an engine failure may be difficult. Therefore, close reliable crew coordination is necessary for early recognition.
>
> The captain *ALONE* makes the decision to "REJECT."
>
> On the B-737, the engine instruments must be closely monitored by the pilot not flying. The pilot flying should also monitor the engine instruments within his capabilities. Any crewmember will call out any indication of engine problems affecting flight safety. The callout will be the malfunction, e.g., "ENGINE FAILURE," "ENGINE FIRE," and appropriate engine number.
>
> The decision is still the captain's, but he must rely heavily on the first officer.
>
> The initial portion of each takeoff should be performed as if an engine failure were to occur.[8]

The NTSB report used this training manual excerpt to show that despite the fact that the co-pilot was the "pilot flying," responsibility for rejection lay squarely and unambiguously with the captain. But intriguingly, this document also pointed in a different direction: that rejection was discussed in the training procedure uniquely in terms of the failure of a single engine. Since engine failure typically made itself known through differences between the two engines' performance instruments, protocol directed the pilot's attention to a comparison (cross-check) between the number one and number two engines, and here the two were reading exactly the same way. Now it is true that the NTSB investigators later noted that the reliance on *differences* could have been part of the problem.[9] In the context of training procedures that stressed the cross-check, the absence of a difference between the left and right engines strikes me not as incidental, but rather as central. In particular it may help explain why the first officer saw something as wrong – but not something that fell into the class of expectations. He did not see a set of instruments that protocol suggested would reflect the alternatives "ENGINE FAILURE" or "ENGINE FIRE."

But even if the first officer or captain unambiguously knew that, say, N1 was low for a thrust setting of the EPR readout of 2.04, the rejection process itself was riddled with problems. Principally, it makes no sense. The airspeed V1 *functioned* as the speed below which it was supposed to be safe to decelerate to a stop and above which it was safe to proceed to takeoff even with an engine failure. But this speed was so racked with confusion that it is worth discussing. Neil Van Sickle gives a typical definition of V1 in his *Modern Airmanship*, where he writes that V1 is "The speed at which ... should one engine fail, the distance required to complete the takeoff exactly equals the distance required to stop."[10] So before V1, if the engine failed, you could stop in less distance than you could get off the ground. Other sources defined V1 as the speed at which air would pass the rudder rapidly enough for rudder authority to keep a plane with a dead engine from spinning. Whatever its basis, as the Air Florida Flight Operations Manual for the Boeing 737 made clear, pilots were to reject a takeoff if the engine failed before V1; afterwards, presumably, the takeoff ought be continued. The problem is that, by its use, the *speed* V1 had come to serve as a marker for the crucial *spatial point* where the speed of the plane and distance to go made it possible to stop (barely) before overrunning the runway. In the supporting documents of the NTSB report (called the Docket) one finds in the Operations Group "factual report" the following hybrid definition of V1:

> [V1 is] the speed at which, if an engine failure occurs, the distance to continue the takeoff to a height of 35 feet will not exceed the usable takeoff distance; or the distance to bring the airplane to a full stop will not exceed the acceleration-stop distance available. V1 must not be greater than the rotation speed, Vr [rejecting after rotation would be enormously dangerous], or less than the ground minimum control speed Vmcg [rejecting before the plane achieves sufficient rudder authority to become controllable would be suicidal].[11]

Obviously, V1 cannot possibly do the work demanded of it: it is the wrong parameter to be measuring. Suppose the plane accelerated at a slow, constant rate from the threshold to the overrun area, achieving V1 as it began to cross the far end of the runway. That would, by the book, mean it could safely take off where in reality it would be within a couple of seconds of collapsing into a fuel-soaked fire. The question should be whether V1 has been reached by a certain point on the runway where a maximum stop effort will halt the plane before it runs out of space (a point known elsewhere in the lore as the acceleration-stop distance). If one is going to combine the acceleration-stop distance with the demand that the plane have rudder authority and that it be possible to continue in the space left to an engine-out takeoff, then one way or another, *the speed V1 must be achieved at or before a fixed point on the runway*. No such procedure existed.

Sadly, as the NTSB admitted, it was technically unfeasible to marry the very precise inertial navigation system (fixing distance) to a simple measurement of time elapsed since the start of acceleration. And planting distance-to-go markers on the runway was dismissed because of the "fear of increasing exposure to unnecessary high-speed aborts and subsequent overruns ... .[that might cause] more accidents than they might prevent."[12] With such signs the rolling protocol would presumably demand that the pilots reject any takeoff where V1 was reached after a certain point on the runway. But given the combination of technical limitations and cost-benefit *decisions* about markers, it was, in fact, impossible to know in a protocol-following way whether V1 had been achieved in time for a safe rejection. This meant that the procedure of rejection by V1 turns out to be completely unreliable in just that case where the airplane is accelerating at a less than normal rate. And it is *exactly* such a low-acceleration case that we are considering in flight 90. What is demanded of a pilot – a pilot on *any* flight using V1 as a go-no-go speed – is a judgment, a protocol-defying judgment, that V1 has been reached "early enough" (determined without an instrument or exterior marking) in the takeoff roll and without a significant anomaly. (Given the manifest and recognized dangers of aborting a high-speed roll, "significant" here obviously carries much weight; Air Florida, for example, forbids its pilots from rejecting a takeoff solely on the basis of the illumination of the Master Caution light.)[13]

The NTSB report "knows" that there is a problem with the V1 rejection criterion, though it knows it in an unstable way:

> It is not necessary that a crew completely analyze a problem before rejecting a takeoff on the takeoff roll. An observation that something is not right is sufficient reason to reject a takeoff without further analysis ... The Safety Board concludes that there was sufficient doubt about instrument readings early in the takeoff roll to cause the captain to reject the takeoff while the aircraft was still at relatively low speeds; that the doubt was clearly expressed by the first officer; and that the failure of the captain to respond and reject the takeoff was a direct cause of the accident.[14]

Indeed, after a careful engineering analysis involving speed, reverse thrust, the runway surface, and braking power, the NTSB determined the pilot could have aborted even with a frictional coefficient of 0.1 (sheet ice) – the flight 90 crew should not have had trouble braking to a stop from a speed of 120 knots on the takeoff roll. "Therefore, the Safety Board believes that the runway condition should not have been a factor in any decision to reject the takeoff when the instrument anomaly was noted."[15]

What does this mean? What is this concept of agency that takes the theoretical engineering result computed months later and uses it to say "therefore ... should not have been a factor"? Is it that the decision that runway condition "should not have been a factor" would have been apparent to a Laplacian computer, an ideal pilot able to compute friction coefficients by sight and from it deceleration distance using weight, wind, breaking power, and available reverse thrust? Robert Buck, a highly experienced pilot – a 747 captain, who was given the Air Medal by President Truman – wrote about the NTSB report on flight 90: "How was a pilot to know that [he could have stopped]? No way from training, no way was there any runway coefficient information given the pilot; a typical NTSB after-the-fact, pedantic, unrealistic piece of laboratory-developed information."[16]

Once the flight was airborne with the stickshaker vibrating and the stall warning alarm blaring, the NTSB had a different criticism: the pilot did not ram the throttles into a full open position. Here the report has an interesting comment. "The Board believes that the flightcrew hesitated in adding thrust because of the concern about exceeding normal engine limitations which is ingrained through flightcrew training programs." If power is raised to make the exhaust temperature rise even momentarily above a certain level, then, at bare minimum, the engine has to be completely disassembled and parts replaced. Damage can easily cost hundreds of thousands of dollars, and it is no surprise that firewalling a throttle is an action no trained pilot executes easily. But this line of reasoning can be combined with arguments elsewhere in the report. If the captain believed (as the NTSB argues) that the power delivered was normal takeoff thrust, he might well have seen the stall warning as the result of an over-rotation curable by no more than some forward pressure on the yoke. By the time it became clear that the fast rate of pitch and high angle of attack were not easily controllable (737s notoriously pitch up with contaminated wings), he did apply full power – but given the delay in jet engines between power command and delivery, it was too late. The NTSB recommended changes in "indoctrination" to allow for modification if loss of aircraft is the alternative.[17]

In the end, the NTSB concluded their analysis with the following statement of probable cause, the bottom line:

> The National Transportation Safety Board determines that the probable cause of this accident was the flightcrew's failure to use engine anti-ice during ground operation and takeoff, their decision to take off with snow/ice on the airfoil surfaces of the aircraft, and the captain's failure to reject the takeoff during the early stage when his attention was called to anomalous engine instrument readings.[18]

But there was one more implied step to the account. From an erroneous gauge reading and icy wing surfaces, the Board had driven their "probable cause" back to a localizable faulty human decision. Now they began, tentatively, to put that human decision itself under the microscope. Causal diffusion shifted to causal localization.

3. SOCIOLOGY ON THE FLIGHTDECK

In the NTSB's final judgment of probable cause was an explicit reference to the fact that the captain failed to reject the takeoff "when his attention was called to anomalous engine instrument readings." Though not formalized in the probable cause assessment, the investigative team did comment elsewhere in the report that

the Safety Board strongly believed in the training program of command decision, resource management, role performance, and assertiveness. As the NTSB pointed out, it had already, in June of 1979 (A-79-47), recommended flightdeck resource management, boosting the merits of participative management and assertiveness training for other cockpit crewmembers. Here a new analytical framework entered, in which causal agency fell not to individual but to group (social) psychology. That framework (dubbed Cockpit Resource Management or CRM) was fairly recent and came in the wake of what became a set of canonical accidents. The NTSB-interpreted record of Air Florida flight 90 became a book in that canon.

For United Airlines, the transformation in their view of CRM came following the December 28, 1978 loss of their flight UA 173. Departing Denver with 46,700 pounds of fuel, with 31,900 predicted necessary for the leg to Portland, the DC-8 came in for final approach. When the gear lowered, those in the body of the plane heard a loud noise and sharp jolt. The captain felt that the gear had descended too rapidly, and noted that the gear lights did not illuminate. Asking his second officer to "give us a current card on weight, figure about another fifteen minutes," he received a query in reply, "fifteen minutes?" To this, the captain responded "Yeah, give us three or four thousand lbs. on top of zero fuel weight." Second officer: "not enough. Fifteen minutes is really gonna really run us low on fuel here," then later: "we got about three on the fuel and that's it." When the first officer urged, "We're going to lose an engine," the captain responded "why?" To which the first officer responded "Fuel!" Within eight minutes the plane was down in the woods outside the city, with a loss of ten lives.[19] The canonical interpretation read the accident in terms of a failure of communication: Why, United Airlines personnel wanted to know, was the captain not listening to his officers?

According to United Airlines' CRM curriculum of the mid 1990s, the conversion of Delta Airlines to CRM came seven years after the United 173 crash, in the aftermath of its own disastrous flight 191. Approaching Dallas Fort Worth airport on August 2, 1985, Delta's L-1011 hit a microburst, descended into the ground, and disintegrated. The question raised by investigators was why the otherwise prudent captain had entered an area of known lightning – that is to say a thunderstorm – close to the ground and in a shaft of pounding rain. "Probable cause" included the decision to enter the cumulonimbus area, a lack of training in escape from windshear, and lack of timely windshear warning. Unlike the captain of United 173 or Air Florida 90, no one suggested here that the Delta captain was not listening to the flightcrew. Instead, "given the fact that the captain was described as one who willingly accepted suggestions from flightcrew members," the Board did not infer that they were intimidated by him. But because neither first nor second officer dissented from the continued approach, the NTSB held the flightcrew responsible for the decision to continue. "Suggestions were not forthcoming," concluded the investigation, on the basis of which the NTSB argued that air carriers should provide formal cockpit resource management and assertiveness training for their crews.[20]

When, in the mid 1980s, the airlines began to develop their CRM courses, they invariably turned back to the by-then widely-discussed proceedings of a meeting held under NASA's auspices in San Francisco over 26-28 June 1979. In various ways, that conference set out the outline for hundreds of courses, books, and pamphlets designed to characterize and cure the "dangerous" failures of communication on the flightdeck. Most prominent among the speakers was Robert Helmreich, a social psychologist from the University of Texas at Austin, who came to the problem through his work on Navy and NASA crew training efforts for the space program. Psychology (Helmreich declared at the San Francisco meeting) had so far failed those in the cockpit. On one side, he noted, there was personality psychology which had concentrated solely on exclusion of unacceptable candidates, failing utterly to capture the positive individual qualities needed for successful flight. On the other side, Helmreich contended, social psychologists had so far ignored personality and focused on rigorous laboratory experiments only loosely tied to real-life situations. Needed was an approach that joined personality to social interaction. To this end he advocated the representation of an individual's traits by a point on a two-dimensional graph with *instrumentality* on one axis and *expressivity* on the other. At the far end of instrumentality lay the absolutely focused goal-oriented pilot, on the extreme end of expressivity lay the pilot most adept at establishing "warmer" and more effective personal relationships. In a crisis, (argued the authors of United's CRM course) being at the high end of both was crucial, and likely to conflict with the "macho pilot" who is high in instrumentality and low in expressivity.[21]

In various forms, this two-dimensional representation of expressivity and instrumentality crops up in every presentation of CRM that I have seen. Perhaps the most sophisticated reading of the problem came in another plenary session of the 1979 meeting, in the presentation by Lee Bolman from the Harvard Graduate School of Education. Bolman's idea was to pursue the mutual relations of three different "theories": first, there was the principals' short-term "theory of the situation" which captured their momentary understanding of what was happening, here the pilots' own view of the local condition of their flight. Second, Bolman considered the individual's longer-term "theory of practice," that collection of skills and procedures accumulated over a period of years. Finally, at the most general level, there was a meta-theory, the "theory-in-use" that contained the general rules by which information was selected, and by which causal relationships could be anticipated. In short, the meta-theory provided "core values," "beliefs," "skills," and "expected outcomes." Deduced from observation, the "theory in use" was the predictively successful account of what the subject will actually do in specific situations. But Bolman noted that this "theory-in-use" only partially overlapped with views that the subject may explicitly claim to have ("the espoused theory"). Espoused knowledge was important, Bolman argued, principally insofar as it highlighted errors or gaps in the "theory in use":

> Knowledge is "intellectual" when it exists in the espoused theory but not in the theory-in-use: the individual can think about it and talk about it, but cannot do it. Knowledge is "tacit" when it exists in the theory-in-use but not the espoused theory; the person can do it, but cannot explain how it is done. Knowledge is "integrated" when there is synchrony between espoused theory and theory-in-use: the person can both think it and do it.[22]

Bottom line: Bolman took the highest level theory ("theory-in-use") to be extremely hard to revise as it involved fundamental features of self-image and lifelong habits. The lowest level theory ("theory of the situation") might be revised given specific technical inputs (one gauge corrected by the reading of two others) but frequently will only actually be revised through an alteration in the "theory of practice." It was therefore at the level of a "theory of practice" that training was most needed. Situations were too diverse and patterns of learning too ingrained to be subject to easy alteration. At this level of practice could be found the learnable skills of advocacy, inquiry, management, and role modification. And these, Bolman and the airlines hoped, would contribute to a quicker revision of a faulty "theory of the situation" when one arose. CRM promised to be that panacea.

Textbooks and airlines leaped at the new vocabulary of CRM. Stanley Trollip and Richard Jensen's widely distributed *Human Factors for General Aviation* (1991) graphed "relationship orientation" on the y-axis against "task orientation" on the abscissa. High task orientation with low relationship orientation yields the dreadful amalgam: a style that would be "overbearing, autocratic, dictatorial, tyrannical, ruthless, and intimidating."

According to Trollip and Jensen, who took United 173, Delta 191, and Air Florida 90 as principal examples, the co-pilot of Air Florida 90 was earnestly asking after take-off procedures when he asked about the slushy runway departure, and was (according to the authors) being mocked by captain Wheaton in his response "unless you got something special you'd like to do," a mockery that continued in the silences with which the captain greeted every subsequent intervention by the co-pilot.[23] Such a gloss assumed that copilot Pettit understood that the EPR was faulty and defined the catastrophe as a failure of his advocacy and the captain's inquiry. Once again agency and cause were condensed, this time to a social, rather than, or in addition to, an individual failure. Now this CRM reading may be a way of glossing the evidence, but it is certainly not the only way; Pettit may have noted the discrepancy between the EPR and N1, for example, noted too that both engines were reading identically, and over those few seconds not known what to make of this circumstance. I want here not to correct the NTSB report, but to underline the fragility of these interpretive moments. Play the tape again:

> F.O. Pettit (CAM-1): "That's not right … well … "
>
> Captain Wheaton (CAM-1): "Yes it is, there's eighty"
>
> Pettit (CAM-2): "Naw, I don't think that's right … . Ah, maybe it is."
>
> Wheaton (CAM-1): "One hundred twenty"
>
> Pettit (CAM-2): "I don't know."

Now it might be that in these hesitant, contradictory remarks Pettit is best understood to be *advocating* a rejected takeoff. But it seems to be at least worth considering that when Pettit said, "I don't know," that he meant, in fact, that he did not know.

United Airlines put it only slightly differently than Trollip and Jensen when the company used its instructional materials to tell new captains to analyze themselves

The Grid Approach To Job Performance

A study of how the Grid framework applies to the cockpit can aid individuals in exploring alternative possibilities of behaviour which may have been unclear. Understanding these concepts can enable a person to sort out unsound or ineffective behavior and replace it with more effective behaviors.

The Grid below can be used as a frame of reference to study how each crewmember approaches a job.

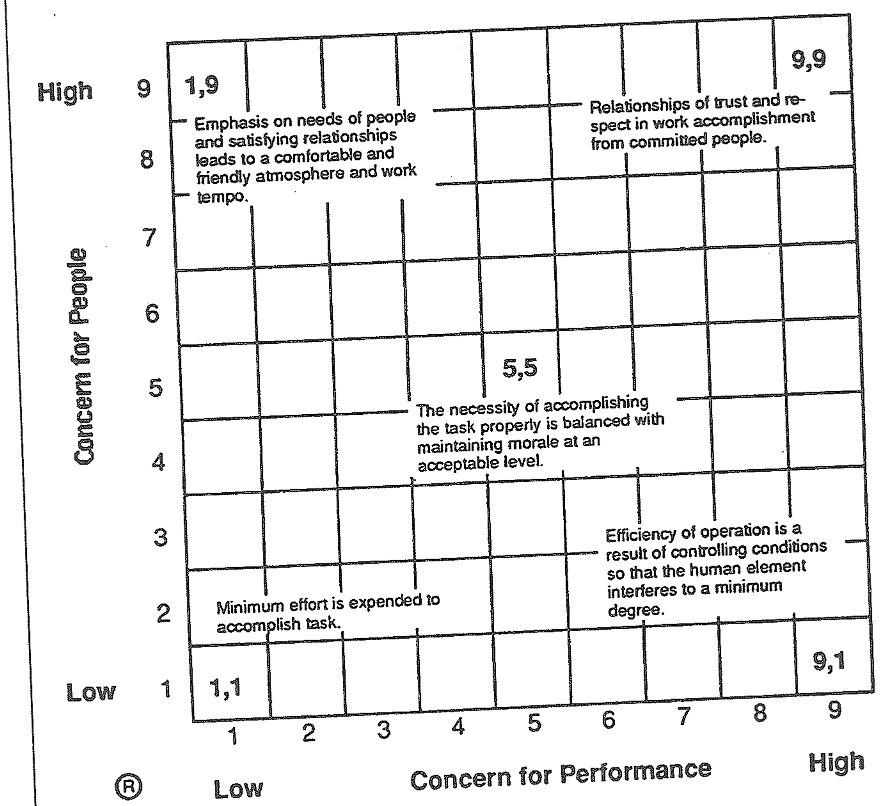

Figure 4. United CRM Grid. Source: United Airlines training manual, "Introduction to Command/Leadership/Resource Management," MN-94, 10/95, p. 9.

and others on the Grid, a matrix putting "concern for people" against "concern for performance." Each of several decision-making elements then get graphed to the Grid: inquiry, advocacy, conflict resolution, and critique. Inquiry, for example, comes out this way in the (1,9) quadrant: "I look for facts, decisions, and beliefs that suggest all is well; I am not inclined to challenge other crewmembers" and in the (9,1) quadrant as "I investigate my own and others' facts, decisions, and beliefs in depth in order to be on top of any situation and to reassure myself that others are not making mistakes."[24] United's gloss on Flight 90's demise is not much different from that of Trollip and Jensen: the first officer made various non-assertive comments "but he never used the term, 'Abort!' The Captain failed to respond to the inquiry and advocacy of the First Officer."[25]

Not surprisingly, the 747 pilot I quoted before, Robert Buck, registered, in print, a strenuous disagreement. After lampooning the psychologists who were intruding on his cockpit, Buck dismissed the CRM claim that the accident was a failure of assertiveness. "Almost any pilot listening to the tape would say that was not the case but rather that the crew members were trying to analyze what was going on. To further substantiate this is the fact the copilot was well-known to be an assertive individual who would have said loud and clear if he'd thought they should abort."[26] With snow falling, a following plane on their tail, ATC telling them to hurry, and the raging controversy over V1 still in the air, Buck was not at all surprised that neither pilot aborted the launch.

Again and again we have within the investigation a localized cause in unstable suspension over a sea of diffuse necessary causes.[27] We find agency personalized even where the ability to act lies far outside any individual's control. And finally, we find a strict and yet unstable commitment to protocol even when, in other circumstances, maintenance of that protocol would be equally condemned. In flight 90 the final condemnation fell squarely on the shoulders of the captain. According to the NTSB, Wheaton's multiple errors of failing to deice properly, failing to abort, and failing to immediately engage full power doomed him and scores of others.

I now want to turn to a very different accident, one in which the captain's handling of a crippled airliner left him not condemned but celebrated by the NTSB. As we will see even then, the instabilities of localized cause, protocol, and the human/technological boundary pull the narrative into a singular point in space, time, and action, but always against the contrary attraction of necessary causes that pull everywhere else.

4. OUT OF CONTROL

United Airlines flight 232 was 37,000 feet above Iowa traveling at 270 knots on 19 July 1989, when, according to the NTSB report, the flightcrew heard an explosion and felt the plane vibrate and shutter. From instruments, the crew of the DC-10-10 carrying 285 passengers could see that the number 2, tail-mounted engine, was no longer delivering power (see figure 5). The captain, Al Haynes, ordered the engine shutdown checklist, and first officer Bill Records reported first that the airplane's

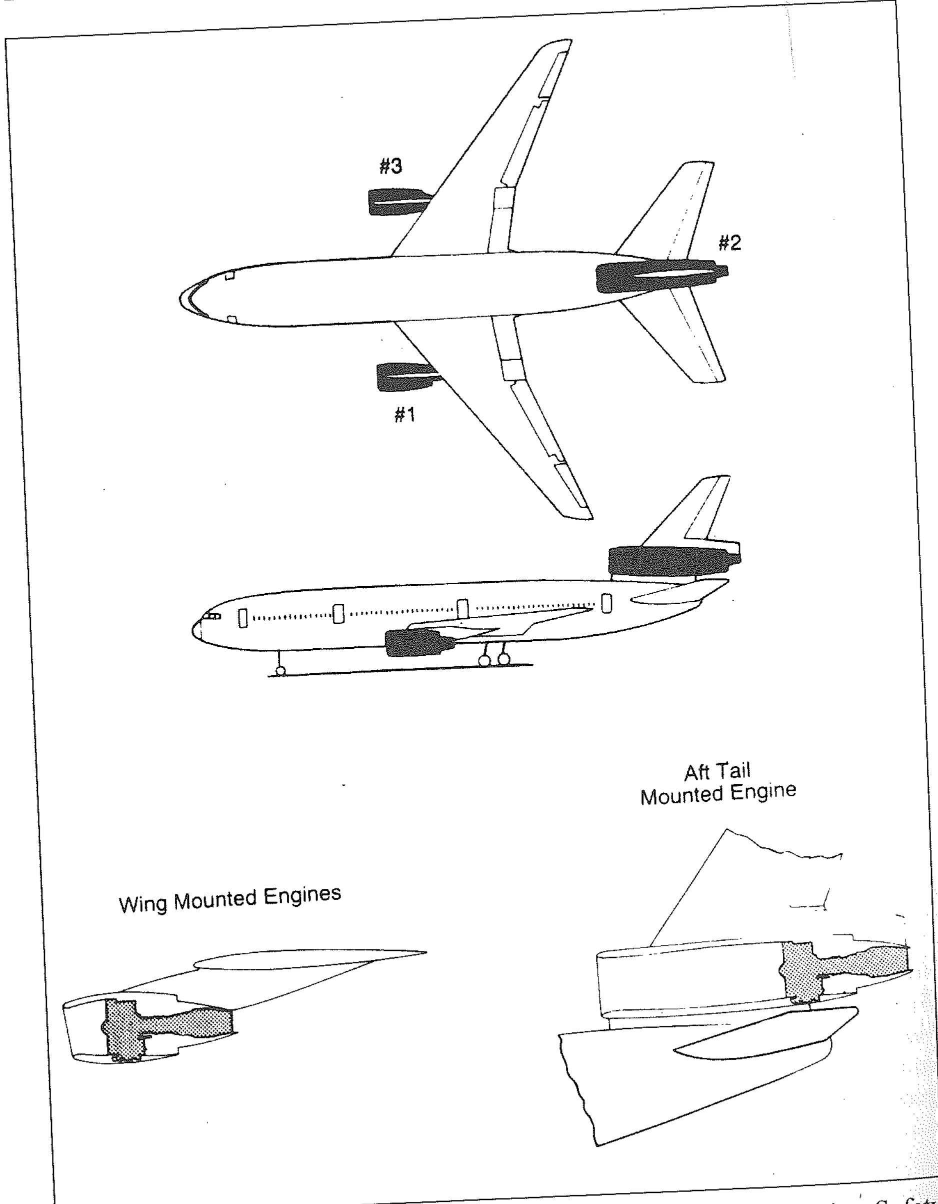

Figure 5. DC-10 Engine Arrangement. Source: National Transportation Safety Board, Aircraft Accident Report, United Airlines Flight 232, McDonnell Douglas DC-10-10, Sioux Gateway Airport, Sioux City, Iowa, July 19, 1989, p. 2, figure 1. Hereafter, NTSB-232.

normal hydraulic systems gauges had just gone to zero. Worse, he notified the captain that the airplane was no longer controllable as it slid into a descending right turn. Even massive yoke movements were futile as the plane reached 38 degrees of right roll. It was about to flip on its back. Pulling power completely off the number 1 engine, Haynes jammed the number three throttle (right wing engine) to the firewall, and the plane began to level off. "I have been asked," Haynes later wrote, "how we thought to do that; I do not have the foggiest idea."[28] No simulation training, no manual, and no airline publication had ever contemplated a triple hydraulic failure;[29] understanding how it could have happened became the centerpiece of an extraordinarily detailed investigation, one that, like the inquiry into the crash of Air Florida 90, surfaced the irresolvable tension between a search for a localized, procedural error and fault lines embedded in a wide array of industries, design philosophies, and regulations.

At 15:20, the DC-10 crew radioed Minneapolis Air Route Traffic Control Center declaring an emergency and requesting vectors to the nearest airport.[30] Flying in a first class passenger seat was Dennis Fitch, a training check airman on the DC-10, who identified himself to a flight attendant, and volunteered to help in the cockpit. At 15:29 Fitch joined the team, where Haynes simply told him: "We don't have any controls." Haynes then sent Fitch back into the cabin to see what external damage, if any, he could see through the windows. Meanwhile, second officer Dudley Dvorak was trying over the radio to get San Francisco United Airlines Maintenance to help, but without much success: "He's not telling me anything." Haynes answered, "We're not gonna make the runway fellas." What Fitch had to say on his return was also not good: "Your inboard ailerons are sticking up," presumably held up by aerodynamic forces alone, and the spoilers were down and locked. With flight attendants securing the cabin at 1532:02, the captain said, "They better hurry we're gonna have to ditch." Under the captain's instruction, Fitch began manipulating the throttles to steer the airplane and keep it upright.[31]

Now it was time to experiment. Asking Fitch to maintain a 10-15° turn, the crew began to calculate speeds for a no-flap, no-slat landing. But the flight engineer's response – 200 knots for clean maneuvering speed – was a parameter, not a procedure. Their DC-10-10 had departed from its very status as an airplane. It was an object lacking even ailerons, the fundamental flight controls that were, in the eyes of many historians of flight, Orville and Wilbur Wright's single most important innovation. And that wasn't all: flight 232 had no slats, no flaps, no elevators, no breaks. Haynes was now in command of an odd, unproven hybrid, half airplane and half lunar lander, controlling motion through differential thrust. Among other difficulties, the airplane was oscillating longitudinally with a period of 40-60 seconds. In normal flight the plane will follow such long-period swings, accelerating on the downswing, picking up speed and lift, then rising with slowing airspeed. But in normal flight, these variations in pitch (phugoids) naturally damp out around the equilibrium position defined by the elevator trim. Here, however, the thrust of the numbers one and three engines which were below the center of gravity had no compensating force above the center of gravity (since the tail-mounted number two engine was now dead and gone). These phugoids could only be damped by a difficult and counter-intuitive out-of-phase application of power on the

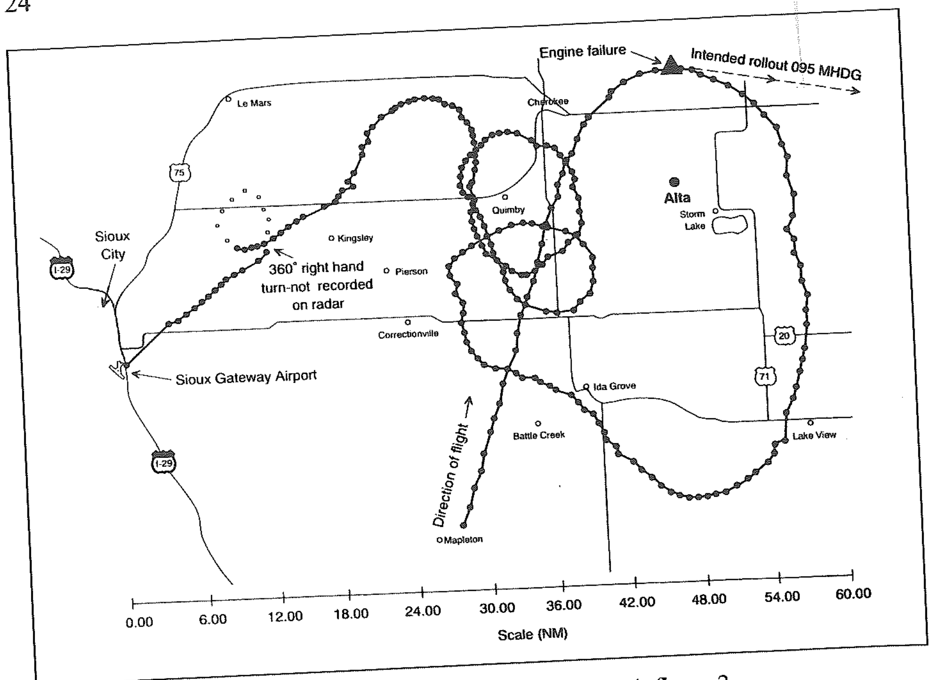

Figure 6. Ground Track of Flight 232. Source: NTSB-232, p. 4, figure 2.

downswing and, even more distressingly, throttling down on the slowing part of the cycle.[32] At the same time, the throttles had become the only means of controlling airspeed, vertical speed, and direction: the flight wandered over several hundred miles as the crew began to sort out how they would attempt a landing (see figure 6).

To a flight attendant, Haynes explained that he expected to make a forced landing, allowed that he was not at all sure of the outcome, and that he expected serious difficulty in evacuating the airplane. His instructions were brief: on his words, "brace, brace, brace," passengers and attendants should ready themselves for impact. At 15:51 Air Traffic Controller Kevin Bauchman radioed flight 232 requesting a wide turn to the left to enter onto the final approach for runway 31 – and to keep the quasi-controllable 370,000 pound plane clear of Sioux City itself. However difficult control was, Haynes concurred: "Whatever you do, keep us away from the city." Then, at 15:53 the crew told the passengers they had about four minutes before the landing. By 15:58 it became clear their original plan to land on the 9,000 foot runway 31 would not happen, though they could make the closed runway 22. Scurrying to redeploy the emergency equipment that were lined up on 22 – directly in the landing path of the quickly approaching jet–Air Traffic Control began to order their last scramble, as tower controller Bauchman told them: "That'll work sir, we're gettin' the equipment off the runway, they'll line up for that one." Runway 22 was only 6,600 feet long, but terminated in a field. It was the only runway they would have a chance to make and there would only be one chance. At

1559:44 the ground proximity warning came on … then Haynes called for the throttles to be closed, to which check airman Fitch responded "nah I can't pull 'em off or we'll lose it that's what's turnin' ya." Four seconds later, the first officer began calling out "left Al [Haynes]" "left throttle," "left," "left," left." As they plunged towards the runway, the right wing dipped and the nose dropped. Impact was at 1600:16 as the plane's right wing tip, then the right main landing gear, slammed into the concrete. Cartwheeling and igniting, the main body of the fuselage lodged in a corn field to the west of runway 17/35, and began to burn. The crew compartment and forward side of the fuselage settled east of runway 17/35. Within a few seconds, some passengers were walking, dazed and hurt, down runway 17, others gathered themselves up in the midst of seven-foot corn stalks, disoriented and lost. A powerful fire began to burn along the exterior of the fuselage fragment, and emergency personnel launched an all-out barrage of foam on the center section as surviving passengers emerged. One passenger went back into the burning wreckage to pull out a crying infant. As for the crew, for over thirty-five minutes they lay wedged in a waist-high crumpled remnant of the cockpit – rescue crews who saw the airplane fragment assumed anyone inside was dead. When he regained consciousness, Fitch was saying something was crushing his chest, dirt was in the fragmented cockpit. Second officer Dvorak found some loose insulation which he waved out a hole in the aluminum to attract attention. Finally, pried loose, emergency personnel brought the four injured crewmembers (Haynes, Records, Dvorak, and Fitch) to the local hospital.[33] Despite the loss of over a hundred lives, it was, in the view of many pilots, the single most impressive piece of airmanship ever recorded. Without any functional control surface, the crew saved 185 of the 296 passengers on flight 232.

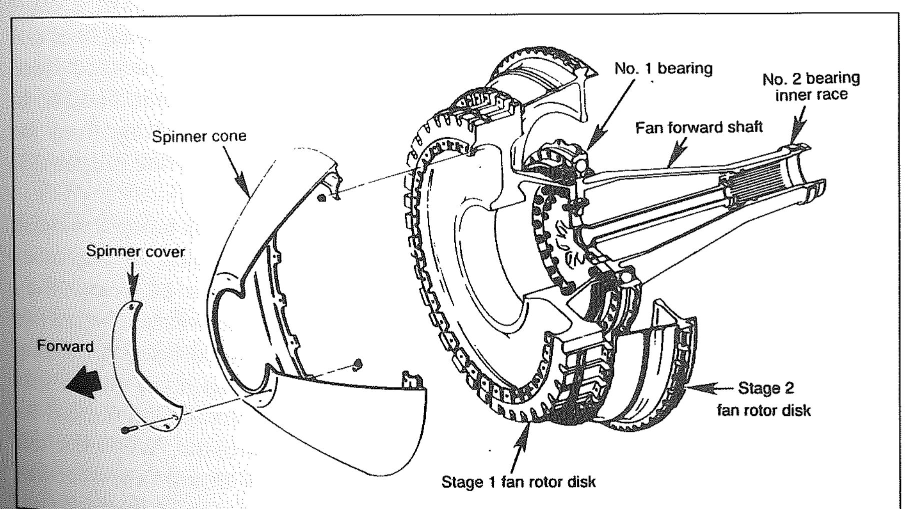

Figure 7. Fan Rotor Assembly. Source: NTSB Report,p. 9, figure 5.

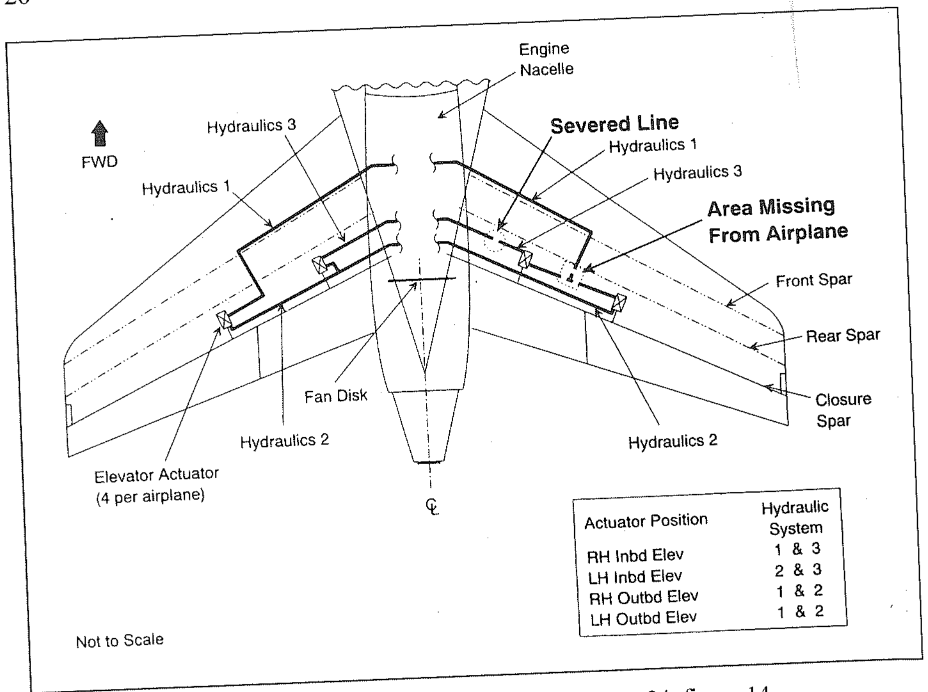

Figure 8. Planform Elevator Hydraulics. Source: NTSB-232, p. 34, figure 14.

From the start, the search for probable cause centered on the number 2 (tail-mounted) engine. Not only had the crew witnessed the destruction wrought at the tail end of the plane, but Sioux City residents had photographed the damaged plane as it neared the airport; the missing conical section of the tail was immortalized in photographs. And the stage 1 fan (see figure 7), conspicuously missing from the number 2 engine after the crash, was almost immediately a prime suspect. It became, in its own right, an object of localized, historical inquiry.

From records, the NTSB determined that this particular item was brought into the General Electric Aircraft Engines facility between 3 September and 11 December 1971. Once General Electric had mounted the titanium fan disk in an engine, they shipped it to the Douglas Aircraft Company on 22 January 1972 where it began life on a new DC-10-10. For seventeen years, the stage 1 fan worked flawlessly, passing six fluorescent penetrant inspections, clocking 41,009 engine-on hours and surviving 15,503 cycles (a cycle is a takeoff and landing).[34] But the fan did fail on the afternoon of 19 July 1989, and the results were catastrophic. When the tail engine tore itself apart, one hydraulic system was lost. With tell-tale traces of titanium, shrapnel-like fan blades left their distinctive marks on the empennage (see figure 8). Worst of all, the flying titanium severed the two remaining hydraulic lines.

With this damage, what seemed an impossible circumstance had come to pass: in a flash, all three hydraulic systems were gone. This occurred despite the fact that each of the three independent systems was powered by its own engine. Moreover, each system had a primary and backup pump, and the whole system was further backstopped by an air-powered pump powered by the slipstream. Designers even physically isolated the hydraulic lines one from the other.[35] And again, as in the Air Florida 90 accident, the investigators wanted to push back and localize the causal structure. In Flight 90, the NTSB passed from the determination that there *was* low thrust to *why* there was low thrust to *why* the captain had failed to command more thrust. Now they wanted to pass from the fact *that* the stage 1 fan disk had disintegrated to *why* it had blown apart, and eventually to *how* the faulty fan disk could have been in the plane that day.

Three months after the accident, in October of 1989, a farmer found two pieces of the stage 1 fan disk in his corn fields outside Alta, Iowa. Investigators judged from the picture reproduced here that about one third of the disk had separated, with one fracture line extending radially and the other along a more circumferential path. (See figure 9.)

Upon analysis, the near-radial fracture appeared to originate in a pre-existing fatigue region in the disk bore. Probing deeper, fractographic, metallographic and chemical analysis showed that this pre-existing fault could be tracked back to a metal "error" that showed itself in a tiny cavity only 0.055 inches in axial length and 0.015 inches in radial depth: about the size of a slightly deformed period at the end of this typed sentence. Titanium alloys have two crystalline structures, alpha and beta, with a transformation temperature above which the alpha transforms into beta. By adding impurities or alloying elements, the allotropic temperature could be lowered to the point where the beta phase would be present even at room temperature. One such alloy, Ti-6Al-4V was known to be hard, very strong, and was expected to maintain its strength up to 600 degrees Fahrenheit. Within normal Ti-6Al-4V titanium, the two microscopic crystal structures should be present in about equal quantities. But inside the tiny cavity buried in the fan disk lay traces of a "hard alpha inclusion" titanium with a flaw–a small volume of pure alpha-type crystal structure, and an elevated hardness due to the presence of (contaminating) nitrogen.[36]

Putting the myriad of the many other necessary causes for the accident aside, the gaze of the NTSB investigators focused on the failed titanium, and even more closely on the tiny cavity with its traces of an alpha inclusion. What caused the alpha inclusion? There were, according to the investigation, three main steps in the production of titanium-alloy fan disks. First, foundry workers melted the various materials together in a "heat" or heats after which they poured the mix into a titanium alloy ingot. Second, the manufacturer stretched and reduced the ingot into "billets" that cutters could slice into smaller pieces ("blanks"). Finally, in the third and last stage of titanium production, machinists worked the blank into the appropriate geometrical shapes – the blanks could later be machined into final form.

Hard alpha inclusions were just one of the problems that titanium producers and consumers had known about for years (there were also high-density inclusions, and

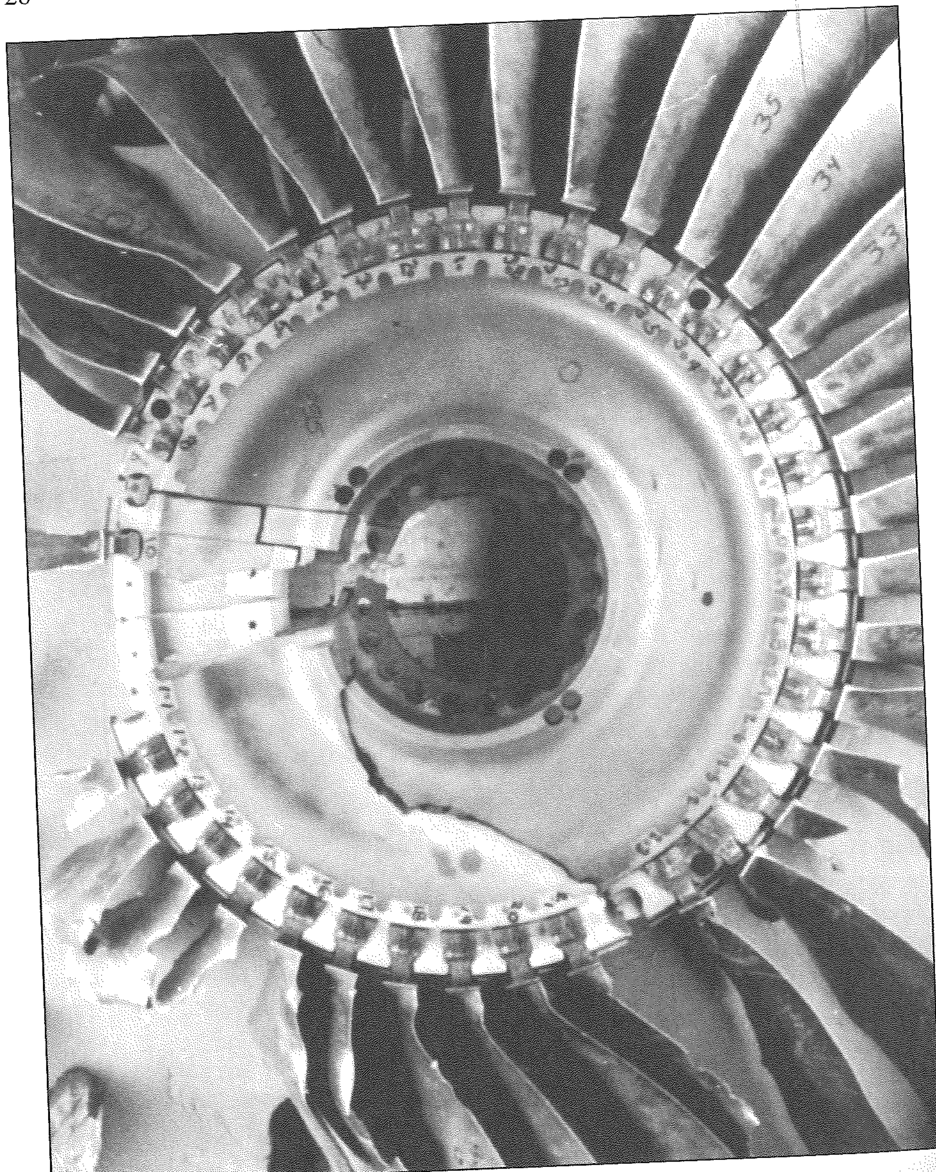

Figure 9. Stage 1 Fan Disk (Reconstruction).Source: UAL 232 Docket, figure 1.10.2.

the segregation of the alloy into flecks). To minimize the hard alpha inclusions, manufacturers had established various protective measures. They could melt the alloy components at higher heats, they could maintain the melt for a longer time, or they could conduct successive melting operations. But none of these methods offered (so to speak) an iron-clad guarantee that they would be able to weed out the impurities introduced by inadequately cleaned cutting, or sloppy welding residues. Nor could the multiple heats absolutely remove contamination from leakage into the furnace or even items dropped into the molten metal. Still, in 1970-71, General Electric was sufficiently worried about the disintegration of rotating engine parts that they ratcheted up the quality control on titanium fan rotor disks – after January 1972, the company demanded that only triple-vacuum-melted forgings be used. The last batch of alloy melted under the old, less stringent (double-melt) regime was Titanium Metals Corporation heat K8283 of February 23, 1971. Out of this heat, ALCOA drew the metal that eventually landed in the stage 1 fan rotor disk for flight 232.[37]

Chairman James Kolstad's NTSB investigative team followed the metal, finding that the 7,000 pound ingot K8283 was shipped to Ohio for forging into billets of 16" diameter; then to ALCOA in Cleveland, Ohio, for cutting into 700 pound blanks; the blanks then passed to General Electric for manufacture. These 16" billets were tested with an ultrasonic probe. At General Electric, samples from the billet were tested numerous ways and for different qualities – tensile strength, microstructure, alpha phase content and amount of hydrogen. And, after being cut into its rectilinear machine-forged shape, the disk-to-be again passed an ultrasonic inquisition, this time by the more sensitive means of immersing the part in liquid. The ultrasonic test probed the rectilinear form's interior for cracks or cavities, and it was supplemented by a chemical etching that aimed to reveal surface anomalies.[38] Everything checked, and the fan was then machined and shot peened (that is, hammered smooth with a stream of metal shot) into its final form. On completion, the now finished disk fan passed a fluorescent penetrant examination – also designed to display surface cracking.[39] It was somewhere at this stage – under the stresses of final machining and shot peening – that the investigators concluded cracking began around the hard alpha inclusion. But since no ultrasonic tests were conducted on the *interior* of the fan disk *after* the mechanical stresses of final machining, the tiny cavity remained undetected.[40]

The fan's trials were not over, however, as the operator – United Airlines – would, from then on out, be required to monitor the fan for surface cracking. Protocol demanded that every time that maintenance workers disassembled part of the fan, they were to remove the disk, hang it on a steel cable, paint it with fluorescent penetrant, and inspect it with a 125-amp ultraviolet lamp. Six times over the disk's lifetime, United Airlines personnel did the fluorescence check, and each time the fan passed. Indeed, by looking at the accident stage-1 fan parts, the Safety Board found that there were approximately the same number of major striations in the material pointing to the cavity as the plane had had cycles (15, 503). This led them to conclude that the fatigue crack had begun to grow more or less at the very beginning of the engine's life. Then (so the fractographic argument went) with each takeoff and landing the crack began to grow, slowly, inexorably,

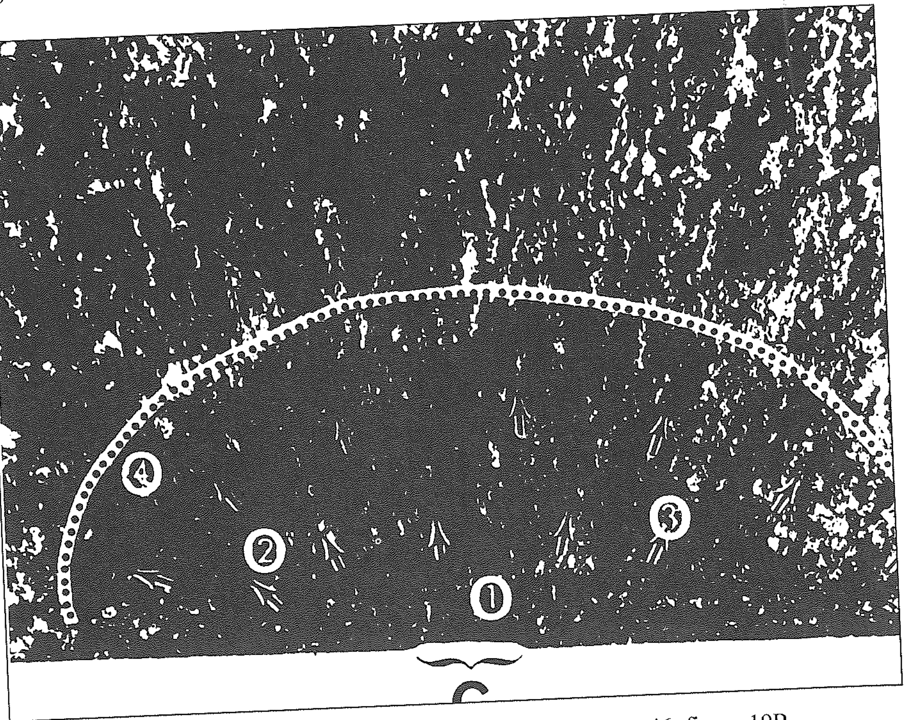

Figure 10. Cavity and Fatigue Crack Area. Source: NTSB-232, p. 46, figure 19B.

out from the 1/100" cavity surrounding the alpha inclusion, over the next 18 years. (See figure 10.)

By the final flight of 232 on 19 July 1989, both General Electric and the Safety Board believed the crack at the surface of the bore was almost fi" long.[41] This finding exonerated the titanium producers, since interior faults, especially one with no actual cavity, were much harder to find. It almost exonerated General Electric because their ultrasonic test would not have registered such an interior filled cavity with no cracks, and their etching test was performed before the fan had been machined to its final shape. By contrast, the NTSB laid the blame squarely on the United Airlines San Francisco maintenance team. In particular, the report aimed its cross hairs on the inspector who last had the fan on the wire in February 1988 for the Fluorescent Penetrant Inspection. At that time, 760 cycles before the fan disk disintegrated, the Safety Board judged that the surface crack would have grown to almost fi". They asked: why didn't the inspector see the crack glowing under the illumination of the ultraviolet lamp?[42] The drive to localization had reached its target. We see in our mind's eye an inculpatory snapshot: the suspended disk, the inspector turning away, the half-inch glowing crack unobserved.

United Airlines' engineers argued that stresses induced by rotation could have closed the crack, or perhaps the shot peening process had hammered it shut,

preventing the fluorescent dye from entering.[43] The NTSB were not impressed by that defense, and insisted that the fluorescent test was valid. After all, chemical analysis had shown penetrant dye *inside* the half-inch crack found in the recovered fan disk, which meant it *had* penetrated the crack. So again: why didn't the inspector see it? The NTSB mused: the bore area rarely produces cracks, so perhaps the inspector failed to look intently where he did not expect to find anything. Or perhaps the crack was obscured by powder used in the testing process. Or perhaps the inspector had neglected to rotate the disk far enough around the cable to coat and inspect all its parts. Once again, a technological failure became a "human factor" at the root of an accident, and the "performance of the inspector" became the central issue. True, the Safety Board allowed that the UA maintenance program was otherwise "comprehensive" and "based on industry standards." But non-destructive inspection experts had little supervision and not much redundancy. The CRM equivalent conclusion was that "a second pair of eyes" was needed (to ensure advocacy and inquiry). For just this reason the NTSB had come down hard on human factors in the inspection program that had failed to find the flaws leading to the Aloha Airlines accident in April 1988.[44] Here then was the NTSB-certified source of flight 232's demise: a tiny misfiring in the microstructure of a titanium ingot, a violated inspection procedure, a humanly-erring inspector. And, once again, the NTSB produced a single cause, a single agent, a violated protocol in a fatal moment.[45]

But everywhere the report's trajectory towards local causation clashes with its equally powerful draw towards the many branches of necessary causation; in a sense, the report unstably disassembled its own conclusion. There were safety valves that could have been installed to prevent the total loss of hydraulic liquid, screens that would have slowed its leakage. Engineers could have designed hydraulic lines that would have set the tubes further from one another, or devised better shielding to minimize the damage from "liberated" rotating parts. There were other ways to have produced the titanium – as, for example, the triple-vacuum heating (designed to melt away hard alpha defects) that went into effect mere weeks after the fateful heat number 8283. Would flight 232 have proceeded uneventfully if the triple-vacuum heating had been implemented just one batch earlier? There are other diagnostic tests that could have been applied, including the very same immersion ultrasound that GEAE used – but applied to the final machine part. After all, the NTSB report itself noted that other companies were using final shape macroetching in 1971, and the NTSB also contended that a final shape macroetching would have caught the problem.[46] Any list of necessary causes – and one could continue to list them ad libidum – ramified in all directions, and with this dispersion came an ever-widening net of agency. For example, in a section labeled "Philosophy of Engine/Airframe Design," the NTSB registered that in retrospect design and certification procedures should have "better protected the critical hydraulic systems" from flying debris. Such a judgment immediately dispersed both agency and causality onto the entire airframe, engine, and regulatory apparatus that created the control mechanism for the airplane.[47]

At an even broader level of criticism, the Airplane Pilots Association criticized the very basis of the "extremely improbable design philosophy" of the FAA. This "philosophy" was laid out in the FAA's Advisory Circular 25.1309-1A of 21 June 1988, and displayed graphically in its "Probability versus Consequence" graph (figure 11) for aircraft system design.[48] Not surprisingly, the FAA figured that catastrophic failures ought to be "extremely improbable," (by which they meant less likely than one in a billion) while nuisances and abnormal procedures could be "probable" (1 in a hundred thousand). Recognizing that component failure rates were not easy to render numerically precise, the FAA explained that this was why they had drawn a wide line on figure 11, and why they added "the expression 'on the order of' when describing quantitative assessments."[49] A triple hydraulic failure was supposed to lie squarely in the one in a billion range – essentially so unlikely that nothing in further design, protection, or flight training would be needed to counter it. The pilots union disagreed. For the pilots, the FAA was missing the boat when it argued that the assessment of failure should be "so straightforward and readily obvious that … any knowledgeable, experienced person would unequivocally conclude that the failure mode simply would not occur, unless it is associated with a wholly unrelated failure condition that would itself be catastrophic." For as they pointed out, a crash like that of 232 was *precisely* a catastrophic failure in one place (the engine) causing one in another (the flight control system). So while the hydraulic system might well be straightforwardly and obviously proof against independent failure, a piece of flying titanium could knock it out even if all three levels of pumps were churning away successfully. Such externally induced failures of the hydraulic system had, they pointed out, already occurred in a DC-10 (Air Florida), a 747 (Japan Air Lines) and an L-1011 (Eastern). "One in a billion" failures might be so in a make-believe world where hydraulic systems flew by themselves. But they don't. Specifically, the pilots wanted a control system that was completely independent of the hydraulics. More generally, the pilots questioned the procedure of risk assessment. Hydraulic systems do not fly alone, and because they don't, any account of causality and agency must move away from the local and into the vastly more complex world of systems interacting with systems.[50] The NTSB report – or more precisely one impulse of the NTSB report – concurred: "The Safety Board believes that the engine manufacturer should provide accurate data for future designs that would allow for a *total safety assessment of the airplane as a whole*."[51] But a countervailing impulse pressed agency and cause into the *particular* and *localized.*

When I say that instability lay within the NTSB report it is all this, and more. For contained in the conclusions to the investigation of United 232 was a dissenting opinion by Jim Burnett, one of the lead investigators. Unlike the majority, Burnett saw General Electric, Douglas Aircraft and the Federal Aviation Agency as equally responsible.

> I think that the event which resulted in this accident was foreseeable, even though remote, and that neither Douglas nor the FAA was entitled to dismiss a possible rotor failure as remote when reasonable and feasible steps could have been taken to "minimize" damage in the event of engine rotor failure. That additional steps could have been taken is evidenced by the corrections readily made, even as retrofits, subsequent to the occurrence of the "remote" event.[52]

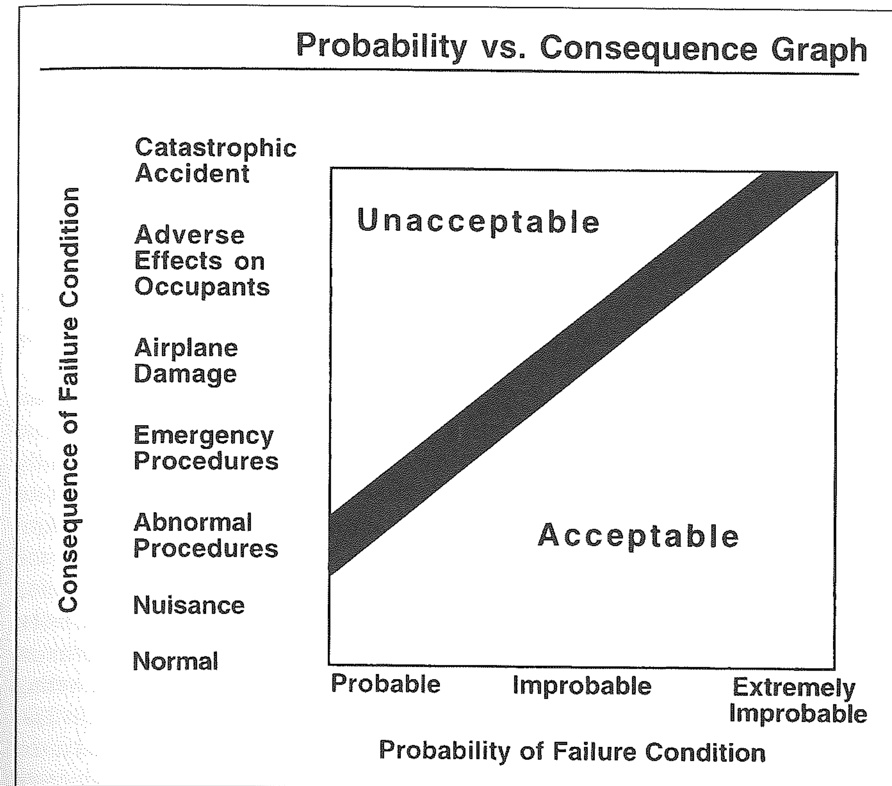

Figure 11. Probability Versus Consequence. Source: UAL 232 Docket, U.S. Department of Transportation, Federal Aviation Administration, "System Design and Analysis," 6/21/88, AC No. 25.1309-1A, fiche 7, p. 7.

Like a magnetic force from a needle's point, the historical narrative finds itself drawn to condense cause into a tiny space-time volume. But the narrative is constantly broken, undermined, derailed by causal arrows pointing elsewhere, more globally towards aircraft design, the effects of systems on systems, towards risk-assessment philosophy in the FAA itself. In this case that objection is not implicit but explicit, and it is drawn and printed in the conclusion of the report itself.

Along these same lines, I would like, finally, to return to the issue of pilot skill and CRM that we examined in the aftermath of Air Florida 90. Here, as I already indicated, the consensus of the community was that Haynes, Fitch, Dvorak, and Records did an extraordinary job in bringing the crippled DC-10 down to the threshold of Sioux City's runway 22. But it is worth considering how the NTSB made the determination that they were not, in fact, contributors to the final crash landing of Flight 232. After the accident, simulators were set up to mimic a total, triple hydraulic failure of all control surfaces of the DC-10. Production test pilots were brought in, as were line DC-10 pilots; the results were that flying a machine in that state was simply impossible, the skills required to manipulate power on the engines in such a way as to control simultaneously the phugoid oscillations, airspeed, pitch, descent rate, direction, and roll were quite simply "not trainable." While individual features could be learned, "landing at a predetermined point and airspeed on a runway was a highly random event"[53] and the NTSB concluded that "training … would not help the crew in successfully handling this problem. Therefore, the Safety Board concluded that the damaged airplane, although flyable, *could not have been successfully landed* on a runway with the loss of all hydraulic flight controls." "[U]nder the circumstances," the Safety Board concluded, "the UA flightcrew performance was highly commendable, and greatly exceeded reasonable expectations."[54] Haynes himself gave great credit to his CRM training, saying it was "the best preparation we had."[55]

While no one doubted that flight 232 was an extraordinary piece of flying, not everyone concurred that CRM ought take the credit. Buck, ever dissenting from the CRM catechism, wrote that he would wager, whatever Haynes's view subsequently was, that Haynes had the experience to handle the emergency of 232 with or without the aid of earthbound psychologists.[56] But beyond the particular validity of cockpit resource management, the reasoning behind the NTSB satisfaction with the flightcrew is worth reviewing. For again, the Safety Board used post hoc simulations to evaluate performance. In the Air Florida Flight 90, the conclusion was that the captain could have aborted the takeoff safely, and so he was condemned for not aborting; because the simulator pilots could fly out of the stall by powering up quickly, the captain was damned for not having done so. In the case of flight 232, because the simulator-flying pilots were *not* able to land safely consistently, the crew was lauded. Historical re-enactments were used differently, but in both cases functioned to confirm the localization of cause and agency.

5. THE UNSTABLE SEED OF DESTRUCTION

We now come to a point where we can begin to answer the question addressed at the outset. A history of a nearly punctiform event, conducted with essentially unlimited resources, yields a remarkable document. Freed by wealth to explore at will, the NTSB could mock up aircraft or recreate accidents with sophisticated simulators. Forensic inquiries into metallurgy, fractography, and chemical analysis have allowed extraordinary precision. Investigators have tracked documents and parts back two decades, interviewed hundreds of witnesses, and in some cases ferreted out real-time photographs of the accident in progress. But even when the evidence is in, the trouble only just begins. For deep in the ambition of these investigations lie contradictory aims: inquiries into the myriad of necessary causes evaporate any single cause or single cluster of causes from fully explaining the event. At the same time, the drive to regain control over the situation, to present recommendations for the future, to lodge moral and legal responsibility all urge the narrative towards a condensed causal account. Agency is both evaporated and condensed in the investigative process. Within this instability of scale the conflict between undefinable skill and fixed

procedure is played out time and again. On the flightdeck and in the maintenance hangers, pilots and technicians are asked at one and the same time to use an expansive, protocol-defying judgment and to follow restricted set procedures. Both impulses – towards diffused and localized accounts – are crucial. We find in systemic or network analysis an understanding of the connected nature of institutions, people, philosophies, professional cultures, and objects. We find in localization the prospect of immediate and consequential remediation: problems can be posed and answered by pragmatic engineering. To be clear: I do not have the slightest doubt that procedural changes based on accident reports have saved lives. At the same time, it is essential to recognize in such inquiries and in technological-scientific history more generally, the inherent strains between these conflicting explanatory impulses.

In part, the impulse towards condensation of cause, agency, and protocol in the final "probable cause" section of the accident report emerges from an odd alliance among the sometimes competing groups that contribute to the report. The airplane industry itself has no desire to see large segments of the system implicated, and pushes for localization both to solve problems and to contain litigation. Following United's 232 crash, General Electric (for example) laid the blame on United's fluorescent penetration inspection and ALCOA's flawed titanium.[57] Pilots have a stake in maintaining the status of the captain as fully in control of the flight: their principal protest in the 232 investigation was that the FAA's doctrine of "extremely improbable" design philosophy was untenable. In particular, the pilots lobbied for a control system for wide body planes that would function even if all hydraulic fluid escaped.[58] But just in the measure that the pilots remain authors of the successful mission, they also have their signatures on the accident, and their recommendation was aimed at insuring that a local fix be secured that would keep their workplace control uncompromised. Government regulators, too, have an investment in a regulatory structure aimed at local causes admitting local solutions. Insofar as regulations protect safety, the violation of regulations enter as potential causal elements in the explanation of disaster. Powerful as this confluence of stakeholders can be in focusing causality to a point, it is not the whole of the story.

Let us push further. In the 1938 Civil Aviation Act that enjoined the Civil Aeronautics Authority to create accident reports, it is specified that the investigation should culminate in the ascription of a "probable cause" of the accident.[59] Here "probable cause" is a *legal* concept, not a probabilistic one. Indeed, while probability plays a vital role in certain sectors of legal reasoning, "probable cause" is not one of them. Instead, "probable cause" issues directly from the Fourth Amendment of the U. S. Constitution, prohibiting unreasonable searches and seizures, probable cause being needed for the issuance of a warrant. According to Fourth Amendment scholar Wayne R. LaFave, the notion of probable cause is never defined explicitly in either the Amendment itself nor in any of the federal statutory provisions; it is a "juridical construct." In one case of 1925, the court ruled that if a "reasonably discreet and prudent man would be led to believe that there was a commission of the offense charged," then, indeed, there was "probable cause justifying the issuance of a warrant."[60] Put bluntly in an even older (1813) ruling, probable cause was not "proof" in any legally binding sense; required were only reasonable grounds for belief. "[T]he term 'probable cause' … means less than evidence which would justify condemnation."[61]

Epistemically and morally, probable cause inculpates but does not convict. It points a finger and demands explanation of the evidence. Within the framework of accidents, however, in only the rarest of cases does malicious intent figure in the explanation, and this very circumstance brings forward the elusive notion of "human error." Now while the notion of probable cause had its origins in American search and seizure law, international agreements rapidly expanded its scope. Delegates from many countries assembled in Chicago at the height of World War II to create the Convention on International Civil Aviation. Within that legal framework, in 1951 the Council of the International Civil Aviation Organization (ICAO) adopted Annex 13 to the Convention, an agreement specifying standards and practices for aircraft accident inquiries. These were not binding, and considerable variation existed among participating countries.

Significantly, though ICAO documents sometimes referred to "probable cause" and at other times to "cause," their meanings were very similar – not surprising since the ICAO reports were so directly modeled on the American standards. ICAO defined "cause," for example, in 1988 as "action(s), omission(s), event(s), condition(s), or a combination thereof, which led to the accident or incident."[62] Indeed, ICAO moved freely in its documents between "cause" and "probable cause," and for many years ICAO discussion of cause stood extremely close to (no doubt modeled on) the American model.[63] But to understand fully the relation between NTSB and ICAO inquiries, it would be ideal to have a case where *both* investigations inquired into a single crash.

Remarkably, there is such an event precipitated by the crash of a Simmons Airlines/American Eagle Avions de Transport Regional-72 (ATR-72) on 31 October 1994 in Roselawn, Indiana. On one side, the American NTSB concluded that the probable cause of the accident was a sudden and unexpected aileron hinge reversal, precipitated by a ridge of ice that accumulated beyond the de-ice boots. This, the NTSB investigators argued, took place 1) because ATR failed to notify operators how freezing precipitation could alter stability and control characteristics and associated behaviors of the autopilot; 2) because the French Directorate Général pour Aviation Civile failed to exert adequate oversight over the ATR-72, and 3) because the French Directorate Général pour Aviation Civile failed to provide the Federal Aviation Authority with adequate information on previous incidents and accidents with the ATR in icing conditions.[64] Immediately the French struck back: It was not the French plane, they argued, it was the American crew. In a separate volume, the Bureau Enquêtes Accidents submitted, under the provisions of ICAO Annex 13, a determination of probable cause that, in its content, stood in absolute opposition to the probable cause adduced by the National Transportation Safety Board. As far as the French were concerned, the deadly ridge of ice was due to the crew's prolonged operation of their flight in a freezing drizzle beyond the aircraft's certification envelope – with an airspeed and flap configuration altogether incompatible with the Aircraft Operating Manual.[65]

In *both* American and French reports we find the same instability of scale that we have already encountered in Air Florida 90 and United 232. On one hand both Roselawn reports zeroed in on localized causes (though the Americans fastened on a badly designed de-icing system and the French on pilot error), and *both* reports pulled back out to a wider scale as they each pointed a finger at inadequate oversight and research (though the Americans fastened on the French Directorate Général and the French on the American Federal Aviation Authority). For our purposes, adjudicating between the two versions of the past is irrelevant. Rather I want to emphasize that the tension between localized and diffused causation remains a feature of all these accounts, even though some countries conduct their inquiries through judicial rather than civil authority (and some, such as India, do both). Strikingly, many countries, including the United States, have become increasingly sensitive to the problematic tension between condensed and diffused causation–contrast, for example, the May 1988 and July 1994 versions of Annex 13:

> **May 1988**: "State findings and cause(s) established in the investigation."
> **July 1994**: "List the findings and causes established in the investigation. The list of causes should include both the immediate and the deeper systemic causes."[66]

Australia simply omits a "cause" or "probable cause" section. And in many recent French reports – such as the one analyzing the January 1992 Airbus 320 crash near Strasbourg – causality as such has disappeared. Does this mean that the problem of causal instability has vanished? Not at all. In the French case, the causal conclusion is replaced by two successive sections. One, "Mechanisms of the Accident," aimed specifically at local conditions and the second, "Context of Use" (Contexte de l'exploitation") directed the reader to the wide circle of background conditions.[67] The drive outwards and inwards now stood, explicitly, back to back. Scale and agency instability lie deep in the problematic of historical explanation, and they survive even the displacement of the specific term "cause."

There is enormous legal, economic, and moral pressure to pinpoint cause in a confined spacetime volume (an action, a metal defect, a faulty instrument). A frozen pitot tube, a hard alpha inclusion, an ice-roughened wing, a failure to throttle up, an overextended flap – such confined phenomena bring closure to catastrophe, restrict liability and lead to clear recommendations for the future. Steven Cushing has written effectively, in his *Fatal Words,* of phrases, even individual words, that have led to catastrophic misunderstandings.[68] "At takeoff," with its ambiguous reference to a place on the runway and to an action in process, lay behind one of the greatest aircraft calamities when two jumbo jets collided in the Canary Islands. Effectively if not logically, we want the causal chain to end. Causal condensation promises to close the story. As the French Airbus report suggests, over the last twenty-five years the accident reports have reflected a growing interest in moving beyond the individual action, establishing a mesoscopic world in which patterns of behavior and small-group sociology could play a role. In part, this expansion of scope aimed to relieve the tension between diagnoses of error and culpability. To address the dynamics of the small "cockpit culture," the Safety Board, the FAA, the pilots, and the airlines brought in sociologists and social psychologists. In the Millsian world of CRM that they collectively conjured, the demon of unpredictable action in haste, fear or boredom is reduced to a problem of information transfer. *Inquire* when you don't know, *advocate* when you do, *resolve* differences, *allocate* resources – the psychologists urged a new set of attitudinal corrections that would soften the macho pilot, harden the passive one and create coordinated systems. Information, once blocked by poisonous bad attitudes, would be freed, and the cockpit society, with its benevolent ruling captain, assertive, clear-thinking officers, and alert radio-present controllers, would outwit disaster. As we saw, under the more sociological form of CRM, it has been possible, even canonical, to re-narrate crashes like Air Florida 90 and United 232 in terms of small-group dynamic. But beyond the cockpit scale of CRM, sociologists have begun to look at larger "organizational cultures." Diane Vaughan, for example, analyzed the Challenger launch decision not in terms of cold O-rings or even in the language of managerial group dynamics, but rather through organizational structures: faulty competitive, organizational, and regulative norms.[69] And James Reason, in his *Human Error* invoked a medical model in which ever-present background conditions located in organizations are like pathogens borne by an individual: under certain conditions disease strikes. Reason's work, according to Barry Strauch, Chief of the Human Performance Division at the NTSB, had a significant effect in bolstering attention to systemic, organizational dynamics as part of the etiology of accidents.[70]

Just as lines of causation radiate outwards from individual actions through individuals to small collectives, so too is it possible to pull the camera all the way back to a macroanalysis that puts in narrative view the whole of the technological infrastructure. Roughly speaking, this was Charles Perrow's stance in his *Normal Accidents*.[71] For Perrow, given human limitations, it was simply inevitable that tightly-coupled complex, dangerous technologies have component parts that interact in unforeseen and threatening ways.

Our narration of accidents slips between these various scales, but the instability goes deeper in two distinct ways. First, it is not simply that the various scales can be studied separately and then added up. Focusing on the cubic millimeter of hard alpha inclusion forces us back to the conditions of its presence, and so to ALCOA, Titanium Metals Inc., General Electric, or United Airlines. The alpha inclusion takes us to government standards for aircraft materials, and eventually to the whole of the economic-regulative environment. This scale-shifting undermines any attempt to fix a single scale as the single "right" position from which to understand the history of these occurrences. It even brings into question whether there is any single metric by which one can divide the "small" from the "large" in historical narration.

Second, throughout these accident reports (and I suspect more generally in historical writing), there is an instability between accounts terminating in *persons* and those ending with *things*. At one level, the report of United 232 comes to rest in the hard alpha inclusion buried deep in the titanium. At another level, it fingers the maintenance technician who did not see fluorescent penetrant dye glowing from a crack. Read different ways, the report on Air Florida flight 90 could be

interpreted as spotlighting the frozen pitot tube that provided a low thrust indication; read another way the 737's collision impact into the Fourteenth Street Bridge was due to the pilot's failure to de-ice adequately, to abort the takeoff, or to firewall the throttle at the first sign of stall. Protocol and judgment stood in a precarious and unstable equilibrium. What to the American investigators of the Roselawn ATR-72 crash looked like a *technological* failure appeared to the French team as a *human* failing.

Such a duality between the human and the technological is general. It is *always* possible to trade a human action for a technological one: failure to 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. In a rather different context, Bruno Latour and Michel Callon have suggested that the non-human be accorded equal agency with the human.[72] I would rather bracket any fixed division between human and technological in our accounts and put it this way: *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.*

Though airplane crashes are far from the world of the historian of science and technology or that of the general historian interested in technology, the problems that engaged the attention of the NTSB investigators are familiar ones. We historians also want to avoid ascribing inarticulate confusion to the historical actors about whom we write – we seek a mode of reasoning in terms that make sense of the actors' understanding. We try to reconstruct the steps of a derivation of a theorem or the construction of an object just as NTSB investigators struggle to recreate the Air Florida 90's path to the Fourteenth Street Bridge. We interpret the often castaway, fragmentary evidence of an incomplete notebook page or overwritten equation; they argue over the correct interpretation of "really cold" or "that's not right."

But the heart of the similarity lies elsewhere, not just in the hermeneutics of interpretation but in the tension between the condensation and diffusion of historical explanation. The NTSB investigators, like historians, face a world that often doesn't make sense; and our writings seek to find in it a rational kernel of controllability. We know full well how interrelated, how deeply embedded in a broader culture scientific developments are. At the same time we search desperately to find a narrative that at one moment tracks big events back to small ones, that hunts a Copernican revolution into the lair of Copernicus's technical objections to the impure equant. And at another moment the scale shifts to Copernicus's neo-Platonism or his clerical humanism.[73] At the micro-scale, we want to find the real source, the tiny anomaly, asymmetry, or industrial demand that eats at the scientific community until it breaks open into a world-changing discovery. Value inverted, from the epoch-defining scientific revolution to the desperate disaster, catastrophe too has its roots in the molecular: in a badly chosen word spoken to the ATC controller, in a too sharp application of force to the yoke, in a tiny, deadly alpha inclusion that spread its flaw for fifteen thousand cycles until it tore a jumbo jet to pieces.

At the end of the day, these remarkable accident reports time and time again produce a double picture printed once with the image of a whole ecological world of causation in which airplanes, crews, government, and physics connect to one another, and printed again, in overstrike, with an image tied to a seed of destruction, what the chief investigator of flight 800 called the "eureka part." In that seed almost everyone can find satisfaction. All at once it promises that guilty people and failed instruments will be localized, identified, confined, and that those who died will be immortalized through a collective immunization against repetition through regulation, training, simulation. But if there is no seed, if the bramble of cause, agency, and procedure does not issue from a fault nucleus, but is rather unstably perched between scales, between human and non-human, and between protocol and judgment, then the world is a more disordered and dangerous place. These reports, and much of the history we write, struggle, incompletely and unstably, to hold that nightmare at bay.

ACKNOWLEDGMENTS

I would like to thank Deborah Coen for enormously helpful research assistance with this project, and I am equally grateful to Alex Roland, George Smith, and Barry Strauch for insightful comments. I benefited from discussion of this material at the Dibner Institute, Cornell University, and the Max Planck Institute for History of Science (Berlin).

NOTES

[1] National Transportation Safety Board, Aircraft Accident Report, Air Florida, Inc. Boeing 737-222, N62AF, Collision with 14th Street Bridge, Near Washington National Airport Washington, D.C. January 13, 1982, p. 1-10. Hereafter, NTSB-90.

[2] NTSB-90, p. 10.

[3] NTSB-90, p. 22.

[4] "Addendum to Aircraft Performance Engineer's Factual Report of Investigation," SA 477, 10 May 1982, AF 90 Docket: Exhibit 13-A, Fiche 19-A (hereafter, "E13-A, F19-A"); NTSB-90, pp. 26-27.

[5] NTSB-90, p. 57.

[6] NTSB-90, p. 58.

[7] See e.g. "Other Factors Relating to Accident," NTSB-90, pp. 68ff. for discussion of traffic spacing, runways at Washington National, 737 pitch-up characteristics, among others.

[8] NTSB-90, p. 40.

[9] NTSB-90, p. 64.

[10] Van Sickle, *Modern Airmanship* (Tab: Blue Ridge Summit PA, 1990), p. 540.

[11] "Operations Group Chairman's Preliminary Factual Report," DCA-82-AA-011, p. 8 (stamped 000017), AF 90 Docket: E2A, F1.

[12] NTSB-90, p. 75.

[13] NTSB- 90, p. 40.

[14] NTSB-90, p. 65.

[15] NTSB-90, p. 70.

[16] Robert Buck, *The Pilot's Burden* (Ames: Iowa State University, 1994), p. 207.

[17] See e.g. Peteris Galins and Mike Shirkey, "737 Wing Leading Edge Condition – Part II," *Boeing Airliner*, Oct.-Dec. 1981, p. 19 (stamped 001519), AF 90 Docket: E13-V, F17: "Stall characteristics with

both symmetric and asymmetric simulated frost were characterized by a very apparent pitch-up, yaw rate, and roll-off." Also, NTSB-90, p. 66.

[18] NTSB-90, p. 82.

[19] Cited in United Airlines training manual, "Introduction to Command/Leadership/Resource Management," MN-94, 10/95, p. 25.

[20] National Transportation Safety Board, Aircraft Accident Report, Delta Air Lines, Inc., Lockheed L-1011-385-1, N726DA, Dallas/Fort Worth-International Airport, Texas, August 2, 1985, NTSB/AAR-86/05, (Flight 191), hereafter, NTSB-191, p. 71.

[21] Robert Helmreich, "Social Psychology on the Flight Deck," in George E. Cooper, editor, *Resource Management on the Flight Deck*. Proceedings of a NASA/Industry Workshop Held at San Francisco, California, June 26-28, 1979, N80-22283, pp. 17-30.

[22] Lee Bolman, "Aviation Accidents and the 'Theory of the Situation,'" in ibid., pp. 31-58, on p. 40.

[23] Stanley R. Trollip and Richard S. Jensen, *Human Factors for General Aviation*, (Jeppeson Sanderson: Englewood, CO, 1991), p. 9-8.

[24] United Airlines, "Introduction," MN-94, p. 13.

[25] Ibid., p. 26.

[26] Buck, *Pilot's Burden* (1994), p. 207.

[27] One of the widest-ranging accounts of the crash came from the Aviation Consumer Action Project (ACAP) that included Ralph Nader as Chairman of the Advisory Board. In their letter of 15 April 1982 to the NTSB (AF 90 Docket: F19A), ACAP lambasted the pilots' performance, the poor safety oversight by the FAA, Washington National Airport for its inadequate runways and rescue plans, the 737 for its susceptibility to icing, and Air Florida for its precipitous and poorly executed expansion.

[28] Alfred Haynes, "United 232: Coping with the Loss of All Flight Controls," in *Air Line Pilot* 55 (October 1991): 10-14, 54-55, this reference, p. 54; part II, (November 1991): 26-28.

[29] "Operations Group Chairman's Factual Report," UAL 232 Docket: E2A, F2, p. 16 (stamped 175).

[30] National Transportation Safety Board, Aircraft Accident Report, United Airlines Flight 232, McDonnell Douglas DC-10-10, Sioux Gateway Airport, Sioux City, Iowa, July 19, 1989 (hereafter, NTSB-232), p. 1.

[31] NTSB-232, p. 22.

[32] Ibid. p. 71, and Haynes, "United 232," p. 11.

[33] Haynes, "United 232," pp. 54-55, and NTSB-232, pp. 21-23, 35-38; also interview by Operations Group with Second Officer Dudley Joseph Dvorak, 22 July 1989, UAL 232 Docket, Addition 1: E2D, F1.

[34] NTSB-232, p. 15.

[35] NTSB-232, pp. 17-19, 32-35.

[36] NTSB-232, p. 47; see also B. J. Moniz, *Metallurgy* (Homewood, Illinois: American Technical Publishers, Inc., 1992), 346-50.

[37] NTSB-232, pp. 49-52.

[38] NTSB-232, pp. 55-58.

[39] NTSB-232, p. 80.

[40] NTSB-232, p. 83.

[41] NTSB-232, pp. 15, 77, 85.

[42] NTSB-232, p.87.

[43] UAL Final Report, 8 March 1990, "Conclusion 3.10." UAL 232 Docket, Addition 5: item 1, F1.

[44] NTSB-232, p. 88: As a result of the Aloha Airlines 737 crash in April 1988, the Safety Board forwarded two recommendations to the FAA that were relevant to maintenance: from A-89-56, "Require formal certification and recurrent training of aviation maintenance inspectors performing nondestructive inspection functions. Formal training should include apprenticeship and periodic skill demonstration." In A-89-57 they asked for specific training programs that would require "operators to periodically test personnel on their ability to detect the defined defects."

[45] NTSB-232, p. 88.

[46] NTSB-232, p. 85.

[47] NTSB-232, pp. 89-90.

[48] See e.g. figure 1 of FAA, Advisory Circular AC 25-2309-1A, "System Design and Analysis," pp. 7ff, UAL 232 Docket, Addition 1: E9H, F7.

[49] Ibid., paragraph 10.

[50] Airline Pilots Association Report, UAL 232 Docket, Addition 5: F 15.

[51] Emphasis added, NTSB-232, p. 91.

[52] Jim Burnett, dissenting opinion, NTSB-232, p. 109.

[53] NTSB 232, pp. 72-73. The NTSB's "Simulator Study-Initial Report" (17 October 1989) concludes by quoting the consensus of the test pilots who flew the simulator: "You could pick your touchdown position, direction, attitude, or vertical velocity. Achieving all desired conditions at the same time [was] virtually impossible" (UAL 232 Docket, Addition 1: E16C, F11).

[54] NTSB-232, p. 76, emphasis added.

[55] Haynes, "United 232," p. 14.

[56] Buck, *Pilot's Burden* (1994), p. 214.

[57] "General Electric Aircraft Engineers Report," 23 March 1990, UAL 232 Docket, Add. 5: Item 3, F3, p. iv.

[58] "Airline Pilots Association Report," 7 March 1990, UAL 232 Docket, Add. 5: Item 16, F15. In particular, the Airline Pilots Association pointed out that even if the likelihood of failure of all hydraulic pumps and their backups were one in a billion, such calculations would be irrelevant should some *other* factor cause the hydraulic fluid to be drained. Two such incidents had occurred in which all but one hydraulic line was drained, and in 1985 all hydraulic systems failed in the crash of a JAL jumbo jet which killed almost all aboard.

[59] Under Section 702 of the Civil Aeronautics Act of 1938 (52 Stat. 1013, 49 U.S.C 582), the Civil Aeronautics Board is responsible for investigating aircraft accidents: "It shall be the duty of the Board to ... (2) Investigate such accidents and report to the Authority the facts, conditions, and circumstances relating to each accident and the probable cause thereof ... "

[60] Dumbra v. United States, 268 U.S. 435, 439, 441 (1925), cited in Wayne R. LaFave, *Search and Seizure. A Treatise on the Fourth Amendment*, Third Edition, Volume 5 Sections 11.1 to End, (West Publishing Co.: St. Paul, Minn., 1996), p. 1172.

[61] Lock v. United States, 7 Cr. (11 U.S.) 339, 348 (1813), cited in LaFave, *Search and Seizure* (1996), p. 1172, note 9.

[62] See International Standards and Recommended Practices Aircraft Accident Investigation Annex 13 to the Convention on International Civil Aviation. Seventh Edition – May 1988.

[63] Note, for example, that in the ICAO Manual of Aircraft Accident Investigation, document 6920, AN-855, 2nd Edition, October 1961, their chapter 9 ("human factor") consistently uses "probable cause," whereas elsewhere "cause" is invoked. The NTSB, for its part, has in its "Investigation Manual Aviation," Vols. 1-4 (March 1994 disk version), *only* references to "probable cause" (never "cause") except for two instances. One case occurs in the section "Drafting the Report," and here probable cause is first used to indicate the full statement of the conclusion. The Manual then goes on to say this: "For example, in a survivable accident believed caused by an operational factor, the first section of the analysis, following the presentation of issues, should address the direct cause of the accident." The other occurrence contrasts the naive view of the news reporter with the NTSB practice of determining "probable cause": "Reporters want to know the cause of the accident and are unfamiliar with Board procedures regarding the determination of probable cause. For example, a discussion of alcohol or drug testing could lead reporters to ask if the Board suspects that the pilots were under the influence of drugs or alcohol at the time." Earlier Civil Aeronautics Authority documents such as the 1938 statutes speak about cause, e.g. in the section "Terminology and Classification of Accident Causes," and this section is virtually identical to the corresponding section of ICAO Doc. 6920 (1951), pp. 14-18, "Causes of Accidents."

[64] The NTSB also laid some contributing cause culpability to the FAA for inadequate supervision of the ATR planes. National Transportation Safety Board Aircraft Accident Report Volume 1: Safety Board Report, "In-Flight Icing Encounter and Loss of Control Simmons Airlines, d.b.a. American Eagle Flight 4184. Avions de Transport Regional (ATR) Model 72-212, N401AM. Roselawn, Indiana, October 31, 1994. Volume 1: Safety Board Report, p. 210.

[65] The Bureau laid its contributing causes at the feet of the crew, who, they contended, failed to exercise situational awareness, cockpit resource management, or standard sterile cockpit – and left some blame also for Airworthiness Authorities, Air Traffic Control, and to European and American, and ATR for not

having investigated more fully Aileron hinge reversal in icing conditions. See ibid., Volume II: Response of Bureau Enquêtes-Accidents to Safety Board's Draft Report, p. 266.

[66] International Standards and Recommended Practices Aircraft Accident Investigation Annex 13 to the Convention on International Civil Aviation. Seventh Edition – May 1988, p. 18; and ibid, eighth edition, July 1994, p. 18.

[67] Commission d'enquête sur l'accident survenu le 20 janvier 1992 à l'Airbus A 320 F-GGED près du mont Sainte-Odile (Bas-Rhin), rapport final. Journal officiel de la République Française, édition des documents administratifs.

[68] Steven Cushing, *Fatal Words. Communication Clashes and Aircraft Crashes* (Chicago: University of Chicago Press, 1994).

[69] Diane Vaughan, *The Challenger Launch Decision. Risky Technology, Culture, and Deviance at NASA* (Chicago: University of Chicago Press, 1996), e.g. pp. 34, 456ff.

[70] James Reason, *Human Error* (Cambridge: Cambridge University Press, 1990). Interview with Barry Strauch, 1 April 1999.

[71] Charles Perrow, *Normal Accidents. Living with High-Risk Technologies* (New York: Basic Books, Inc., 1984).

[72] See e.g. Michel Callon, "Some Elements of a Sociology of Translation: Domestication of the Scallops and the Fishermen of St. Brieuc Bay," and Bruno Latour, "Give Me a Laboratory and I Will Raise the World," both reprinted in M. Biagioli, *Science Studies Reader* (New York and London: Routledge, 1999).

[73] For a recent summary of views of Copernicus, see David C. Lindberg and Robert S. Westman, *Reappraisals of the Scientific Revolution* (Cambridge: Cambridge University Press, 1990).