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Analysis of the Columbia Shuttle Disaster—Anatomy of a Flawed Investigation in a Pathological Organization

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Abstract—Ten days after the Columbia shuttle disaster, the members of two of my classes were assembled to do an analysis of the event. One of the classes was studying Creative Problem Solving and the other Incident Investigation. The shuttle disaster provided an opportunity to relate our studies to a current real-world event. The excitement and energy in the two sessions was phenomenal, and the depth and quality of information brought to the sessions was amazing for undergraduate researchers. It was obvious that our findings were not the same as those of the National Aeronautics and Space Administration (NASA). Their scenario, almost uninterrupted since the disaster, has focused on a block of foam insulation that came loose from the Hydrogen-Oxygen vessel and impacted the leading edge of the left wing of the shuttle. Their contention is that this breached the integrity of the left wing and allowed hot gases to enter on re-entry and destroy the wing. We will show that this scenario does not fit the data well and gives inordinate weight to suspect data and to ground testing that does not duplicate the lift-off conditions. We will present a different scenario that includes structural failures inside the wing on lift-off which fits all of the evidence available to us, including the information presented in the official Columbia Accident Investigation Board (CAIB). The action items for this much more likely scenario are very different than those proposed in the NASA conclusions. We will discuss the cultural, organizational, and management characteristics of the NASA organization and their impact in the flawed investigation of the Columbia shuttle disaster.

Keywords: accidents—organizations—organizational culture—coverups—NASA—Columbia—bad science

Introduction

In this paper we will first give a brief account of the event so that the readers can re-familiarize themselves with the particulars of the tragedy. We will introduce the members of the Utah Valley State College (UVSC) investigation teams[1] and give a brief account of our investigative methodology. We will comment on the apparent methodology of the National Aeronautics and Space Administration (NASA) and their investigative efforts, and the NASA management culture and its impact on their investigation. The next section will discuss in detail our findings and why we feel that the NASA scenario is unlikely. Finally, we will present the recommendations that we feel are necessary for the integrity of future shuttle missions.

Since our presentation to the annual meeting of the Society for Scientific Exploration in Kalispell, Montana, in June of 2003, the Columbia Accident Investigation Board (CAIB) has released its official report and there have been several press releases regarding future directions and activities for NASA. This information is now incorporated into our analysis. It has not changed our findings substantially. Videos of both the impact of the foam blocks during lift-off and the so-called "smoking gun" test that blew a substantial hole in the wing's leading edge have been obtained and studied. They have lent significant evidence for our position. Additional research into the available data on Columbia has enhanced our position and added some other possibilities for the observed failures. NASA management activities since release of the CAIB report have only indicated that the cultural problems have not and are not likely to be changed.

One of our reviewer/contributors to this paper is Dr. Ron Westrum of Eastern Michigan University. He holds positions in both the Technology School and the Sociology Department there. Dr. Westrum has extensively studied organizational behavior in general, how that relates to safety critical systems, and NASA cultural behavior in particular. He defines safety critical and other behavior in terms of Generative, Bureaucratic, and Pathological behavior modes. Unless otherwise noted, we will use in this paper the term "pathological" to mean "sick", which will include the bad or worst organizational behaviors in Westrum's Bureaucratic mode and Pathological mode. We will refer to some of Westrum's modes later.

Summaries of Conflicting Scenarios

NASA's failure scenario is that, during lift-off, a block of insulating foam broke away from the Hydrogen-Oxygen vessel, was accelerated to a differential velocity with the shuttle of about 500 mph, impacted the carbon-carbon leading edge of the left wing, and broke a substantial hole in it. Thus, during re-entry, hot gases burned or melted through an insulated first bulkhead, entered the wing proper, made a 90-degree left turn to the wheel well, and began destroying the structural integrity of the left wing, which subsequently destroyed the shuttle.

Our failure scenario is that during lift-off, the severe vibrational and random "jerky" movement loads, along with potential metal fatigue and/or cracking in the wing structures near the fuselage, aggravated by a wind shear, an impact by the foam block, and excessive payload, caused structural failure along the wing-fuselage boundary. This allowed excessive flexure of the wing, causing many tiles to pop off in the area of the wing-fuselage boundary. On re-entry, the unprotected aluminum skin of the wing quickly melted through, allowing hot gases to enter a very large breach that expanded quickly. Flow of hot gases between this breach and a possible *small* one caused by impact of the foam block likely greatly accelerated the destruction of the wing's internal structure, destroying the shuttle.

The UVSC Investigation

First, let me assure you that I personally am an avid supporter of the manned space program, as are the vast majority of my students. When we decided to participate actively in the investigation, at NASA's invitation, we felt that we could perform the role of an outside observer. This is a vital role in any incident investigation. In the Incident Investigation class taught by Failure Analysis Associates, the outside observer is listed as an important, albeit part-time, member of the investigation team. Those on the team itself are usually so inundated with data and information that they find it hard to sort out what is important and what isn't. Outside observers are valuable in that they can ask themselves "dumb" questions that frequently are very important, and to propose alternative scenarios that may be more likely than those being considered, or at least to create some alternate avenues for investigation. At the conclusion of our investigation session, I asked the question, "Knowing what you know at present, how many of you would take a ride on the next shuttle mission?" About two thirds raised their hand (me included, although my wife is not of the same opinion). The same question at the end of the presentation to the scientists in June garnered a little over a third.

The Columbia shuttle incident occurred February 1, 2003, and e-mail instructions to gather as much data as possible were transmitted to the students on February 5th. Two analysis sessions were held on February 10th, one with each class. Sessions were in the same room, so the second session had the benefit of the work of the first session. Initially, the investigation had as its objective the case study of a high-profile incident to give the students experience in both creative problem solving and incident investigation, both part of the curriculum in the two classes. When it became apparent that what we saw as the most likely series of causal factors was not the same as what NASA was telling the public, our objective changed to provide information to NASA that hopefully would improve their investigation and help prevent future similar tragedies. NASA at this point was actually soliciting assistance from outside entities.[2] A telephone contact with NASA at this time revealed their desire to inspect our findings.

On February 19th we sent an e-mail to NASA with our findings and recommendations. Members of the classes had an opportunity to comment on the e-mail before we sent it to NASA. We hoped that we would provide for NASA the role of outside observer. The following day we received an acknowledgment of our e-mail. On March 27th we received a further e-mail from NASA soliciting any further information. At this time investigations were still under way in the Houston NASA facility.

Students continued to submit information, and we were invited to present our findings at the Society for Scientific Exploration annual meeting in Kalispell, Montana, in June of 2003. We had considerable UVSC and student participation in constructing that presentation. In preparation for that and the final report to be sent to NASA, I conducted several "sanity checks" on our findings with well-credentialed scientists and engineers. I met with two engineering scientists and a social scientist in Houston prior to the SSE meeting for about three hours in an in-depth discussion of our analyses and results. At the SSE presentation, we solicited critical commentaries from the audience as another "sanity check" on our findings. Neither the scientists in Houston nor the SSE scientists and engineers had any negative comments. Several had constructive suggestions to include in the analysis.

Repeating an important concept put forth earlier, in both incident investigation and creative problem solving, I have found that the outside observer who provides the "sanity check" (or peer review if you prefer) has always been a most valuable part of the team. The Houston scientists provided this before we made the presentation to the SSE, and the SSE attendees provided this before we sent our final report to NASA. We hoped that NASA would view the considerable expertise included in our report to them as the input from a group of outside observers.

Sources of information. Much of the information used came from articles in various public news sources, mostly newspapers. It is recognized that information from these sources can be flawed, primarily because the technical expertise of reporters is frequently lacking and their interpretation of what NASA released may be erroneous. We found, in fact, that some of the reports were even somewhat silly, technically and logically. Some of the best information came from the NASA web-site. Videos shown on TV and photographs in the media were especially valuable. A video of an ABC *Primetime Monday* presentation on July 7, 2003, *Final Mission*, had video of both the foam-block impact and the alleged "smoking gun" test at Southwest Research Institute that blew a large hole in the leading edge of a shuttle-wing mockup. This video has allowed close inspection of both events, which has helped greatly in validating our findings. Valuable information was obtained from two officers at Hill Air Force Base and from the web-site of Kirtland Air Force Base. One student brought in a risk analysis of the tile system done by Stanford and Carnegie-Mellon researchers. My own personal information and the expertise of students in adhesives, the Challenger disaster, and incident case studies were also helpful. The CAIB final report of August 27, 2003, was also of great value. Dr. Ron Westrum, of Eastern Michigan University, was a valuable source of information regarding NASA management, cultural and organizational matters, and their effects on the causal factors of the tragedy and investigation.

Quality of Data

We are well aware of the limitations of our data and that there are things that NASA has in their hands that we do not. We are also very aware that information from news media can be inaccurate or slanted to a particular viewpoint. A related point is that we feel the real story of exactly what happened will never be known. With the exception of about 7–8 minutes of telemetry during re-entry, all other data are suspect. All of the recovered pieces, including the computer, went through the 3000°C firestorm and fell from about 200,000 feet. These other data are of interest and may provide clues, but it is inappropriate to base the conclusions on such data. NASA did mention the telemetry data in passing, but only as support for the other data from the recovered computer. During the first week or two, NASA was very free with information and data. Shortly after our investigation sessions, the live telemetry data were removed from their web-site (between February 10th and 16th) and the information gleaned from the recovered computer was not revealed until the CAIB report was released in August.

Since the telemetry data suggest that the initial breach was near the wing-fuselage boundary close to the wheel well, rather than at the leading edge in the theory favored by NASA, one may be suspicious that they were manipulating the data to favor their theory. We don't know why they would do that, because the telemetry data can easily support their favored scenario or our favored scenario. One source we consulted was an officer of the 388th Fighter Wing at Hill Air Force Base. He said it was common in military incident investigations for data that were potentially damaging to specific individuals to get classified and disappear from open databases. He found the removal of the live telemetry data especially significant, as did we and others with whom we have consulted.[3]

The Event

The Columbia Space Shuttle lifted off on January 16, 2003, at 9:39 AM CST carrying 7 astronauts and a payload of 86 scientific experiments.[4,5] At an elevation of 32,000 feet, Columbia encountered a wind shear of about 25 mph. NASA calculations showed airframe stresses at this time at 70% of design.

About 82 seconds into the lift-off, at nearly 66,000 feet, a chunk of foam insulation about 21 inches long, 15 inches wide, and 5 inches thick, weighing about 1.7 pounds, came loose from the Hydrogen-Oxygen vessel and began to be accelerated by a wind of about 1570 mph. At the time it impacted the wing, its relative velocity to the shuttle had increased from 0 when it came loose to about 500 mph. According to NASA, the trip the foam block took lasted 0.16 seconds. This is an average acceleration of about 10g. These numbers are based on an analysis of the video taken, and there is a claimed accuracy for them of about ± 10%.[6] It is not known if the substantially reduced air pressure at this altitude was taken into consideration when determining this velocity. If it wasn't, the relative velocity between the foam block and the shuttle wing would be significantly less.

On February 1, 2003, Columbia began its re-entry procedures over the Indian Ocean. At 13:43 GMT, it reached re-entry interface over the Pacific Ocean,

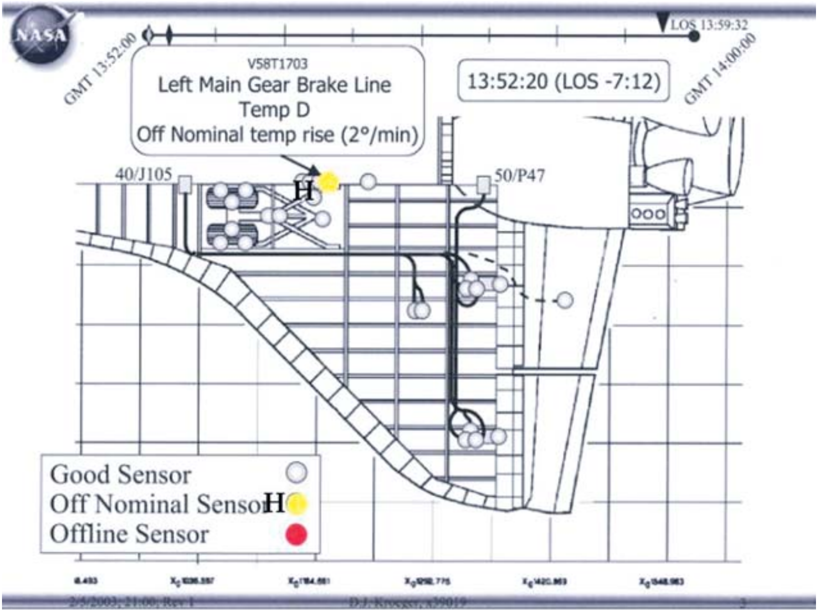

Fig. 1. Left wing instrument layout. First indication of trouble at 13:52:20 Greenwich Mean Time (GMT). Sensor going off-normal high. Inboard side of left wheel well under fuselage.

when the atmospheric friction-heat began to be apparent. At 13:49:26, Columbia began two sweeping S-turns to assist in velocity reduction. The shuttle rolls about 23 degrees in either direction during this maneuver. At 13:51:00, it crossed the California coast and was observed from the ground.[7]

At 13:52:20, the first indication of a temperature rise within the left wheel well was noted by live telemetry data[8] (see Figures 1–6 for a cutaway view of the left-wing internals and left side of the fuselage with the left wheel well). By 13:52:48, two more wheel-well sensors were showing increasing temperatures. At 13:52:59, temperature sensors in the rear of the wing began to go off-line without showing any temperature increase. By 13:54:22, five of these sensors had gone off-line without spiking high, and a temperature sensor in the fuselage was increasing. By 13:58:39, all sensors within the wheel well were showing high temperatures and many had gone off-line. Also, two more wing sensors had gone off-line without spiking high. At 13:59:32, there was a loss of signal from the shuttle, and no more data were received in Mission Control[9] (see Figures 2–5 showing this sequence). At that point in time, one of the astronaut pilots was cut off in mid-comment acknowledging off-normal temperatures.

Shortly after this, the shuttle was over New Mexico and the telephoto from Kirtland Air Force Base was taken (see Figure 7).[10] NASA has discounted any value of this photo. From our perspective and others we have talked to, it shows the leading edge of the left wing torn up and a trailing debris field from the left

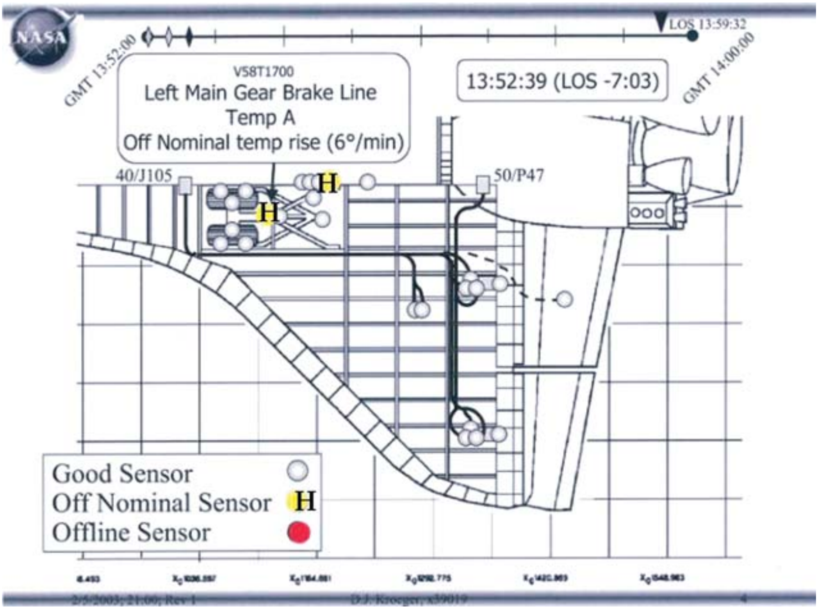

Fig. 2. Left wing instrument layout. Second sensor in left wheel well starts heating up at 13:52:39 GMT. Sensor going off-normal high. Center of left wheel well under fuselage.

wing-fuselage boundary. Some NASA analysts said that the anomalies in the photo are due to distortion from shock waves; however, there are no other similar distortions elsewhere in the photo. However, they do say that the indicated damage is consistent with their failure scenario theory.[11] It is not clear why they discount the photo on the one hand and then say it supports their scenario on the other. It is also consistent with our failure scenario and additionally gives information ignored by NASA. In order to get the silhouette shown in the photo, the shuttle would have to be flying nearly on its left side. This is from simple geometry from the location of Kirtland and the altitude of the shuttle. This could be due to the loss of lift on the left wing from the damage, resulting in a left roll. At this point in time, control efforts were ineffective and the upper surface of the wing and the left side of the fuselage were exposed to excessive re-entry temperatures.

Shortly after the Kirtland photo, the left wing would have separated and the continuing aerodynamic lift on the right wing would have sent the shuttle into a longitudinal spin, exposing all parts of the shuttle to the re-entry temperatures and facilitating the breakup of the vehicle. Figure 8 shows the debris field in Texas stretching from near the Dallas-Ft. Worth area to western Louisiana.[12] This map of debris locations was generated from data accumulated by the 84th Radar Evaluation Squadron at Hill Air Force Base in Ogden, Utah. It pinpoints objects about one square foot in area and larger. The spinning of the shuttle

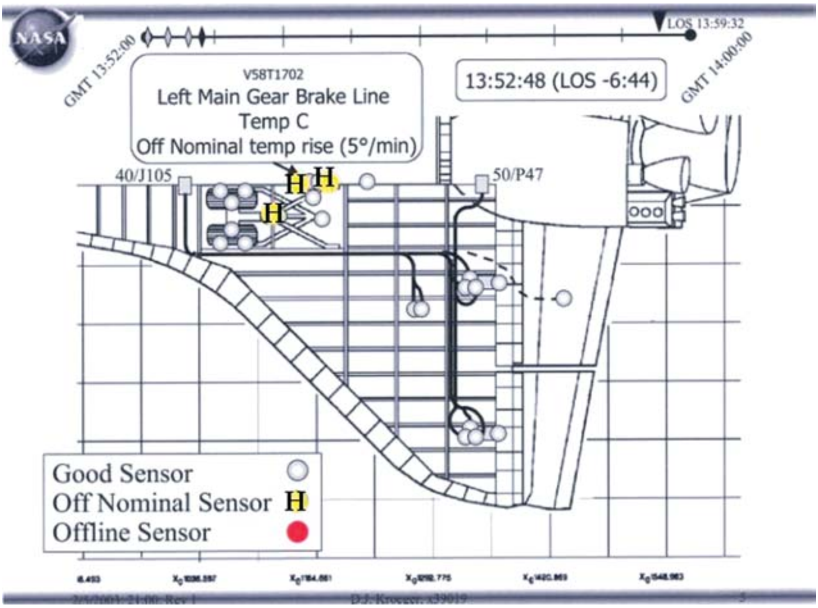

Fig. 3. Left wing instrument layout. Third sensor in left wheel well starts heating up at 13:52:48 GMT. Inboard side of left wheel well.

would generate lateral forces on debris, explaining the nearly 55-mile width of the debris field at its widest point. It also makes molten metal spatter on recovered debris irrelevant, because molten drops of metal were being thrown in all directions as the shuttle broke up.

NASA's Approach to the Problem

While again we reiterate that reliance on news media can be problematic, it appears from this source that NASA attacked a shotgun of solutions rather than first identifying what the problem was. The first thing to do in solving a problem is to define what the problem really is. This is not always easy. An error here can take one in a wrong direction. In the early days of the investigation, numerous solutions were thrown out to the news media as the answer. They included the shuttle being hit by space junk, corrosion from a painting system, loss of tiles on the wing, wiring problems, loss of the wheel-well hatch, some malfunction in the payload, aging of the spacecraft, Boeing and Lockheed-Martin "messed-up," uneven drag on the wings, and the matchless foam-block impact. All of these showed up in the news in the first three days.

Starting on February 3rd, there began a steady stream of news releases pointing to the foam block as the solution to the problem. These occurred February 5th, 6th, 7th, 19th, 23rd, 24th, March 11th, 22nd, April 16th, 18th, and

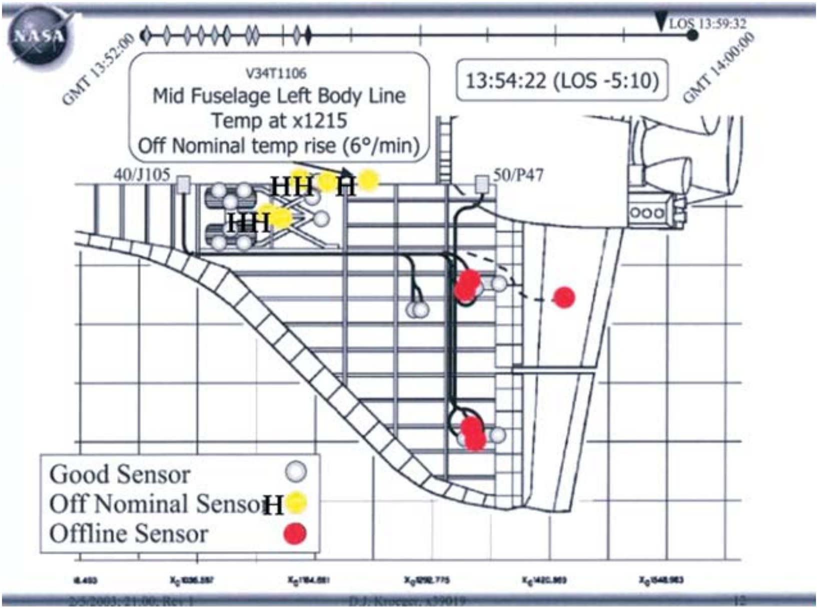

Fig. 4. Left wing instrument layout. By 13:54:22, two more sensors in the left wheel-well area are heating up: one in the center of the well and one near the inboard wall and slightly to the rear of the left wheel well. It is *after* this point in time that the recovered computer shows anomalies in instrument measurements in the left wing.

23rd, May 6th, 14th, and 30th, and June 7th.[13–34] It appears that NASA had decided as early as February 3rd, when any real investigation had hardly begun, that the foam block was "The Cause". Some of the releases in May, and the one on June 7th, reported failed attempts to produce any significant damage to the leading edge of the wing with an impact by a foam block at around 500 mph. In numerous other press releases on other subjects over the past several months, continual repetition of the foam block as "The Cause" is promoted. *On February 4th, NASA engineers were at Southwest Research Institute to get them started on finding out how to make significant damage in the wing with a block of foam*.[35] Finally, on July 8th, scientists and engineers at Southwest Research Institute were able to devise a set of conditions that theoretically predicted significant damage. Doing the experiment with those conditions did indeed blow a substantial hole in the leading edge of the wing.

We must comment on the CAIB report. It is evidence that a great amount of very good work was done by a lot of very technically competent scientists and engineers. Many technically sophisticated analyses were accomplished. The trouble with them is that they seemed mostly to be focused toward proving the foam-block impact as "The Cause". That is a problem. There is a great principle

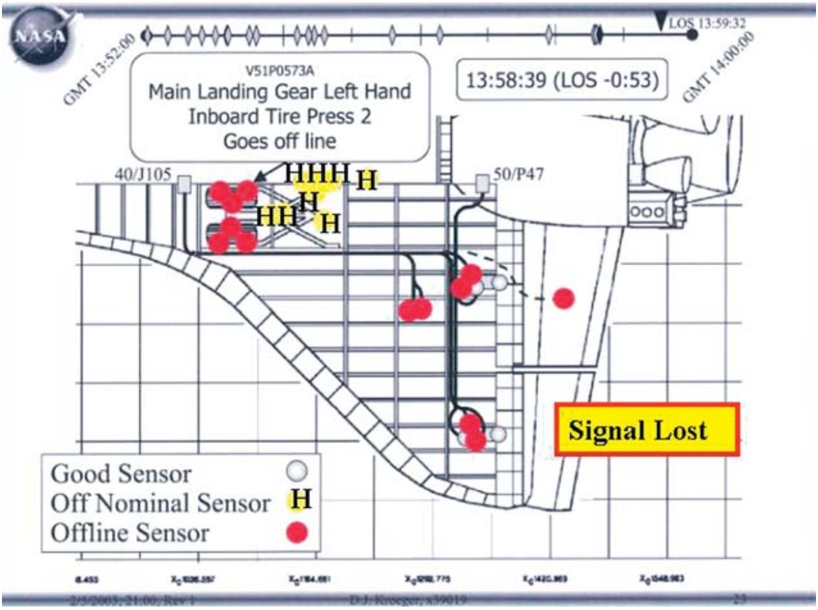

Fig. 5. Left wing instrument layout. By 13:58:39, seven sensors inside the wheel well and one in the fuselage behind the wheel well were heating up; six sensors inside the front part of the wheel well had gone off-line, and seven sensors behind the third and fourth bulkheads had gone off-line. Cabling for these other sensors in the wing can be seen going along the outboard side of the wheel well. At this point in time, all signals were lost from the shuttle.

of Reliability Engineering and of Incident Investigation that there is rarely a single cause of an incident or accident. In complex systems such as the shuttle, interacting with an admittedly problematic organizational culture, it is pragmatically impossible to have a single causal factor. Indeed, as we progress through this analysis, the reader will be able to identify numerous causal factors.

The NASA Management Culture

The one area that the CAIB did fault NASA over was the presence of severe problems in the management of the organization, mostly related to the worst aspects of Westrum's Bureaucratic or Pathological cultures prevalent throughout the whole organization. The CAIB would have lost all credibility if it had not been severely critical of those problems. Revelation of those kinds of problems is widespread over a long period of time and in a plethora of publications and studies. We will examine a sampling of these comments in the media dating back to the Challenger event. It should be noted that such organizational problems are present in many organizations besides government agencies, including many in "Corporate America" and Academia.

Problems in the NASA culture were evident after the Challenger disaster. This

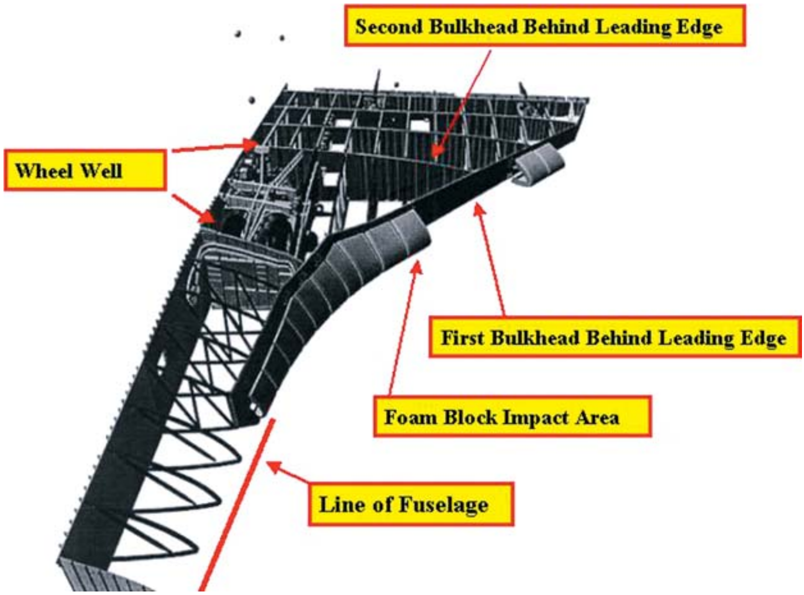

Fig. 6. Cutaway view of the left wing showing portions of the fuselage, including the wheel well and the structural members and bulkheads within the wing.

is discussed in a NASA study of the criticality of the tile system by researchers from Stanford and Carnegie-Mellon, M. Elisabeth Pate-Cornell and Paul S. Fischbeck.

Despite these benefits [of quantified risk analysis], NASA has not used risk analysis. This is because, in the early 1960's, a consultant using risk analysis had computed a very small probability of success of NASA's mission to the moon. Fearing that such results would scare the public and discourage congressional funding, NASA forbid the use of any formal probabilistic risk analysis (PRA). Yet, after the Challenger accident, it became clear that the space shuttle system was much more vulnerable than NASA had been willing to admit—to itself and to the rest of the world—and that a realistic assessment of the risk was in order. . . . The Challenger accident had also revealed that many of the weaknesses that had finally doomed the mission were rooted in the organization itself. . . . This hardware failure [the o-ring problem] was the direct result of management failures that included poor communication, misinterpretation of information, incentive to launch unless categorically proven *unsafe*, and excessive optimism under schedule pressures.[36]

By the time of the Pate-Cornell–Fischbeck study, issued in early 1994, things seemed to have gotten worse. They observed then:

The management factors that affect the tiles are often part of more general organizational characteristics of NASA. Space shuttle operations involve NASA, its headquarters, its space centers, its contractors (which are more closely associated with one of the space centers), The United States Congress, which votes the funds for the space programs, the media, and the public that eventually decides through the electoral process which pro-

Fig. 7. Kirtland Air Force Base Telephoto. This photo was taken from about 35 miles perpendicular distance from the shuttle path, while the shuttle was at about 39 miles elevation. Note the discontinuity on the leading edge of the left wing and an apparent debris trail coming from the wing-fuselage boundary.

grams are more desirable. Under political pressures, NASA became a fragmented organization, divided among space centers as well as space programs. . . . Rivalries among centers are unavoidable because they must share a budget that is perceived within NASA as increasingly tight. At the same time, NASA seems to have grown from a can-do organization to a large bureaucracy in which the influence of the scientists has markedly decreased.[37]

The recommendations in the Pate-Cornell–Fischbeck study were favorably received by NASA management; however, improvements that may have been made have been completely overshadowed by recent revelations following the Columbia accident. The Pate-Cornell–Fischbeck work prophetically stated, ‘‘NASA cannot afford financially or politically to lose another orbiter’’.[38]

So, let us move to more recent events for evidences that the culture has not improved or has even gotten worse. Shortly after the accident, I noted a turf battle between two separate groups of engineers that erupted into the media as to which one would get to do a sophisticated analysis of the foam-block impact.[39] Turf battles are common in Westrum’s Bureaucratic and Pathological organizations.

On March 29th, Dr. Ron Westrum of Eastern Michigan University wrote to Admiral Harold W. Gehman, the NASA-appointed leader of CAIB. Dr. Westrum is familiar with aviation safety; he has worked on a committee of the National Research Council (NRC) evaluating NASA’s safety research, and he is on an advisory board of the NASA-Ames ‘‘Human and Organizational Risk Management’’ program. He has developed a useful model, mentioned earlier, of Generative, Bureaucratic, and Pathological organizations and their good and bad behaviors and attitudes. He postulates that a technological system

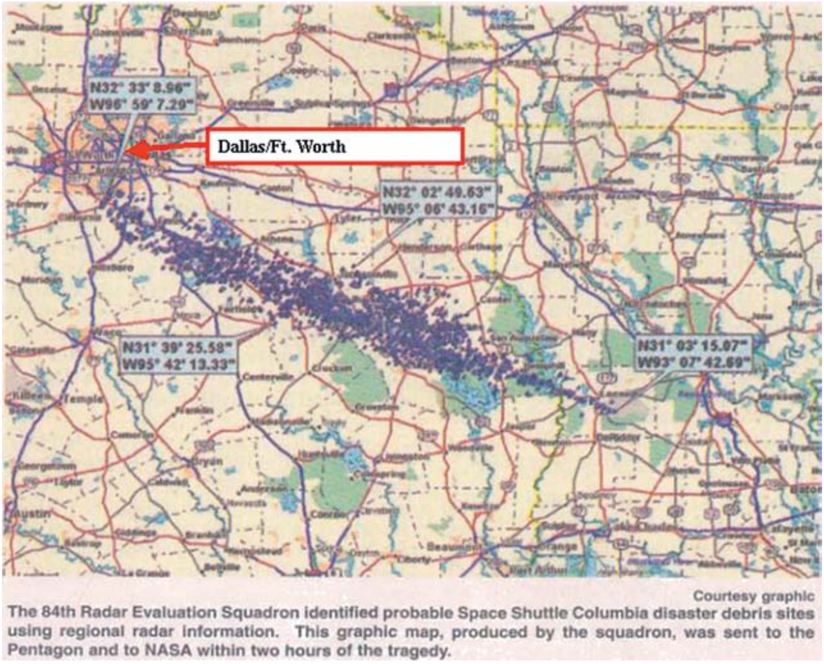

Fig. 8. Map of debris locations as determined by radar. The upper left side of the debris locations is near the Dallas-Ft. Worth area and the lower right portion extends into Louisiana.

must be surrounded by a human envelope of care, made up of its designers, operators, managers, and maintainers. The more complex the system, the greater is the need for the human envelope of care. He commented to Admiral Gehman:

However, in a Bureaucratic environment there is always a tendency to cut deep into the envelope to save money. This appears to be what happened to Challenger's envelope as well as to Columbia's. A basic problem with the shuttle is that it is enormously complicated, and therefore requires a huge envelope whose management must necessarily be a nightmare. This is a job for a technological maestro, not an average bureaucrat. Such people were fairly common during the Apollo missions, but seem very thin on the ground at NASA now. I think the mismatch in resources and leadership is the underlying problem with the loss of Columbia. Regarding the accident itself, it appears that many of the underlying problems with the culture of shuttle operations that appear in Diane Vaughn's book on the Challenger Launch Decision are still present. These problems are essentially a mismatch between NASA's bureaucratic culture and the requirement to manage the kind of uncertain and dynamic situation constituted by shuttle operations.[40]

An article in the *Safety Online Newsletter* from The Canadian Press on February 3, 2003, outlined some stinging indictments:

Investigators looking into the space shuttle disaster will have a well-documented record of years past reflecting mounting safety concerns, tight budgets and shortages of key experts in the NASA program. . . . As President George W. Bush took office, the General Accounting Office, the investigative arm of Congress, found in 2001 that the shuttle workforce had declined significantly. Critics said staff shortages had reached the point where they reduced NASA's ability to safely support the program.

Many key areas were not sufficiently staffed by qualified workers and the remaining workforce showed signs of overwork and fatigue, the GAO said. When it visited the problem again, it reported last week that staffing shortages in many key areas still remain a problem.[41]

On July 11, 2003, Admiral Gehman in a press conference gave a preview of the CAIB report that made severe criticism of NASA's cultural problems: "The board's final report, expected in late August, will stop short of assigning blame for the Columbia accident that killed seven astronauts. . . . We have said from the first day, the first hour, that we are not going to address personal responsibility or personal accountability". The article continues: "But more than half the report will deal with NASA management failures as well as inadequacies in the agency's safety and quality assurance programs, investigators said at the news conference".[42]

Criticism of the NASA culture started early after the disaster. On March 7th, an AP story reported on an interview with Henry McDonald, a former NASA safety investigator and engineering professor. He said that few of the recommendations made three years earlier had been implemented. He complained that engineers and managers both were unconvinced of his criticism of risk management and faulty statistical logic.[43] On May 15th, Admiral Gehman before a Congressional committee said, "the agency's engineering directorate and safety program are ineffectual".[44,45] On May 16th, Sally Ride (who is on the CAIB and was also on the investigation into the Challenger accident) observed that she had a sense of déjà vu as she noted a recurrence of the same problems that were supposedly solved after the Challenger disaster in 1986.[46] News items from this point to late August, when the full report was released by CAIB, chronicle numerous cultural and management problems.

On August 28th, the day after the CAIB report release, Sean O'Keefe (the head of NASA) loudly proclaimed, "We get it". But does he?[47] On September 4th, Congressmen complained that NASA would not name the people responsible for the disaster, apparently so they could loudly proclaim to their constituents that they had punished the guilty parties.[48] The same day, O'Keefe said that no more employees would be fired; that 15 had been fired and that there would be no more.[49] These are the actions of a seriously pathological organization. Congress perpetuates the pressure and NASA falls into line. When the organization has been sick unto death for 30 or so years, it is doubtful that any one person or 15 persons are responsible for the incident. And what is so magical about 15 firings and no more? At this stage of the revamp of NASA, it is doubtful that the most culpable people are even identified.

Despite O'Keefe's limit on firings, nine members of a safety advisory panel resigned on September 24th. They left under intense pressure from Congressional sources who said they were ineffective. This is akin to firing your doctor because you are still sick and won't take the medicine he prescribed. Nothing has changed. The pathological organization still reigns. Until Congress stops micro-managing the space program, nothing is likely to change. Perhaps it is time for private enterprise to take over the efforts, as was suggested in an op-ed by Robert Zimmerman on September 24th.[50] Some of the problems can be laid directly at the feet of Congress. Since 1981, the year of the first shuttle flight, NASA's budget has fallen 33% in constant 2003 dollars. There seems to be little correlation with which political party was in power. There has been a steady decline in purchasing power of NASA's funding. In that atmosphere, Dr. Westrum's comments above are very telling.

Money alone will not solve the problems, however. The culture needs to change. There are organizational experts like Dr. Westrum who can help formulate changes. However, NASA has had a history of ignoring good recommendations. Will this event make a change, or will NASA just ignore them until people forget they didn't follow the recommendations? That is the operational mode of a badly pathological organization I consulted with.

Can it be corrected? A better criterion than indiscriminate firings and fining contractors would be identifying and keeping those who have the technical ability and who are really and truly willing and capable of changing their whole way of doing their daily business. Not only do they have to find out who can and wants to change, including everyone at the very top, but they also have to develop a re-training protocol with effective evaluation to make sure behavior modification takes place.

In a paper that Dr. Westrum is now publishing, entitled "Removing Latent Pathogens", he defines three tools to help change the culture and encourage and motivate behavior modification. They are *Alignment, Awareness,* and *Empowerment*. According to Dr. Westrum,

> *Alignment* is the first factor. When people in an organization feel it is their personal responsibility to prevent accidents, they are motivated to take action. The process by which organizations get individuals to "buy-in" to the organization's vision, regarding safety or anything else, has been well studied by sociologists.
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> ... *Awareness* is a key tool in spotting pathogens. Unless people in an organization understand "the big picture" they will not understand how an anomalous condition can lead to a catastrophic failure. Providing such understanding is therefore a critical part of organizational health. This understanding helps supply the requisite imagination to see how an unsafe condition contributes to the risk of failure. Awareness includes not only the facts, but also the ability to assemble facts in meaningful ways to build scenarios about what might happen. Encouragement to "think creatively" or "outside the box" may reveal unexpected hazards, for instance, in the combined effects of pathogens.
>
> ... *Empowerment* is the third element of the tool set. Empowerment is the ability to make and carry out a decision. Empowerment is the opposite of micro-management. Just as micro-management discourages independent thinking, empowerment encourages both action and thought. Create the ability to act, and you encourage the ability to think.

It would appear from the foregoing that there exists significant knowledge to correct the problems in NASA. Part of the equation is, of course, to significantly reduce the micro-management by technological deficients in Congress. This will be a daunting task. The other problem is to get NASA to take these kinds of action. In my own consulting experience, it is easy to find things for a sick organization to do to make them well, but it is very difficult to get them to do the things that are obvious to the outside observer.

Why the NASA Scenario Is Unlikely

The replication of the foam impact at Southwest Research. At the Southwest Research Institute (SRI), James Walker, a brilliant staff scientist from the University of Utah knowledgeable in the physics of impacts, was given the task of doing computer simulations and finding a way that a foam block could make a hole in the leading edge. With an outstanding piece of engineering analysis and simulation, he and his associates in SRI did just that. Even more remarkable was that when they did the test according to their simulation, they got a large hole.[51] This was what Scott Hubbard of the CAIB called the "smoking gun".[52] The ABC *Primetime* video, *Final Mission*, shows slow-motion videos of that test and the impact of the foam block. This was wonderful engineering but, in our opinion, bad science. I have several concerns regarding the replication of lift-off conditions. In the test, the blocks of foam were fired from only about 15 feet away at a wing mockup that was firmly fastened to a structure. During lift-off, the wings were vibrating and being subjected to numerous random "jerky" stresses. NASA said that was irrelevant, but I am skeptical. During the test, there was an 11.5-inch tall by 5.5-inch wide by 19-inch deep block fired in a longitudinal position so as to concentrate the impacts. It was not spinning as NASA reported for the lift-off situation.[53] Even this NASA proclamation is very unlikely because the lift-off foam block was irregular with no axis of symmetry. Nor was it chaotically tumbling as is obvious from the lift-off video and as would be expected of an irregular object being accelerated by a high-velocity wind.

The other problem with the test is that the full weight of the foam block was used in the test in such a fashion as to concentrate the momentum on the impact. During lift-off, the foam block had fifty feet or so to travel and was in the process of breaking up under the stress of 10*g* of acceleration. At least two or possibly three pieces are evident from the lift-off video along with several smaller pieces. This was also announced to the press early on by Ron Dittmore. The video also shows the pieces moving apart as they approached the wing, thus reducing the energy available to impact the wing in a concentrated point as in the test. While there are several concerns with the Southwest Research test replicating the lift-off conditions, the most serious and telling is that of the test being done with the whole block's mass and concentration impact, when it is obvious to even the casual observer that the foam is breaking up and the pieces are moving away from each other, not concentrating to a single point. This seems compelling evidence that data are being manufactured to prove the NASA scenario. That is bad science.

It should be noted that this is in no way a criticism of Southwest Research. I personally have great respect for the capabilities of Southwest Research. They are a well-respected organization. I think they did just what NASA asked them: Find a way a foam block can make a big hole. Again, fantastic engineering by Southwest, bad science by NASA.

However, despite the legendary intellectual integrity of SRI, without details of the official and private instructions given by NASA, we must also consider the possibility that SRI focused on the foam block in order to cater to an existing or potential good customer's pet theory.

Burning or melting a large hole into the wing from a breach in the leading edge. A few things should be noted about the system we are dealing with. First, at 200,000 feet, the atmosphere is very thin. In every cubic foot of air there are not very many molecules to carry heat into the wing. At that altitude, there are about 0.000115, or a little over one ten-thousandth, of the molecules that there are at sea level. Even at 3,000 degrees, it takes a lot of air to heat heavier materials like metals to the melting point. At 12,500 mph, the speed of the shuttle at breakup, there are lots of molecules flowing across the wing to heat the exterior surface. However, when you slow them down or stop them, as *inside* a wing, they need to have substantial flow to cause widespread thermal damage.

The next thing that it is important to realize is that you cannot have gas flow indefinitely into the wing, unless it has some place to get out. The pressure in the wing will build up somewhat to balance the force of the gas coming in and then any more that comes in will have to go out somewhere else. This means that it will have to exit through the same hole it is going in. This is possible; I have personally observed adjacent high-velocity gas flows in opposite directions in at least two separate equipment configurations. However, it also means that the melting process is significantly slowed down. Atlantis mission STS-45 had exactly this situation. There was a hole in the leading edge that was about 1.5 × 2 inches on the outside and 0.5 × 0.1 inches on the inside. This did not cause a serious problem to the shuttle, even though there was a channel clear through the carbon-carbon leading-edge tile. The reason that it did not is that there was no place for the hot gas to go. Any hot gas entering the hole has to exit from the same opening unless the hot gas can get out of the wing somewhere else. Damage to the wing in that instance was confined to a small area around the hole.[54]

The problem of the pattern of temperature-sensor behavior. The first heating reported by the live telemetry data was inside the wheel well and on the fuselage just behind the wheel well—refer to Figures 1 through 3. Then the sensors behind the fourth wing bulkhead went off-line. Their leads travel on the outside of the outboard side of the wheel well (see Figures 4 & 5). They go off-line because the insulation either burns or melts off and the leads short out. If the leads themselves burn out, the sensors will spike high or full scale before going off-line.

If you accept NASA's scenario that a large hole was punched in the leading edge by the foam block, you have to accept that the telemetry data are no good or that a hot 12,500 mph wind is going to make a 90-degree left turn after breaching the first bulkhead and travel about 10–15 feet to the wheel well without heating the second bulkhead. My knowledge of fluid mechanics makes me very skeptical of that situation even though I have witnessed some very weird things in fluid-flow patterns. According to that scenario, all the temperature sensors behind the third and fourth wing bulkheads would have started heating up from the hot bulkheads in front of them. Then they would go off-line as the insulation on their leads melted or burned off. That is not what happened. They all went off-line without showing any temperature increase. If you assume the more likely scenario that the large hole allowed the hot gases to bore straight back into the wing, then you get the same problem. The sensors behind the third and fourth bulkheads would heat up before going off-line. In either eventuality, the flow would be greatly retarded because the hot gas has no place to get out except where it came in.

Other considerations. Something that makes me suspicious is the removal of the only really good data from the NASA web-site shortly after our analysis sessions. That was the 7½ minutes of live telemetry just before loss of signal from the shuttle. Every other piece of data is contaminated by the 3,000-degree firestorm and falling from 200,000 feet. Only three pieces of off-normal data from the recovered computer happened before the heating in the wheel well started shown in the live telemetry data. One was on a thermocouple imbedded in the T-joint between carbon-carbon tiles (one would expect high temperature here even without any problems); another was high stress on a strain gauge on a wing structural member; the third was a thermocouple somewhere in the wing. Almost all the data from the recovered computer were *after* the warming in the wheel well.[55] The CAIB report mostly ignored the telemetry data except for the high pressure in the tires. They hung their whole assessment primarily on the data from the recovered computer.

Another cause for suspicion about the quality of the data from the computer is that no alarms or warnings were signaled to the crew or to the live telemetry. As an engineer experienced in computer monitoring systems, I find it hard to believe that there were no alarms. If there were, why did we not hear about them? If there were not, it seems an unconscionable design flaw. The other possibility is that the data from the recovered computer are no good.

Miscellaneous concerns. The CAIB report does not address directly the testimony that there was an excessive payload on Columbia on its final flight. According to an AP report of meetings in mid January during the mission, "Managers seemed far more worried during these meetings about Columbia's unusually heavy weight—at 234,011 pounds—and the possible effect on the shuttle's flying characteristics, airframe stress and landing tires".[56] In analyzing the airframe stresses for the wind shear at 32,000 feet, they stated that these stresses were, as we noted earlier, at 70% of design. They did not comment on this, implying that if it were less than 100%, it would be OK. Seventy percent of design is, in my opinion, far too close to operate, especially in a structure that has to withstand severe vibrational and sudden random "jerky" movement stresses for 28 missions. The CAIB report did not address possible metal-fatigue problems. Nor have we seen any evidence that any investigation into fatigue as a primary or contributing factor has been conducted.

The National Transportation Safety Board (NTSB, the Federal agency that investigates aviation accidents) recently criticized the Federal Aviation Agency (FAA) for not having sufficiently rigid inspections and specifications for aircraft that had been through turbulence or sudden random "jerky" maneuvers.[57] This seems like a perfect description of shuttle lift-off and re-entry. Is it possible that the NTSB knows something that NASA does not about what brings down aircraft?

I consulted some expert structural engineers in the ChevronTexaco organization regarding fatigue. Fatigue is very hard to observe. Only in recent years has it become possible to use scanning-electron-microscopy to observe fatigue progress; and for that, one must cut out a sample to inspect in a laboratory setting. Has NASA been doing this? I don't know, but if, as has been reported, they are using thumb pressure to determine the integrity of the carbon-carbon system between missions, then I am skeptical about the validity of fatigue inspections.

One can reasonably ask why NASA would not address possible metal fatigue. Consider the pathological culture discussed above and then think of the possible ramifications of finding metal fatigue in the wing. In all likelihood, Atlantis and Discovery would have to be grounded, or at the very least substantially reduced in payload capability, leaving only Endeavor for a few more missions. The effect on the progress of the International Space Station would be enormous, as there is no developing technology in the near future for replacement of the aging shuttle fleet. Many projects have been proposed, but have failed to go forward.[58] Failure to seriously consider such an abhorrent eventuality is typical of an organization with serious cultural deficiencies. It is far more comfortable to *assume* that there are no routine structural problems.

There is another aspect that seems to have been ignored in the investigation. Columbia had been out of service for repairs after mission 26—for about 31 months, from August 1999 to March 2002. It flew only one mission after that successfully. A problem with shutdowns for repairs is the possibility of not putting something back together properly. This is another axiom of reliability engineering. Preventive maintenance has this problem, whereas predictive maintenance has less likelihood of that as shutdowns and inspections are less frequent and comprehensive. Columbia was plagued with a multitude of problems in its 22nd, 25th, and especially 26th missions.[5]

The UVSC Investigation Findings

During the many months of our investigation, we have at times struggled to make all the pieces of the puzzle fit together. As discussed in the previous section, we have serious misgivings about the quality of the thinking processes in the NASA failure scenario. We think that we have come to a possible scenario that ties up most of the loose ends in the NASA analysis and makes our own more likely because we do not need to neglect data or depend on suspect information, and can include the possibility of the foam impact being either a contributory cause of structural failure or making a small hole in the wing leading edge that could accelerate the destruction of the wing.

So here is a summary of pertinent factors:

- By NASA's own admission early in the investigation, they were worried about the excessive payload (likely due to the pressure to get more work done with less money). As mentioned earlier, they were worried about three things: overstressing the airframe, poor controllability during landing, and blowing the tires on landing.
- There was a wind-shear load at 32,000 feet.
- There was an impact load from the foam block about 80 seconds into the mission, at about 66,000 feet.
- The NTSB recently criticized the FAA for inadequate standards when commercial aircraft have been through turbulence and random "jerky" maneuvers. Turbulence and "jerky" motions are apparent to a great extent on both lift-off and re-entry.
- Then there is the problem of fatigue. When does the shuttle need to be put out to pasture? Is it close to 28 missions? Has this been studied by NASA?

When these things are taken into account, combined with the great difficulty that NASA had in replicating the substantial damage to the leading edge required for their scenario, and even then needing conditions significantly deviant from lift-off conditions, we feel we must look elsewhere for contributing factors to the failure. We also felt that the live telemetry data had to be given quality priority over other data.

As recounted earlier, the live telemetry data showed heating on the *inboard* side of the wheel well *before* the suspect recovered computer showed any off-normal data. What could cause that? We considered several possibilities, but most seemed less likely than a simple structural failure within the wing. Where would that happen? The point of highest stress in those structures is where they fasten into the fuselage. If there were a failure there and the wing flexed more than normal in the random "jerky" and vibrational movements of lift-off, then where would tiles pop off? In the place where there would be the most flexure, right where the wing connects to the fuselage and adjacent to the wheel well (see Figure 9 for tile details and Figure 10 for the most critical tile areas). Why didn't the whole wing break off then? Overstressing had been relieved by the failure and since it may have occurred at 66,000 feet when the foam block impacted, loads from turbulence are decreasing because the air is rapidly getting thinner and thinner. Atmospheric density at that altitude is about 7% of that at sea level.

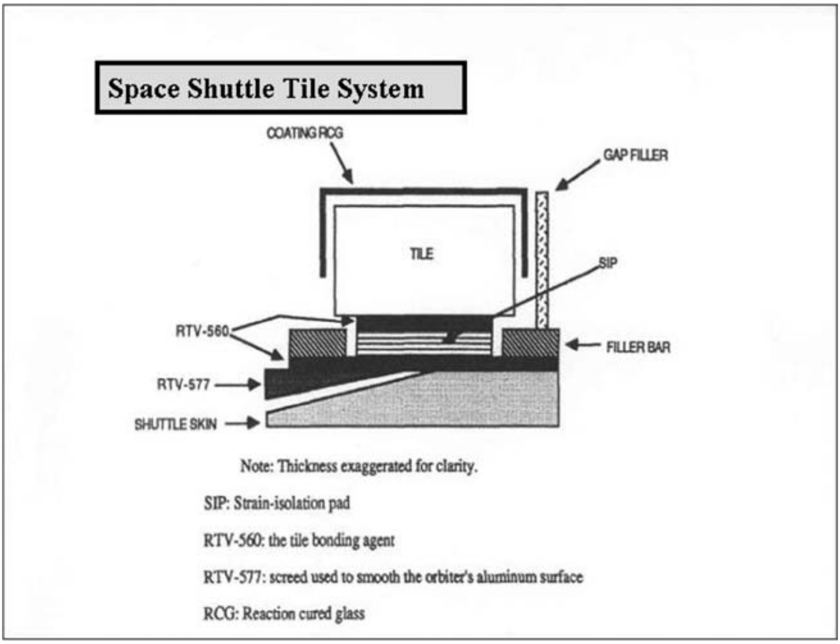

Fig. 9. The tile system showing the tile, the exterior coating, the filler between the tiles, the soft flexible pad between the tile and the wing, the filling material to give the tile system a smooth surface to bond to, and the adhesive material bonding the tile to the flexible pad and the pad to the wing.

It is possible that the impact load at that point triggered the first failure at a point in time when stresses were just below failure. The proverbial ''straw that broke the camel's back'' comes to mind. I am aware of another instance where some very small impact loads in a piping system caused a long-present defect to propagate to failure.[59]

Our bird then continues to fly into space where stresses drop to near zero and do not come back until re-entry. It may be that the foam-block impact also made a small hole in the leading edge of the wing as happened with Atlantis, as noted earlier; however, as with Atlantis, it would not bring the bird down.

However, if there was breach in the wing near the fuselage, as could happen with a structural failure in internal structural members of the wing, it would result in massive loss of tiles along the wing-fuselage line; then there could be flow of hot gases from even a small hole in the leading edge, through the pressure-equalization slot at the bottom of the first bulkhead to the breach near the wheel well. Temperature patterns observed by either the telemetry data alone or with the suspect computer would make sense, and no data would have to be ignored. If the breach on the leading edge were either on the top or bottom part of the carbon-carbon system, then a siphon effect could occur, sucking hot gas from the wheel-well area through the pressure-equalization slot and out to the atmosphere. Temperature sensors would react as if flow was from the leading edge to the wheel well; again, no data would have to be ignored.

The Kirtland telephoto in Figure 7 would seem to support this scenario of reverse flow from the wheel-well breach to the leading edge. Given the 12,000 mph wind, albeit at very low density, the material projecting from the surface of the left wing is puzzling. However, if at this point there were substantial gas flow from the breach at the wing-fuselage boundary to the leading edge of the wing, then some semi-destroyed part of the wing or debris flow might project out in front of the wing as shown in the Kirtland photo.

If there was no breach on the leading edge, then all temperature sensors would behave as the telemetry data say, and data from the computer would not make as much sense, unless there were some tile loss in another part of the wing due to impact or other loads.

It is interesting to note that, according to the CAIB report, very little of the left wing was recovered, and then only small pieces. This is despite the press releases early on that said the left wing was found near Ft. Worth and then about 130 miles southeast of Ft. Worth. Several large pieces of the *right* wing were found, according to the CAIB report. This information would seem to favor the idea of large-scale flow of hot gas through the wing rather than a single breach on the leading edge.

Another point against a large hole in the leading edge is that such a discontinuity would ruin the aerodynamics of the left wing. With the heavy payload, control problems during the S-shaped maneuvers over the Pacific Ocean prior to any temperature problems would surely have been observed. They were not: No indications of control problems were reported by the crew in performing the S-shaped maneuvers. There were some anomalies in the control during this time, but, according to NASA, they do not indicate damage to the left wing and NASA discounted those data as spurious. They may have come from the recovered computer.

Our scenario explains another loose end: the strange going off-line of the temperature sensors behind the third and fourth wing bulkheads. It is important to note that the cables for these sensors go just behind the third and fourth wing bulkheads, thence to the fuselage area, and then forward along the outside of the outboard wheel-well wall. These cables may be seen in the cutaway of the wing in Figures 1 through 6. If the major loss of tiles was in the wheel well and adjacent wing area, then these cables would short out from melted or burned insulation very early. That is what the live telemetry data show. If there were a small hole from the foam impact in the leading edge, there would likely be insufficient hot gas-flow to heat the second, third, and fourth bulkheads and cause temperature rises there before the insulation on the leads burned away. If there were not a small hole, then the telemetry data make sense in this eventuality also. If some of the data from the recovered computer are valid, then they can only be explained by flow of hot gases from a small hole in the leading edge to some other point in the wing where the gases can get out. If we discount the data from the recovered computer, then there can either be a small hole in the leading edge or not.

Therefore, what seems most likely is a massive failure of tiles from structural problems in the wing along the wing-fuselage boundary and a small hole in the leading edge from the foam-block impact. As the underside of the wing melted away near the fuselage, an ever-increasing flow of hot gas began destroying internal structural members of the wing, softening the remaining tile-adhesive, resulting in more exposed wing-skin. The hot gases entering the small hole in the leading edge would flow through the pressure-equalization slot in the first bulkhead to the major breach near the base of the wing, greatly accelerating destruction of the wing and internals. Deteriorating aerodynamic lift on the left wing would put the shuttle into the position shown in the Kirtland photo, and shortly thereafter the shuttle would begin spinning longitudinally, breaking up and spewing pieces to the side, accounting for the wide debris field.

Effect on the Investigation of NASA's Management Culture

Many of those on the CAIB support group came directly out of NASA, and much of the investigative work was done by NASA engineers and scientists, heavily imbued with NASA's cultural problems. It is not surprising that a single-failure scenario has been the focus. If there was not a PR firm directing the campaign to convince the public that "The Cause" was the foam-block impact, then those responsible could likely make more money in the PR field. The numerous concerns enumerated in the foregoing sections make one concerned about the safety of future shuttle missions unless major changes are made in the Hardware, Procedures, and Humans interacting with them. The cultural problems are so pervasive that the CAIB had to come down on those issues. The only thing NASA has done in the right direction is to say that the foam block *and* the cultural difficulties are "The Cause". At least they have got off only *one* causal factor.

Conclusions and Recommendations—Action Items at Variance

It is our conclusion that the Columbia shuttle was a victim of a great deal of mis-management, poor funding, Congressional meddling, and technical errors. These resulted in the most likely scenario being structural failure(s) within the left wing during lift-off due to possible metal fatigue, undetected defects, excessive payload, wind shear, and an impact from a piece of foam block occurring in a short time frame during the heavy vibrational and random "jerking" loads normally present during lift-off. It is postulated that such stresses resulted in the loss of heat-protecting tiles at the left wing-fuselage boundary near the left wheel well. It is also likely that the foam block may have made a small hole in the carbon-carbon leading edge of the left wing. This would have accelerated destruction of the left wing by significant flow-through of hot gases from the hole to the large unprotected area at the base of the left wing, which quickly burned through as re-entry started.

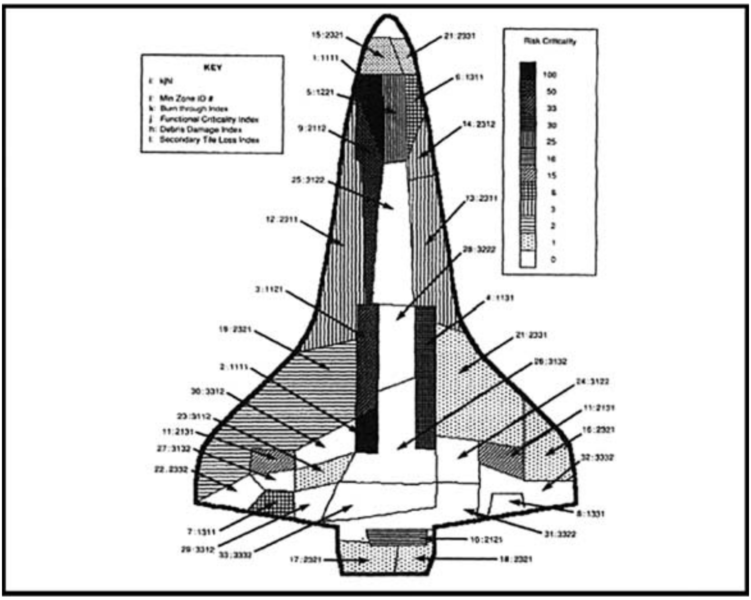

Fig. 10. The layout of the underside of the shuttle showing the risk criticality of various areas as determined in the Pate-Cornell–Fischbeck study. It seems significant that the areas of greatest criticality are in the wheel-well areas.

Recommendations under this failure scenario would be in addition to those formulated by the CAIB. They include:

1. Significantly reduce the likelihood of falling debris hitting the shuttle (one of the points made by CAIB).
2. Inspect remaining shuttles carefully for integrity of the wing structure, using scanning electron microscopy to detect possible metal-fatigue problems. Use modern methods to detect and locate possible cracks. Examine the NTSB information on allowable stresses to airframes in turbulent and random ‘‘jerking’’ operations, and make appropriate changes to shuttle specifications.
3. Prepare for retirement of the aging shuttle fleet.
4. While doing item 3, determine and implement behavior-modification techniques to eliminate the pathological NASA culture. Detailed consideration of Dr. Westrum’s tools for removing latent pathogens, reviewed briefly in the foregoing, should be accomplished.
5. Make the space program a private-enterprise situation to reduce Congressional meddling and imposition of poor organizational behaviors.
6. Thoroughly review the records of repairs and modifications made during the last down-period for Columbia and assess the actions taken to see

if something could have been missed that might have resulted in the observed data.

Final Comments

Do we know our scenario is correct? No. Likewise, NASA does not know that theirs is correct either. Too many data are suspect. We will never know what really happened. Is the NASA scenario possible? Yes. Is our scenario possible? Yes. However, we believe ours is more likely because we do not have to disregard any data or consider weird flow-patterns for hot gases for it all to make sense. Nor do we have to use conclusions based on good engineering but bad science.

We sincerely hope that NASA will take our comments seriously. We do not want to see on the evening news a wing break off in a future shuttle flight. We think it imprudent to disregard potential problems because of a cultural fixation on one failure scenario.

Acknowledgments

I am grateful for the significant contributions and continued moral support to the investigation by the students in both of my classes. The Dean of the School of Technology, Trades, and Industry, Dr. Dee Martin, and his staff gave their continued support to our efforts; and others in UVSC helped in preparing, editing, reviewing, and presenting data, and in disseminating our efforts to various media groups. In this group, we take special note of the efforts of Scott Seals and Gordon Campbell and the patience of their families. I must also acknowledge the continued support of my good wife, Elaine MacLean, and my grown children and their families. Of special note here is the work of my son, Dr. Paul MacLean, who gave comments on our SSE presentation and did a very detailed review of the first draft of this paper, and my daughter, Wendi, who gave me special insights on the ABC program *Final Mission*. Several of my precocious grandchildren had intelligent and valuable comments on our work. Dr. Ron Westrum made valuable comments and contributed significantly to the material in this paper. My initial sanity check was done by Dr. Thomas Krouskopp and by Dr. Robert Baker and his wife, Rose, in the Houston area. Their support and insightful comments were very valuable. The conversations with and information from Lt. Col. John Reidy of the 388th Fighter Squadron and personnel of the 84th Radar Evaluation Squadron, both of Hill Air Force Base, were especially helpful. Special thanks go to many of the members of the SSE for their help, support, and consequential peer review at the June meeting, including but not limited to Dr. Henry Bauer, Dr. Robert Wood, Dr. York Dobyns, Dr. Brenda Dunne, Dr. Marsha Adams, Dr. Roger Nelson, Dr. Harold Puthoff, Dr. Garrett Moddel, Dave Leiter, Gina Leone, and many others. Dr. Larry Peel of Texas A&M offered valuable critique and support after reading media reports of our work. Phillip Smith of Texaco (retired), an excellent structural engineer, proffered information on fatigue assessment. Last but not least is the work of Christi Babbitt of the Provo *Daily Herald* and Angela Gotula, staff writer for the UVSC college relations group, for their efforts to make the publications accurate to our best information.

Notes

[1] The investigation teams were led by John P. MacLean, Adjunct Faculty, Utah Valley State College (UVSC). MacLean's educational and experience background includes a B.S. in Chemical Engineering, a Master's in Interdisciplinary Technology, a P.E. in the State of Texas, 40 years in industry, and adjunct faculty in the Technology Management Program of the School of Technology, Trades, and Industry at UVSC. He has had extensive experience in incident investigation, and has taught that subject in industry while on retainer with Failure Analysis Associates in cooperation with FlightSafety International. MacLean's own experience in incident investigation has ranged from minor problems in chemical processes to major explosions in various high-temperature process equipment to assistance in a light plane crash litigation. He led a team that formulated the Texaco Reliability Engineering Initiative in 1992, which is now being implemented in the ChevronTexaco organization following the Chevron takeover of the Texaco assets.

The students who participated in the analysis have a multidisciplinary educational and experience background and are undergraduate juniors and seniors in Technology Management. The skills and experience of the 57 students are diverse and impressive. They were in two classes: 1) Reliability Engineering and Safety (includes instruction in incident investigation), and 2) Project Risk Analysis and Management (includes study of creative problem-solving techniques). A great many of the students have families and work in various technological endeavors while continuing their education. Their experience levels range from a very few to 30+ years. About a third are in Construction or Construction Management. Another third, including co-authors Campbell and Seals, are in Electrical, Electronic, Robotics, and Automation. The remainder specialize in Manufacturing Technology, Quality, Welding, Machine Tools, Dentistry, Cabinetry, and Automotive. Mr. Campbell is the Technology Manager of the new Heber Valley branch of UVSC, and Mr. Seals is currently Maintenance and Safety Manager of Mountain States Steel, a local steel fabricating company.

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