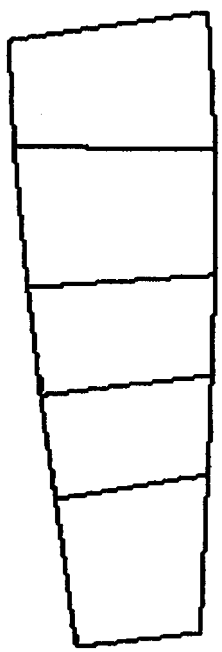
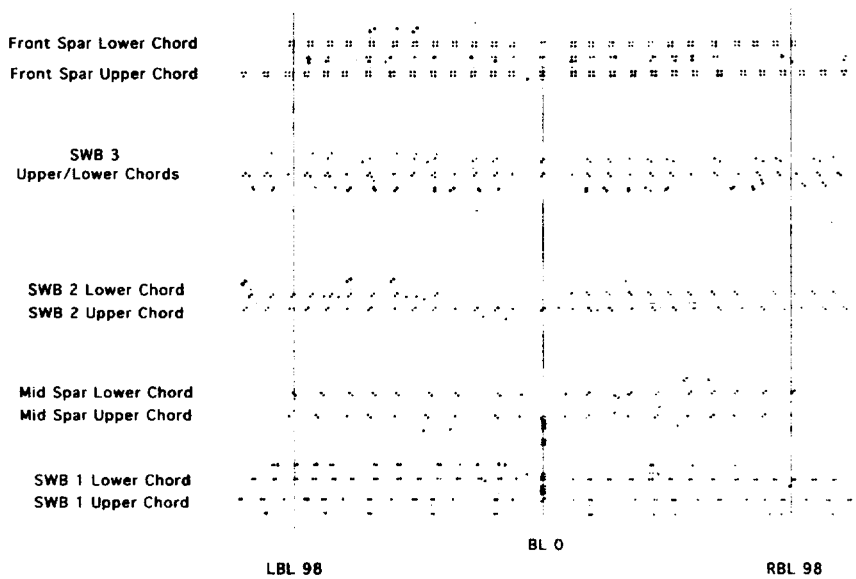


## CWT Side View

*(looking through tank from right to left)*

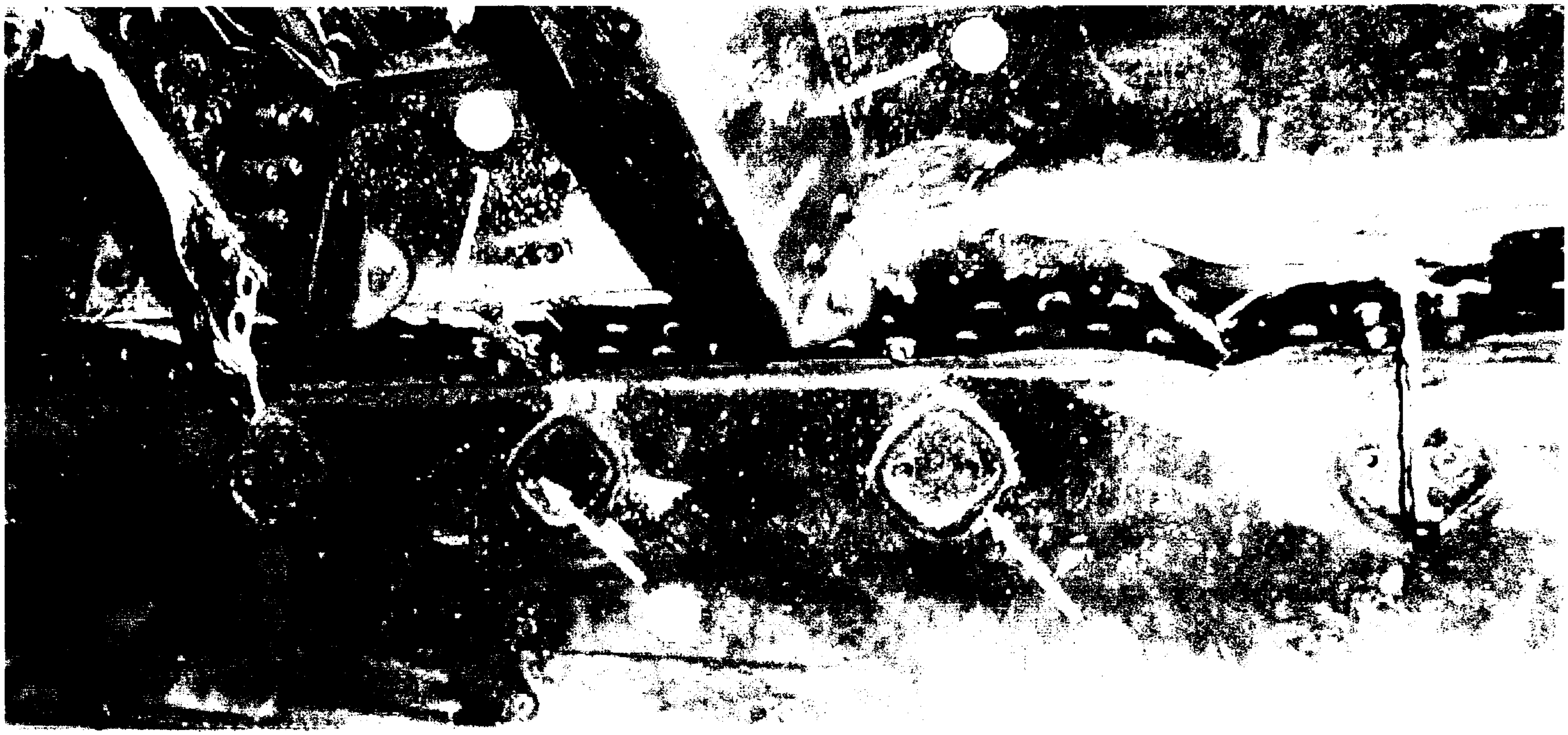



## Shear Tie Failure Map

*(looking down through tank from top to bottom)*

1. Arrows indicate direction of shear tie movement relative to skin
2. Magenta color indicates direction derived from structure remaining on skin
3. Blue color indicates evidence derived from structure remaining on stiffener

Figure 1



4 – Shear Tie Bolt Remnant

5 – [illegible] Lower Chord Remnant

[illegible]

Figure 2

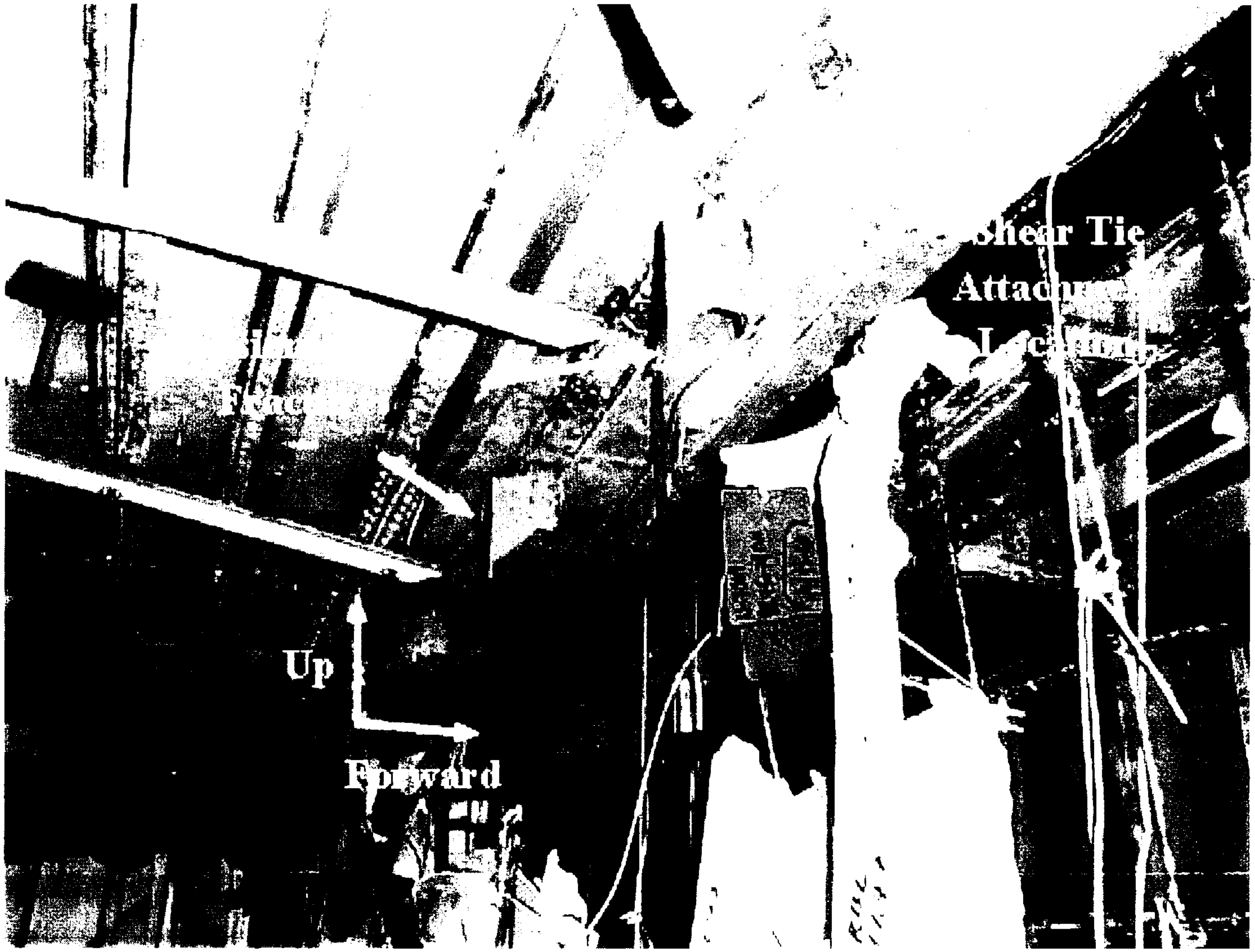



Figure 3

AIR LINE PILOTS ASSOCIATION, INTERNATIONAL
535 HERNDON PARKWAY □ P.O. BOX 1169 □ HERNDON, VIRGINIA 20172-1169 □ 703-689-2270
FAX 703-689-4370

April 30, 2000

Mr. Al Dickinson
Investigator-In-Charge
National Transportation Safety Board
490 L'Enfant Plaza, SW
Washington, DC 20594

Dear Mr. Dickinson:

In accordance with the Board's rules, the Air Line Pilots Association (ALPA) submits the attached comments concerning the accident involving Trans World Airlines Flight 800, which occurred on July 17, 1996, off Long Island, New York.

ALPA appreciates the opportunity to have participated in the investigation and hopes that the attached document is of benefit to the Board.

Sincerely,

Jerry Rekart
Captain Jerome Rekart
Coordinator
Air Line Pilots Association ksa

Attachment

Cc:
J. Hall, NTSB Chairman
J. Hammerschmidt, NTSB Member
J. Goglia, NTSB Member
G. Black, NTSB Member
B. Loeb, NTSB
R. Boushie, Crane Aerospace
J. Manno, FAA
A. Calhoun, IAM
R. Parker, Pratt & Whitney
J. D. Rodrigues, Boeing
L. Taylor, Honeywell
R. Young, TWA

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# 1. Overview

On July 17 1996, at approximately 2032 EDST, a Boeing 747-131 registered as N93119 and operating as TWA Flight 800, was destroyed by an explosion of the fuel/air mixture in the center wing fuel tank (CWT). The aircraft was climbing through 13,700', experienced an inflight breakup, and impacted the Atlantic Ocean approximately fifteen miles off the south shore of Long Island, New York. All 230 passengers and crewmembers aboard the aircraft were fatally injured.

The complexity of this investigation was increased by numerous factors, including:

- The inflight breakup of the aircraft at altitude, and subsequent dispersal of the wreckage over a large area.
- Secondary damage from water impact.
- The requirement for underwater mapping and recovery of the debris.
- Tertiary damage from wreckage recovery and transport.
- Priorities associated with victim recovery.
- The parallel nature of the FBI and NTSB investigations.
- The high media profile of the accident.
- The NTSB's evolving responsibility to liase with the victims' families.
- The inclusion of numerous organizations not typically affiliated with civil aircraft accident investigation (DOD, USAF, USN, USCG, ATF, NASA, local law enforcement, etc.)

Immediately after the accident, there was strong speculation that a criminal act was the cause of the explosion. However, as the wreckage recovery progressed, it became clear that the center wing tank (CWT) was the origin point of the explosion, and the focus of the investigative efforts became the identification of the ignition source. To date, the investigative team has been unsuccessful in determining a specific causal mechanism. However, the investigation has significantly advanced industry knowledge and understanding of many aspects of the 'basic sciences' related to this accident. These areas included aircraft systems design, certification and inspection practices, aircraft systems and component degradation, fuel flammability, and explosion dynamics.

This and other accidents indicate that the Safety Board must address the broad issue of aging certifications. ALPA believes that the fuel system certification criteria to which the Boeing 747-100 was certificated was not adequate to prevent this accident. The engineering knowledge in existence at the time of certification was probably not sufficient to anticipate the types of component degradations discovered in the subsequent accident investigation, and the safety assessment criteria in existence at the time were far less rigorous than they are today. In the last ten years, several other accidents (e.g. UAL 232, USAir 427) have been attributed to systems failures which could be related to the original certification basis of the aircraft. When considered with regard to the industry standards in effect at the time of certification, it becomes apparent that hardware manufactured or in service today, yet whose design certification could be over 30 years old, can constitute an aging system from a safety standpoint.

With respect to fuel tank safety issues, ALPA believes that the Safety Board must address both ignition source reduction and the development of fuel tank inerting technology. Much of the work accomplished or planned in these areas will affect the certification and airworthiness of current and future aircraft. Therefore, the value of this investigation should not be judged on the basis of whether it produces a very specific probable cause, but rather on the benefits derived from the body of investigative data it has produced, and the effectiveness and viability of the ensuing recommendations.

## 2. Investigation Issues

### The Parallel Investigations

Law enforcement requirements took precedence over normal investigative processes during the first portion of this investigation, and the subsequent information flow difficulties hampered the efficiency of the investigation. However, while some evidence may have been lost due to certain procedural differences and resulting inefficiencies, ALPA does not believe that the final outcome of the investigation would have been significantly different if law enforcement agencies had not been involved.

Discussion

The circumstances of the destruction of TWA 800 presented strong implications that a criminal act was responsible, and therefore the requirements of law enforcement agency (FBI, ATF, etc) protocols and procedures dominated the investigation, particularly during its early stages. ALPA understands and agrees with the necessity for this hierarchy. However, the efficiency of the civil (and likely the criminal) investigation was reduced due to the constraints induced by the uniqueness and unfamiliarity of the parallel investigations.

The law enforcement dominance of the investigation process was primarily manifested as a one-way information flow. While the civil investigation provided information to the criminal investigation, the reverse essentially did not occur, at least down to the interested party level. Certain typical civil investigative practices, such as witness interviews and photographic documentation, were prohibited or sharply curtailed and controlled. Finally, some of the methods and behaviors that were practiced or exhibited by the FBI & ATF personnel were directly contrary to established civil investigative techniques. These were primarily due to the agencies' relative unfamiliarity with aircraft or aircraft accident investigation techniques. One example of this was the law enforcement personnel's handling of the wreckage; they did not seem particularly aware of the need to preserve the existing evidence by preventing further damage to aircraft parts. As the investigation progressed, however, conflicts between investigative parties diminished.

It should be noted that the law enforcement agencies did provide significant resources, primarily in terms of manpower, to the investigation. This generally proved helpful in terms of handling, inspecting, documenting and organizing the large quantity of wreckage that was being recovered. As the field phase of the investigation neared completion, these agencies proved valuable in the reconstruction and analysis of several portions of the aircraft.

The air safety industry is constrained by finite resources, and it is therefore incumbent upon all involved to continuously strive to make the most efficient utilization of these resources in any accident investigation. In addition, this drive for efficiency must be balanced with the requirement to maintain the technical integrity of the investigation. The NTSB and FBI should apply the experience gained in this investigation to develop the joint procedures and protocols necessary to ensure that these goals are attainable, and difficulties are minimized, in any future parallel investigations.

## Investigative Group Consensus-Building

The methods used by at least two investigative groups (Sequencing Group and Witness Group), whereby the group gathered factual information and conducted a group study, helps to ensure that NTSB findings will be well accepted. This consensus-building has the further benefit of laying the groundwork for NTSB safety recommendations which will likely be more readily accepted and implemented by industry.

Discussion

An early concern was that the rupture of the center wing tank (CWT), due to the relatively low overpressure of a fuel-air explosion, should not have resulted in destruction of the aircraft. In order to investigate this aspect, the Safety Board formed a special group known as the Sequencing Group. This group was charged with developing an understanding of how the initial failure of the CWT led to subsequent structural failures in the aircraft.

Although the Safety Board does not normally enjoin the parties in developing analysis, in this case the group collectively analyzed the factual evidence, and the parties did reach a consensus conclusion on the failure sequence. Having such agreement allowed the investigation to move beyond the question of how the airplane broke up.

In a similar fashion, although it occurred much later in the investigation, the Witness Group conducted a group study of the reports of the eyewitnesses to the accident. The summary report, complete with group-generated conclusions, was developed from a thorough review of thousands of pages of FBI-generated witness interviews. The documents themselves contained little to assist investigators in determining the cause of the CWT explosion, but the process allowed all parties to fully and collectively participate in the analysis of these documents. In so doing, many potentially difficult issues were resolved long before the issuance of a final report.

The end products of any accident investigation are safety recommendations intended to prevent similar accidents. The way in which the air transport industry chooses to invest in safety improvements is, in large part, driven by industry's confidence that a particular investment will reliably accomplish the desired improvement. This, in turn, is driven by the substantiating technical case for the change. While political forces can bring about changes in policy, and then industry change, a superior approach is to build a technical argument that is unassailable. An unassailable technical argument is far more likely to result in industry 'buy-in' of any recommended change, which substantially eases implementation by improving cooperation, innovation and therefore, safety.

The consensus-study method employed by the Sequencing and Witness investigative groups enabled strong concurrence on the respective technical conclusions, and provides an excellent model for future investigations. ALPA believes that this method is an effective and efficient means of developing findings which can lead to well-grounded safety recommendations.

## Sound Spectrum Analysis

The NTSB and interested parties invested a significant amount of resources in supporting the cockpit voice recorder (CVR) sound spectrum activity. However, the sound spectrum group has never met to review or discuss any of the testing that was conducted. The valuable data that was collected during those tests has never been published, nor has there been any group or party opportunity to analyze the CVR from TWA 800 in the light of the work that was done. Furthermore,. the NTSB has not made the analysis of a third-party's study on this subject available to investigators or the public.

Discussion

Immediately after its recovery, the CVR from TWA 800 was sent to the laboratories of the NTSB in Washington, DC for readout. The CVR group then developed a transcript containing pertinent conversation and audible noises as recorded by the cockpit area microphone. It was evident that careful analysis of the signals recorded on the tape might reveal other important clues. The Sound Spectrum group conducted comparative studies on recordings obtained from the United B-747 cargo door structural failure and the Air India, Avianca and Pan Am Lockerbie in-flight explosions. Waveforms and spectrographic displays of the last 130 milliseconds of the TWA 800 recording were produced, and graphic matching of signal envelopes was attempted. Unfortunately, no conclusions were reached regarding the source or nature of the catastrophic event recorded on the TWA CVR.

The Sound Spectrum group agreed that the increase in the signal levels evident on all three radio channels of the CVR could be significant, and that the recording should be reviewed in greater detail. Further, it was decided that generating additional explosive and/or structural failure data, including its resultant effect(s) on VHF radio characteristics, would be valuable to the group and should be pursued.

The group carefully reviewed a study done several years earlier by Mr. Stuart Dyne of the UK's University of Southampton. In cabin explosion tests conducted in a Trident aircraft, Mr. Dyne had shown that a typical cockpit area microphone acts as both as a pressure transducer (microphone) and structural vibration sensor (accelerometer). Data from those controlled experiments confirmed that if the proper baseline data was available, spectroanalysis of both acoustic and non-acoustic signals near the termination of a CVR recording could yield a wealth of information. Ultimately, that study concluded that it should be possible to determine the type and point of origin of a rapid, destructive pressure event within an aircraft. With regard to the type of event, the study indicated that it should be possible to differentiate between an underpressure (decompression) or an overpressure (explosion), as well as determine whether the explosion was a detonation (high explosive) or a deflagration (low order, e.g. fuel-air) event. The group agreed that applying these principles to the particular circumstances of TWA 800 would be tremendously helpful to the investigation.

The availability of a derelict Boeing 747 in Bruntingthorpe, England provided the group with an opportunity to formulate a plan to generate all of the scientific data necessary for the proper spectroanalysis of the CVR from TWA 800. The test plan that was agreed to included:

- A fuselage 'tap' test to confirm vibration transmission modes within the structure of the B-747 aircraft.
- Five separate CVRs, plus microphones, pressure arrays and a cockpit accelerometer to record the explosions of at least twenty small, non-destructive charges placed in various locations in the fuselage. The effect on a typical VHF receiver would be documented by recording the electromagnetic force (EMF) picked up by the receiver.
- The same instrumentation would be used to measure the effect of small fuel-air explosions inside the aircraft, comparing the signature of this type of explosion with those generated by the previous high-energy charges.

The first phase of the trials, consisting of forty-one high explosive events, was completed during the first week of March 1997. The test instrumentation and recording devices were similar to what had been previously agreed upon, but only a portable VHF radio was used, with no definitive results. A 'stand-alone' three-axis acceleration recorder, still photographs and video augmented the recording devices.

During the second phase of testing, fuel-air mixtures were ignited at various locations within the fuselage, with the resultant pressure rises and vibratory structural responses recorded as they were in the previous tests. The final event in this series was the ignition of a propane mixture inside the center tank of the aircraft, which resulted in catastrophic destruction of the fuselage. Although the wreckage from the final CWT explosion of the derelict aircraft were well documented, the results were inconclusive when compared to damage characteristics of the TWA 800 CWT wreckage.

While security issues concerning the size, type and placement of some high energy explosives within an aircraft fuselage might limit the dissemination of particularly sensitive information, the total value of the Bruntingthorpe testing to the accident investigator must not be overlooked. An enormous amount of time, money and human resources went into planning and conducting this series of tests; the results should have been made available to the Sound Spectrum group in a timely manner, for inclusion into the overall investigation of TWA 800. Additionally, whatever valuable scientific data that could have been developed by careful analysis of the results of these tests should have been published and made available to the worldwide aircraft accident investigation community. Finally, the Sound Spectrum group has never been briefed regarding the analysis of the data completed by the University of Southampton, nor has the group met to finalize any type of report of its activities in relation to the investigation of TWA 800.

## NTSB Dissemination of Factual Information

A significant amount of factual information, including several group chairman's factual reports, CDs and third party reports have only been released to the interested parties in the past few weeks (as of 4/30/00). Also, as noted in the preceding section, certain factual information obtained during the course of the TWA 800 investigation has still not been released to the interested parties. These delays seriously hinder or preclude the parties' ability to evaluate and analyze the data in time to develop a thorough understanding of the accident and timely development of viable safety recommendations.

Discussion
The 1999 RAND Corporation report on the NTSB states:

> "The investigation of accidents and incidents is largely a job of information management. If the NTSB can be legitimately viewed as an information agency, the quality of the official record of domestic aviation accidents...should be viewed as centrally important to the NTSB's overall mission. The accident record not only supports ongoing internal investigations but also is heavily used by external organizations...for planning and decisionmaking related to aviation safety."

The RAND report further notes that "...there is neither oversight nor an emphasis on accuracy in the collection and maintenance of NTSB records" and that poor information control "...complicates the job of conducting investigations..."

Group Chairman's factual reports are typically the first permanent documents to be produced during a major NTSB accident investigation, and the aggregate of these reports comprise the basis for all findings, conclusions and recommendations regarding a particular accident. Access to the information contained in these documents is vital to the investigative team's understanding of the accident facts, circumstances and conditions, as well as the team's satisfaction with the course and thoroughness of the investigation. While certain delays are inevitable and understandable, extremely late release of large amounts of factual information significantly hinders a party's effectiveness in the investigation.

A few examples of data that was released very late in this investigation are cited below:

- On 2/7/00, just weeks prior to the initial date party submissions were due, ALPA received four new reports: Witness group study report (draft), two Systems group addenda, and a contractor report on the ignition of Jet-A by chemical deposits on fuel tank hardware.
- The quarter scale explosion performed by Cal Tech: Contract let 7/22/98; tests completed 5/14/99; final report 9/30/99; report summary page dated 1/25/00; ALPA copy received 2/24/00.
- The CDs containing the Structures group field notes were released to the interested parties during the second week of February 2000. Despite repeated attempts, as of 4/30/00 ALPA still does not have a CD which contains an accessible 'Right Fuselage' file.

While ALPA recognizes that NTSB workload and resource constraints are key factors in this situation, we are concerned that these conditions exist, and the negative impact that they have had on the conduct of this investigation.

It is disappointing and wasteful whenever results of investigative work, whether conducted as a group activity or by a third party, are not made available to organizations inside or, at an appropriate time, those outside the investigation. The RAND report offered the following observations on the NTSB's responsibility to disseminate this "...wealth of knowledge acquired at great cost during the course of its investigations.":

"The NTSB has important information to share. The NTSB has a responsibility to ensure that the knowledge and insights its technical staff has gained are shared as broadly as possible with the aviation community."

ALPA concurs with these RAND observations. It is vitally important to the conduct, thoroughness and technical integrity of the investigation, and by extension, the continued improvements in air safety, that factual information be rapidly and widely disseminated.

## Interested Party Participation

As the 1999 RAND study states, "The [interested] party process itself is based on a recognition that the NTSB cannot operate successfully on its own." In the investigation of TWA 800, the Safety Board contracted for several third-party activities which excluded participation or input by the interested parties. Exclusion of the parties from certain aspects of the investigation will, without exception, reduce the viability, thoroughness and technical integrity of the overall effort.

Discussion

While ALPA recognizes and even advocates the necessity of contracting third party organizations to do accident-related testing and research, we are frustrated by the Board's recent practice of doing so to the exclusion of the interested parties. The NTSB typically excludes the interested parties from the development of the test or research plan, and the parties typically are kept only minimally (if at all) apprised of the progress of the activity. While ALPA recognizes the Board's need to remain independent, the NTSB must carefully balance this with the absolute necessity to ensure that any third-party agency's tasking accounts for the specific and peculiar characteristics of the investigation.

One underlying premise of the interested party system is that an accident is a complex event which requires a multi-disciplinary approach to investigate adequately. The parties are involved to provide expertise, feedback and a system of 'checks and balances'. It is fundamental that the results of any activity conducted in support of an investigation will likely influence the course of the investigation, its conclusions and recommendations, and eventually the safety of the air transport industry. It follows that if such an investigative activity is conducted without certain minimum levels of interaction and feedback with most or all of the investigative team, it is highly probable that the quality and utility of that activity will suffer.

## Wreckage Component Database

Exact knowledge of the recovery location of each component of wreckage is critical to the development of an accurate understanding of an inflight breakup sequence. The 'Tags' database, which documents this information for TWA 800, has been found to contain numerous errors and irregularities, some of which the investigation has been unable to reconcile, despite a significant investment of time and manpower.

Discussion

Determination and documentation of the individual wreckage component locations was complicated by dispersal of the wreckage over an area of approximately 10 square miles, in water approximately 120 feet deep. US Navy SUPSALV diving operations ceased on November 2, 1996, and trawling efforts on May 18, 1997. Approximately 95% of the aircraft was recovered. Detailed accounts of the recovery and databasing activities have been published and are available in the public docket.

A robust system for wreckage identification, cataloging and databasing is required to minimize documentation errors, and such a system requires time and effort to develop. The system utilized for this accident evolved as it was implemented, and consequently was not particularly error resistant in its early stages. As the investigation progressed, it became apparent that certain recovery location information was either missing or erroneous. The database group made a concerted effort to identify the possible means of error introduction, and then conducted an audit of recovered components to assure that the best location values had been obtained and documented correctly. Efforts to recover lost data or resolve unknown component recovery locations were complicated by the disparate methods used by the various agencies involved in the recovery and documentation. Some other error introduction mechanisms that were identified included:

- Indefinite or ambiguous wreckage component identifications/descriptions
- Tagging components shipboard instead of in situ (underwater)
- Typographic errors on initial writeups or during transcription of information
- Errors associated with wreckage from multiple debris fields being placed on the same boats

As noted in the referenced documentation, the discrepancy reconciliation effort was not entirely successful, and not all recovery locations are known, or known with a high degree of confidence. The 'Trajectory Analysis' (Exhibit 22A), which is an NTSB study used to calculate where along the aircraft flight path certain components separated from the aircraft, depends on accurate wreckage location for its accuracy. Inaccurate recovery locations, therefore, result in a lower confidence in final results of the trajectory study. Appendix C of this ALPA submission provides some additional insights on development and utilization of databases.

## Component Trajectory Study

The NTSB trajectory study was conducted to calculate the airborne trajectories of certain key fragments of the aircraft in an effort to determine the breakup sequence of the aircraft. ALPA is concerned that the independent nature of the study, as well as the use of uncertain wreckage recovery location information, weakens any conclusions reached in this trajectory study.

Discussion

The analysis conducted in the trajectory study requires numerous estimates and assumptions, both in initial object travel (velocity and direction) and resultant flight path (coefficient of drag of an individual piece). A minute change in any of these variables can yield a substantial alteration of the calculated trajectory. Since some of the input values can never be known accurately, uncertainty is introduced into the results of the study. Furthermore, although ALPA does not doubt the technical capability of the NTSB, we are concerned that this analysis was essentially accomplished by only one individual at the Board, with little or no party input or participation. It is a well known and accepted tenet of engineering analysis that the output (results) can only be as accurate as the input data. As cited in the previous section, the trajectory study utilized several uncertain or erroneous component recovery locations, increasing the uncertainty of the study's results. Had this study been conducted as a group activity, opportunities would have existed for necessary cross-checking and party 'consensus-building', and it is likely that a more thorough, accurate and universally-accepted product would have been generated.

# 3. Accident and Safety Issues

## Background

The inflight breakup of an airplane with the extensive and successful operating history of the Boeing 747 is unprecedented. More perplexing still, TWA 800 involved an aircraft with thousands of hours and many years of safe operation already logged, operated by a carrier with a recognized, extensive history of technical excellence.

Early in the investigation, the Safety Board established that the CWT was the initiator of the airplane's structural failure, and began an extensive program of tests and research. The results of this work have been varied, but certain fuel system component degradations and, to a lesser extent, weaknesses in standards and specifications have been identified. This body of evidence, while not singling out an ignition source for the explosion of TWA 800's CWT, has and will continue to be enormously valuable to the industry as a resource for improving the management of energy movement within and around a fuel tank.

## ALPA CWT Analysis

ALPA has conducted some degree of analysis of the events within the CWT, and has attached that work as Appendix B of this submission. We believe that a study of the evidence of gas flow left by sooting, when combined with the understanding of structural failure developed by the Sequencing Group, might have been useful toward the validation of test program results and subsequent improvements in those programs.

### Discussion

ALPA's analysis has concluded that the predominant motion of the CWT during the initial pressure rise was probably a vertical expansion of the tank, increasing the separation between the upper and lower skins. This resulted in failures of both the upper and lower skins during the beam failure process, causing pressure venting both above and below the tank. We believe that the spanwise beam 1 probably failed aft, and that the maintenance panel on spanwise beam 2 failed before spanwise beam 3. We believe that liquid fuel in the tank became involved in the combustion, but predominantly between spanwise beams 2 and 1.

The most notable consequence of this possible scenario is not with flight 800, but rather with the NTSB's subsequent quarter scale testing program. In those efforts, the upper and lower skin failures were not modeled. Additionally, spanwise beam 1 was assumed to have remained in place during the entire event. The access panel in spanwise beam 2 consistently failed after spanwise beam 3 during the quarter scale testing. Some of these effects, such as upper/lower skin failures, would have been quite difficult to model; others, such as the access panel failure, could have been more carefully controlled.

There are two important constraints to apply to our views. First, the Sequencing Group necessarily based a part of their analysis on the recovery locations attached to each piece, and as previously noted, the results of that study may not be reliable. A second constraint is that the detailed pursuit of fire evidence on anything other than a macro level has not been thoroughly developed as a forensic science. Fire evidence is enormously difficult to separate, and it cannot often be used for analysis beyond generalizations. In this case, ALPA felt that detailed analysis could be achieved on a limited basis, and that such an analysis could be useful. However, it remains analysis, not fact, and differing analyses may be possible.

## Previous NTSB Recommendations

To reduce the perceived risk of CWT explosions in B-747s, the NTSB issued a series of recommendations to change operational procedures. ALPA is concerned that the Safety Board continues to recommend the implementation strategies that are not consistent with the knowledgeable operation of transport aircraft.

### Discussion

The recommendations, issued late in 1996, were primarily aimed at control of the ullage temperature in the CWT. Also included were recommendations to incorporate CWT temperature information and limitations within the approved flight handbooks or operating manuals and to require installation of a temperature indicating system within the CWT. In addition, the Board recommended that a minimum quantity of fuel be carried in the CWT.

The Safety Board's second approach was to recommend that the FAA require "the development of and implementation of design or operational changes that will preclude the operation of transport-category airplanes with explosive fuel-air mixtures in the fuel tanks." This represented a fundamental change in design philosophy, moving away from segregation of fuel and ignition and towards fuel tank inerting.

The third approach was through the safety recommendations issued in 1998 pertaining to FQIS component degradations and wiring installations. These recommendations presented a comprehensive program of inspections and modifications to include "transient suppression," hopefully preventing excessive electrical energy from entering the tank.

While ALPA understands the potential benefit of reducing the ullage temperature from the standpoint of flammability and ignition energy requirements, we remain troubled by the Safety Board's insistence on implementation strategies that are not consistent with knowledgeable operation of transport aircraft. For example, in A-96-175, the Safety Board has argued for "proper...management of the CWT fuel temperature." Aside from the lack of a definition for "proper" management of the CWT fuel temperature, ALPA notes that the flight crew has nocontrol over ambient temperature, no direct control over fuel temperature and little control over the time of fuel loading. Selective operation of the aircraft air conditioning system (thus limiting system exhaust heat output) is possible, but is sometimes absolutely necessary for the health and safety of the passengers and crew.

Similarly, the Safety Board has argued for the installation of a CWT fuel temperature indicator, but this also presumes that the flight crew can do something with this information. As of now, there are no operational procedures published or guidance given to flight crews regarding CWT fuel temperature.

## B-747 Safety Assessment Requirements

The safety assessment requirements in existence at the time of type certification, and the techniques available at that time to comply with the requirements, were not adequate to prevent the catastrophic event which took place within the center wing tank of N93119.

Discussion

The FAA has stated in correspondence with the NTSB that the Boeing 747 fuel system was certificated in accordance with 14 CFR 25.901(c) and 25.1309(b) in effect at the time of certification. At that time, thirty years ago, the service experience with jet transport aircraft was a fraction of what it is today and was still evolving rapidly. 14 CFR Part 25 was not even five years old, and the requirements for fuel tank certification had been significantly augmented only two years before the 747 certification. Advisory material for both of the new requirements did not yet exist. The thorough, realistic evaluation of certification standards is now appropriate.

It is particularly important to note that at the time, the requirement to employ structured methods of analysis in making a safety assessment had not been codified. This did not occur until the significant changes made to FAR 25 by Amendment 25-23 on May 8, 1970. Additionally, only those risks apparent at the time, including tank temperature and lightning protection, were protected by newly-issued Amendments to FAR 25.

It may also be significant to note that the fuel system on the Philippine Airlines B-737 which exploded at Manila was certificated to the rules in effect on December 15, 1967. The certification basis for this airplane included many additional Amendments, including 25-1 through 25-3, 25-7, 25-8, and 25-15. Since the 737-300 included significantly advanced systems, numerous additional amendments were stipulated. Among these is Amendment 25-51, under which FAR 25.1309 is stipulated as being "Applicable only to new or major modified structure or to new systems and components unique to the 737-300 series airplane with respect to the existing Model 737-200 Series airplane." However, the fuel tank system installation was certificated to the same requirements that it had been in 1967.

These issues are important to establish the requirements in existence at the time that the B-747 design was certificated, and to understand the context in which both the designers and certification authorities would have applied engineering judgement to agree on the methods of compliance.

In the latter part of 1999, the FAA issued a Notice of Proposed Rulemaking which aggressively addressed the weaknesses in the safety assessment requirements for fuel tank installations. The proposed revision to FAR 25.981 would remove the ambiguity regarding the application of a structured safety assessment to newly-designed fuel systems, as well as require a retroactive structured safety assessment of existing fuel systems. ALPA strongly supports the FAA's efforts to revise this Rule. There is no doubt that the safety assessment performed at the time of the B-747-100's certification was consistent with the state-of-the-art, and complied with the requirements the 14 CFR Part 25 as it was then written. Had the service experience and technical knowledge at that time been more extensive, a reduction in uncertainty might have been called for, and a more defined safety assessment criteria applied.

## Aircraft Systems Certificated Prior to FAR Amendment 25-23

In the last ten years, several catastrophic events have occurred which involved aircraft systems certificated prior to Amendment 25-23.

Discussion

The Board pointed out in the USAir 427 report that the rudder system on the B-737 aircraft had been certificated in 1967, at the time of original certification. This was prior to a requirement for a structured safety assessment, which was introduced to 14 CFR 25.671 in 1970 with Amendment 25-23. Again, as in the Philippine case, this particular system was not re-certificated when the derivative version of the airplane was approved in 1984.

ALPA has recommended to the Board previously that derivative certifications be conducted using the certification requirements of 14 CFR Part 25 in effect at the time of application for the derivative certification. We continue to advocate this position. However, in the case of TWA 800, the issue was not a derivative certification. Therefore, there has been no opportunity or method by which the FAA could re-evaluate the failure analysis of the fuel tank components accomplished at certification. Even the newest Boeing aircraft, the 717 (a derivative of the DC-9 and later MD-80 aircraft), is provided exceptions in the application of 14 CFR 25.1309:

> *"Exception applies to DC-9 and MD-80 systems designed to the single failure concept that are unchanged or have minor alterations or improvements will comply through Amendment 25-22..."*

Note that even on this very new model, some systems still appear to be accepted based on a safety assessment method which predates the structured safety assessments introduced with Amendment 25-23.

The justification for these exceptions is our success in identifying potential failures through analysis of the service history of the aircraft. To some degree, it is reasonable to assume that if a system has performed safely for many, many years, its safety assessment is more or less continually revalidated. In many cases, this is true. Yet the center fuel tank of the 747 aircraft had performed very safely up until July 16, 1996. To that date, the service experience would have required no evaluation of the system safety. That could also be argued in the case of the DC-10 hydraulic system. The United 232 accident may not have occurred had the current provisions of AC 25.1309-1A regarding common cause failures been applied at the time of certification.

While the absence of minor or major failures may be adequate reason not to reassess a system, ALPA believes that it is simply not acceptable to wait for catastrophic failures in order to build the service experience necessary to initiate changes to system design. The whole purpose of the structured safety assessment methods introduced with Amendment 25-23 was to anticipate catastrophic failures based, in part, on service experience with lower order failures.

It is time that serious consideration be given to evaluating whether the certification of a system to safety assessment standards in existence prior to Amendment 25-23 continues to provide the level of safety expected by commercial air transportation. We believe that this effort would be consistent with the Gore Commission's stated goal, in paragraph 1.9 of the White House Commission of Aviation Safety and Security, of

> "...encouraging the development of modern technical means to ensure and predict the continued airworthiness of aging non-structural components and systems."

## FAR 25.1309 Applicability to Fuel System Design

The current safety assessment requirements set forth in FAR 25.1309 do not presently apply explicitly to fuel tank components and installations.

Discussion

Part 25.1309 specifically requires that the failure of any aircraft system or component that would prevent the continued safe flight and landing of the aircraft must be "extremely improbable." The present version of Advisory Circular 25.1309-1a reminds us that 25.1309 is a regulation of "general applicability," and as such only applies if other sections of the Part do not. Part 25.901 (Installation of powerplants, and by default, fuel systems) states:

> For each powerplant and auxiliary power unit installation, it must be established that no single failure or malfunction or probable combination of failures will jeopardize the safe operation of the airplane except that the failure of structural elements need not be considered if the probability of such failure is extremely remote.

Therefore, not only are the specific definitions of improbable and extremely improbable are not explicitly set forth by FAR 25.901, but the safety assessment standards set forth by FAR 25.1309 have not been applied to powerplant installations, including fuel tanks.

The Joint Aviation Authorities take a different view. To them, JAR 25.1309 is not a rule of general applicability, but the rule should be applied "in addition" to the requirements of other paragraphs of JAR-25. Through the Harmonization process, the JAA, FAA and industry have agreed on a revised applicability of 25.1309 which essentially retains the JAA view.

Although 25.901(c) is currently excluded from the agreement, there is a pending proposal to apply the requirement to all fuel tank certifications. ALPA believes that, in the midst of evaluating fuel tank safety on the existing fleet, it would be appropriate to issue the harmonized NPRM on 14 CFR 25.1309 as soon as possible.

## Viability of FAR 25.1309

The safety assessment requirements set forth in FAR 25.1309 rely extensively on component failure data. This data is not presently available as a complete body of information; rather, it is assembled piecemeal from various data sources. These events are under-reported as a rule, and is subject to proprietary and liability constraints, both of which negatively impact the data and its utility as a valid safety assessment tool.

Discussion
In their comments to the FAA in response to the proposed 14 CFR 25.981, the Safety Board pointed out that serious deficiencies exist in the collection of service experience data for the purposes of conducting a safety assessment such as an FMEA. The Board stated that:

> "The Safety Board's concerns about the FMEAs are amplified by the fact that no single source exists for reliable and comprehensive data on component failures or malfunctions. Because the calculations in an FMEA are based on failure rates, incomplete or inappropriate failure data can skew the results of an examination. The Board is aware that service history data maintained by manufacturers do not capture data from all operators...Other sources of potentially relevant data are the service histories maintained by the military of its variants of commercial airliners and the Board's accident and incident investigation database; however, neither of these sources provides complete data either"

The Gore Commission report cited this issue as well. In Chapter 1 of the report, paragraph 1.8 states that

> "The FAA should work with the aviation community to develop and protect the integrity of standard safety databases that can be shared in accident prevention programs."

All of these references address peripherally the question of how engineers can obtain the necessary service experience data to perform the safety assessments required under existing and proposed FARs. The type of structured safety assessment currently integrated into 14 CFR Part 25 is the regulatory backbone of systems safety. However, as the Board has pointed out, it cannot function if the data required to operate it are unavailable for proprietary or legal reasons, or simply due to the absence of central organization and tabulation.

ALPA believes that the Safety Board needs to recommend to both FAA and industry organizations such as AIA that this issue be given immediate and focused attention. The assessment methods described in AC 25.1309-1A depend heavily on component failure rate data. The absence of a central repository for this type of data seriously weakens the effectiveness of the requirement.

**FAR Consideration of Latent Failures**

The existing consideration of latent failures as defined in Advisory Circular 25.1309-1A may not adequately protect some systems from catastrophic failures.

Discussion
AC 25.1309-1A defines a latent failure as:

> "A latent failure is one which is inherently undetected when it occurs. A significant latent failure is one which would, in combination with one or more other specific failures or events, result in a hazardous failure condition."

The advisory material also notes that:

(1) The failure of any single element or component of a system during any one flight should be assumed, regardless of its probability. Such single failures should not prevent continued safe flight and landing, or significantly reduce the capability of the airplane or the ability of the crew to cope with the resulting failure conditions.

(2) Subsequent failures during the same flight, whether detected or latent, and combinations thereof, should also be assumed, unless their joint probability with the first failure is shown to be extremely improbable.

Notably, in their proposed revision to 14 CFR 25.981, the FAA has included latent failures as a required consideration within the body of the rule. And to eliminate any ambiguity as to the restriction on latent failures, 25.981(a)(3) explicitly requires that "any anticipated latent failure condition not leave the airplane one failure away from a catastrophic fuel tank ignition."

ALPA believes latent failures are a central issue to the resolution of fuel tank safety. It is highly likely that one or more latent failures were involved in the sequence of failures leading to ignition of the CWT. We share FAA's concerns regarding a latent condition placing the airplane one failure from a catastrophic event, and specifically, we believe that substantive methods must be applied to identifying latent failures within fuel tanks immediately.

Further, ALPA believes that the concept of latent failures needs to be defined in a manner consistent with the FAA's intent. That is, no latent failure should leave the airplane one additional failure away from a catastrophic failure for a period of more than one flight cycle. Therefore, ALPA concurs with the industry's recommendation for this issue to ~~be~~ tasked to ARAC; however, we believe that the Safety Board should urge FAA to task this on a fast-track basis.

## Aging Systems/Design Criteria

Degradations and failures of aging aircraft systems and their components can lead to combustion of any type in any location on the airplane. Aircraft design criteria and standards, maintenance programs and continuing airworthiness programs which are not continually upgraded may not to remain consistent with contemporary knowledge of failure mechanisms.

Discussion

ALPA believes that the Safety Board has an opportunity to take a broad view of the design and certification standards that are in place for fuel system components specifically and for electrical components, including wiring, in general. The question of what reliability standards are actually in place for specific designs has not been pursued. The reliability and risk assessments made at the time of type certification may have complied with requirements existing at that time, but may not comply with those in existence today. The question of how the industry maintains compliance with the standards through the aging process, continuing airworthiness programs and STCs, to name a few, has not been pursued. For example, a number of inflight electrical fires result from cabin electrical systems which are not part of the airplane's original type certificate, but are accomplished through a supplemental type certificate in order to conform to the customer's specifications. The STC process may take place under the guidance of a local FAA office, or an ACO that was not involved in the original certification. It may not be evaluated to the same degree that the original design was.

The FAA has initiated an Aging Transport Non-Structural Systems Plan, and established the Aging Transport Systems Advisory Committee. It is interesting that in the FAA's plan, no reference is made to aging certifications. The basic premise in use today is that the aging problem results from the physical aging of hardware. Indeed, the following definition of an aging system was debated by the ATSRAC last year:

> An Aging Electrical System is: An electrical system or component whose age induced degradation* (including accidental and environmental effects) may affect continued functionality pursuant to safe flight and landing or the ability of the crew to cope with unusual operating conditions.
>
> * Such degradation is that which may not have been directly, adequately and comprehensively addressed and managed under existing maintenance programs.

Again, there does not appear to have been any discussion of the effect of aging on safety assessments themselves. Yet while the hardware may be brand new, the assumptions made at the time of certification are built in. Many of those assumptions were and continue to be valid. But if the certification is based to a large extent on service experience prior to certification, at what point should the service experience obtained subsequent to the certification be applied? If the certification is based to a large extent on the engineering judgement available at the time of certification, at what point should the certification be reviewed based on contemporary engineering judgement?

ALPA believes that the FAA must recognize aging certifications as a part of the aging systems problem. Further, we believe that the Safety Board should plan a special investigation of the certification and maintenance of any equipment, installation or component which can cause ignition of any fuel on board the aircraft while in flight.

## Events Beyond 'Extremely Improbable'

There is presently no mechanism within the certification requirements which contemplates a degree of safety beyond that defined by failures which are already extremely improbable.

Discussion

As previously noted, the current version of FAR 25.1309 states that the occurrence of any failure condition which would prevent the continued safe flight and landing of the airplane is extremely improbable.

The proposed revision to this rule retains this concept. In addition, the FAA's proposed revision to FAR 25.981 states that:

> (a) No ignition source may be present at each point in the fuel tank or fuel tank system where catastrophic failure could occur due to ignition of fuel or vapors. This must be shown by:
>
> (3) Demonstrating that an ignition source could not result from each single failure, from each single failure in combination with each latent failure condition not shown to be extremely remote, and *from all combinations of failures not shown to be extremely improbable.*(italics added) The effects of manufacturing variability, aging, wear, corrosion, and likely damage must be considered.

The accepted definition of extremely improbable, as stated in Advisory Circular 25.1309-1A, is

> "Extremely Improbable: failure conditions are those so unlikely that they are not anticipated to occur during the entire operational life of all airplanes of one type."

The Safety Board issued Safety Recommendation A-96-174, in which they urged the FAA to examine methods of precluding operations with a flammable fuel-air mixture. ALPA testified during the public hearing that we supported efforts to reduce that vulnerability to zero, if possible, and we maintain that position. But at the same time, we believe that it is essential that the standard for ignition source prevention remain at "extremely improbable". Fuel tank ullage must always be considered flammable. The fact is that no inerting system has been developed or utilized, in either civilian or military applications, that has sufficient reliability to tolerate a relaxation in present ignition source design criteria.

ALPA believes that the FAA's proposed revision to 14 CFR 25.981 has considerable merit, and should be pursued with little modification. We believe that the types of analyses required by this proposal, if carefully and competently conducted, will yield a clear requirement for several options, including transient suppression, arc fault circuit protection and flammability reduction.

We believe that the Safety Board should recommend that a program for reducing flammability in fuel tanks, such as ground based inerting, should be pursued vigorously, and that future technologies for flammability reduction be assigned a high priority. We also believe that a structured safety assessment such as that proposed by the FAA must be conducted on existing fuel tank systems in order to bring them to the same standards that other equipment already meets.

## Electrical Circuit Protection Devices

Existing circuit protection devices are not adequate to prevent electrical failures from becoming ignition sources at any location in an airplane.

Discussion

During the safety inspections conducted by the FAA since the TWA 800 accident, one area of notable concern has to do with fuel pump wiring routed through conduit within the tank. The conduit is used to prevent physical damage to the wires which could result in pump failure or electrical malfunctions. However, the FAA found that both the 747 and the 737 exhibited wiring insulation degradations which led to actual arcing between the wires and the conduit. While some damage discovered was minor, nine cases in the 737 resulted in arcing to the fuel pump conduit, and one case wear resulted in actual burn-through of the conduit into the fuel cell.

In 1970, the FAA issued the first advisory material addressing 14 CFR 25.981. AC 25.981-1, states in paragraph 4(c)2:

> Where electric wires are routed through conduits installed in a fuel tank, high surface temperature can be created by short circuits. A critical electrical wiring condition might be one in which the insulation is cracked, broken or of low dielectric strength, allowing intermittent or constant arcing to occur without consuming enough power to cause the circuit protection device to open.

Thus, the argument for an arc-fault circuit interrupter (AFCI) was made thirty years ago.

The technology, however, is coming of age. A near-term goal for this technology is to reduce the size of the interrupter in order to fit into an existing aircraft circuit breaker panel. This would make it easily retrofittable. The device could then address many of ALPA's concerns regarding on-board ignition sources, whether within a fuel tank or not.

We believe that the Safety Board should recommend that this technology be required for any electrical circuit which utilizes a metal conduit within a fuel tank. Further, we believe that the Board should recommend that, in the event that an arc-fault circuit interrupter trips open at any time, it cannot be reset prior to a maintenance inspection of the relevant conduit and wiring.

## Prevention of Electrical Transients in Fuel Tanks

Existing failure analysis for fuel tanks has not adequately addressed the problem of electrical transients.

Discussion

In 1998, the NTSB issued Safety Recommendation A-98-39, which stated:

> Require, an all applicable transport airplane fuel tanks, surge protection systems to prevent electrical power surges from entering fuel tanks though fuel quantity indication system wires.

The FAA responded with AD 98-20-40 and 99-03-04, requiring the installation of shielding and the separation of FQIS wiring to preclude electrical transients. The Safety Board has argued that this action is not adequate, stating in a letter to the FAA that:

> The Board does not believe that wire separation and shielding alone will protect against the entry of power from sources attached to FQIS wires. For example, in a Boeing 747, 115 VAC power and FQIS circuits are contained in common electrical connectors at the fuel gauges and in other components, such as the volumetric shut-off unit. If installed, surge suppression systems would protect against damage that could affect numerous wires at once and against unforeseen circumstances.

ALPA concurs completely with the Safety Board's position. We are aware that several companies are currently developing transient suppression systems that will be effective when used with compatible fuel quantity measurement systems. Further, ALPA is confident that the results of the structured safety assessment proposed by the FAA in the revision to 14 CFR 25.981 will yield considerable support for this emerging technology.

## 4. Safety Recommendations

As a result of our participation in this accident investigation, ALPA makes the following safety recommendations:

To the NTSB

1. The NTSB and FBI should utilize the experience gained in this investigation to develop joint procedures and protocols necessary to ensure improved interagency cooperation and coordination in any future parallel investigations.

2. Encourage the continued or expanded implementation of the consensus-building, participation-oriented methodology applied in the Sequencing and Witness groups.

3. Ensure that all factual information obtained or generated in support of an accident investigation, whether by the NTSB or collectively as a group function, be published and made available to the interested parties in a timely fashion.

4. Ensure that any investigative, research & testing activity conducted in support of an investigation, even if they are conducted by third party organizations such as universities or commercial laboratories, be open to participation and input by the interested parties.

5. Ensure that for accident investigations involving underwater recovery, a robust system of component documentation, location and recovery is developed and implemented, and that all affected personnel are educated in the process before wreckage recovery.

6. Ensure that NTSB Safety Recommendations (especially those directed towards operators) be consistent with acceptable known practical industry practices of operation of transport category aircraft.

7. Undertake a special investigation of electrically induced ignitions within transport category airplanes. The investigation should specifically address aircraft wiring standards and electrical component installation, maintenance and degradations. It should also address methods to prevent these types of failures from leading to catastrophic failures, not only in future designs but specifically with respect to existing aircraft.

8. Urge the FAA, AIA, ATA (and other organizations as appropriate) to develop a specific joint program to maximize the collection and utilization of component failure data throughout the industry, making use of both civil and military data. Standardized data format and organization must be goal of this effort.

9. Urge the FAA and industry to pursue methods of reducing, on a mission specific (flight-by-flight) basis, the fuel tank flammability of transport category aircraft used in scheduled passenger service.

10. Reiterate NTSB Safety Recommendation A-98-39, in light of the consideration already given to wiring separation and the Board's concern that this procedure is not adequate.

11. Implement, and complete in a timely manner, the proposed Safety Study concerning FAA Certification Rules and Procedures.

To the FAA

12. Establish an industry working group to evaluate transport aircraft certification safety assessments that were accomplished prior to required compliance with FAR Part 25 Amendment 25-23. Special emphasis should be placed on identifying aircraft systems malfunctions which could lead to catastrophic failure and loss of the aircraft. Ideally, this working group would utilize the findings of the proposed NTSB Safety Study (Recommendation #11, above) as the baseline for its scope and focus.

13. Issue a notice of proposed rulemaking (NPRM) which proposes the harmonized version of 14 CFR 25.1309.

14. Task an appropriate harmonization working group within ARAC to address the issue of latent failures. Special emphasis should be placed on identifying how latent failures are accounted for in safety assessments. This working group should be formed and operated on a 'fast track' basis, and have a goal of producing recommendations to FAA within one year.

15. Implement, as soon as practical, methods for reducing fuel tank flammability of transport category aircraft used in scheduled passenger service on a fleet average basis.

16. Require the retrofitting of arc fault circuit interruption (ACFI) devices on all electrical circuits within fuel tanks which utilize metal conduit. Additionally, the FAA should require that such AFCI devices cannot be reset until a maintenance inspection of the affected area is completed.

17. Implement, as soon as practical, the fuel tank safety assessment goals contained within the proposed revision to 14 CFR 25.981.

# Appendix A
# Brief History of the Certification Requirements

FAR Part 25 came into existence in its original form on February 1, 1965. A first, it was very similar to Civil Air Regulation 4B, which had preceded it. However, CAR 4b itself had only existed for 15 years, having originated in 1950. During those years, commercial aviation technology had developed rapidly. It continued to do so in the late 1960s, and by 1969, FAR Part 25 was evolving quickly towards the form we know today.

The concept of single failures cited by the Safety Board in their recommendations is well known. However, the CAR 4b version effective on December 31 1953, only contained one reference to single failure effects, and this had to do with brake systems. As CAR 4b was amended, the concept of single failure effects became more prevalent in the requirements. By 1960 it had been applied not only to brake systems, but also to interconnected flaps, horizontal stabilizer actuator systems, turboprop auto-feather/NTS systems, flutter damper systems and engine reverse thrust systems.

Amendment 4b-12 to CAR 4b, effective May 12, 1962, introduced the term "fail-safe" into the certification requirements. It was first applied to cabin pressure vessel rules set forth in 4b.216. Two years later, Amendment 4b-16 applied fail-safe criteria to CAR 4b.308, [Flutter, deformation, and vibration]. In both cases, the concept was applied to structural requirements.

During this period, CAR 4b had fairly limited safety assessment requirements for aircraft systems. 4b.606 [Equipment, systems, and installations] paragraph (a) stated that

> "All equipment, systems, and installations the functioning of which is necessary in showing compliance with the regulations in this subchapter shall be designed and installed to insure that they will perform their intended functions reliably under all reasonably foreseeable operating conditions."

The rule went on to state, in paragraph (b), that

> "All equipment, systems, and installations shall be designed to safeguard against hazards to the airplane in the event of their malfunctioning or failure."

The document which provided guidance for compliance with these rules was the Civil Aeronautics Manual. In section 4b.606-1, the following definition of a probable malfunction was cited:

> "A probable malfunction is any single electrical or mechanical malfunction or failure within a utilization system which is considered probable on the basis of past service experience with similar components in aircraft applications. This definition should be extended to multiple malfunctions when (1) The first malfunction would not be detected during normal system operation of the system, including periodic checks established at intervals which are consistent with the degree of hazard involved or (2) the first malfunction would inevitably lead to other malfunctions."

At the dawn of FAR Part 25, on February 1, 1965, that was the extent of the certification requirements set forth in CAR 4b regarding equipment failure assessment. It is interesting that 4b.606 had not been amended during the entire period. There was no clear requirement in the certification rules or guidance material for any structured safety assessment.

The introduction of Part 25 did not immediately change this. The certification rule that went into effect in 1965, not quite five years before the 747 was certificated, contained four rules specifically referencing the term "fail-safe". An additional five rules referred to single failures. Most of these were the same rules which had used these terms at the sunset of CAR 4b.

In the new Part 25, FAR 25.901 set forth the requirements for fuel tank installations. This rule made no explicit statements regarding fail-safe criteria. The operative language in the rule stated that

> "The components of the installation must be constructed, arranged, and installed so as to ensure their continued safe operation between normal inspections or overhauls."

Part 25 also contained 25.1309, the equivalent rule to CAR 4b.606. It was little changed from the CAR language:

> "(a) The equipment, systems, and installations whose functioning is required by this subchapter, must be designed and installed to ensure that they perform their intended functions under any foreseeable operating condition.
>
> (b) The equipment, systems, and installations must be designed to prevent hazards to the airplane if they malfunction or fail."

Amendment 25-23 introduced the concepts of improbability and extreme improbability into the FAR. The advisory material issued in September, 1980, nearly ten years later, defines the terms as follows:

> "Improbable - Improbable events are not expected to occur during the total operational life of a random single airplane of a particular type, but may occur during the total operational life of all airplanes of a particular type. A probability on the order of $1 \times 10^{-5}$ or less.
>
> Extremely Improbable - Extremely improbable events are so unlikely that they need not be considered to ever occur, unless engineering judgement would require their consideration. A probability on the order of $1 \times 10^{-9}$ or less."

Interestingly, the same amendment changed FAR 25.901 to add a paragraph stating that "The powerplant installation must comply with Sec. 25.1309." This explicit requirement did not enter the FAR until a few months after the 747 was type certificated. It is likely that it was necessary because 25.1309 is considered a rule of general applicability. In this context, it is not applied if a more specific requirement exists, such as 25.901. The addition of a specific requirement forced the application of 25.1309. Subsequently, Amendment 25-41 changed this paragraph to the language in current use, removing the explicit requirement to comply with 25.1309 and re-establishing a specific requirement within the rule itself.

# APPENDIX B
# SOOT, FIRE and FRACTURES in the CWT

## 1.0 Constraints

The approach taken to the analysis of the center tank event was to identify a set of constraints around which the analysis could be built. These constraints were developed from two sources: widespread but uniform failure patterns, and evidence which could be clearly identified as primary.

## 1.1 Sequencing Group Conclusions

The Sequencing Group reached an understanding of how the center tank structure came apart in early 1997. ALPA is not aware of any evidence which would raise questions about the sequence of failures described in the Sequencing Group Study. This sequence is reprinted below, as it represents a set of important constraints which must be understood in order to analyze the soot accretions noted above.

7.2 WCS, Keel Beam, Fuselage Sequence Description

7.2.1 SWB#3 rotated forward and impacted the back of the front spar resulting in fracture between the horizontal and vertical legs of the upper front spar chord across the full span of the WCS front spar. (Refer to section 5.0 for more detail leading up to this point in the sequence and section 4.11 on more specifics regarding the front spar separations.)

7.2.2 Deformation of the front spar upper chord vertical leg indicates the front spar rotated forward about the lower WCS skin attachment with a greater amount of rotation centered at LBL 66 and RBL 66 and a smaller amount of rotation at the centerline, consistent with the center of the spar being partially restrained by the mass of the potable water bottles and the attachment to the keel beam.

7.2.3 Overpressure in the WCS (associated with prior fracture and rotation of SWB#3 as well as responsible for forward rotation of the front spar) acting downward on the WCS lower panel caused vertical downward loading of the forward portion of the keel beam.

7.2.4 This downward load on the forward portion of the keel beam would be reacted by shear loads in the front spar web and in the lower pressure bulkhead web.

7.2.5 Forward rotation of the front spar buckled the stiffeners splicing the lower pressure bulkhead to the main WCS front spar.

7.2.6 The front spar upper chord vertical leg separated in tension at RBL 48 and LBL 66. The front spar web separated immediately at these locations, and the web fractures progressed downward until they reached the lower chord at LBL 66 and RBL 66. The front spar upper chord vertical flange also separated in tension at LBL 114, LBL 18,RBL 66, and RBL 114, but the web at these locations contained bending deformation, indicating that separations at these locations are later than the separations at RBL 48 and LBL 66.

7.2.7 The fasteners common to the splice between the webs of the front spar and lower pressure bulkhead are consistently (left and right sides, BL 26 to BL 75) separated in shear with the lower pressure bulkhead web being pulled downward and somewhat inboard.

7.2.8 Downward loading of the forward portion of the keel beam was then carried only by the lower pressure bulkhead and the fuselage structure forward of the front spar. Stresses in the lower pressure bulkhead from the downward loading of the keel beam caused separation of the bulkhead (except for the ring chord) just inboard of the underwing longeron, at locations corresponding to the early front spar web fractures at RBL 66 and LBL 66 (see Section 7.2.3).

7.2.9 Downward loading of the forward portion of the keel beam was then carried only by the ring chord at the bottom of the lower pressure bulkhead along with the fuselage skin immediately forward of the ring chord at LBL 66 and RBL 66. This structure was also subjected to hoop loads from cabin pressurization and possible vented WCS overpressure.

7.2.10 The ring chord and adjacent fuselage skin at S40R (RBL 66) fractured due to the combined loads described in 7.2.9, initiating the early skin cracking that propagated dynamically forward (first along S40R between pieces LF6A and RF95, then S41R, S42R, and S44R until running to the centerline access cutout between STA 800 and STA 820) and then circumferentially (upward to both the left and right from the bottom center at STA 760 to STA 800), then aft from STA 800 along two cracks, one at S40L and S39L and one at S38R and S37R (reference figures 6-1 and 6-2).

7.2.11 Cabin pressurization as well as any vented WCS overpressure generated a downward load on an isolated or nearly isolated piece of structure from the lower lobe (combined pieces LF6A, LF24A, LF95, and LF55A). The load on this combined piece was transmitted as a downward load acting directly on the forward end of the keel beam through the lower pressure bulkhead web and the keel beam lower chord extensions that attach to the fuselage structure. Downward loading on the forward end of the keel beam was sufficient to peel the keel beam away from the underside of the WCS and fail the keel beam aft of the midspar (see section 5.1).

7.2.12 Separation of the forward portion of the keel beam from the lower WCS skin was accompanied by other fractures along the lower pressure bulkhead interface with the WCS.

7.2.13 A skin crack symmetric to the early crack on the right side (see section 7.2.10, above) initiated on the left side at the ring chord along S39L.

7.2.14 The left side skin crack propagated dynamically forward along S39L and joined up with an early crack progressing aft along S39L and S38L. This fully isolated combined piece LF6A, LF24A, LF95, and LF55A..

7.2.15 Continued downward motion of the isolated fuselage skin panel (LF6A and associated pieces) from the lower lobe separated the keel chord extensions in bending just as the forward keel beam piece was being finally separated from the airplane.

7.2.16 Separation of the keel beam to fuselage splice joint (keel beam lower chord extension) initiated fracture of the lower pressure bulkhead ring chord at LBL9. Completion of the ring chord fracture allowed the final separation of LF6A.

7.2.17 Because the skin cracking described in 7.2.10 was primarily a progression from right to left, cabin pressure loads peeled the skin and frames outward until the frames broke near the centerline. The further progression to the left (across the bottom) was by peeling the skin from the frames.

7.2.18 While fractures within the fuselage proceeded at the extremely fast rate associated with dynamic crack propagation, the front spar was still rotating forward about its lower chord from overpressure within the WCS. Note the loss of LF6A and associated pieces created an opening in the fuselage through which potable water bottles, halon bottles, and associated WCS pieces could have exited the airplane.

7.2.19 The vertical flange of the front spar lower chord was bent forward separating from the horizontal flange and freeing front spar pieces to exit the airplane.

7.2.20 The underwing longerons and adjacent fittings failed primarily in an outward bending/prying mode.

7.2.21 Some fuselage structure ahead of each side of the WCS remained connected to the terminal fitting area and/or was trapped in the adjacent wing leading edge, finally being recovered from the green area.

7.2.22 The remainder of the fuselage red area breakup sequence is described in detail in Section 6.0.

## 1.2 Shear Tie Study

A study was completed of the failure characteristics of the shear ties which secure the beam stiffeners to the upper and lower skins. The results of this study are shown graphically in Figure 1. In general, uniformity in failure mode and direction with respect to the airframe was found in the front spar, spanwise beam 3, and spanwise beam 1. In the case of both the mid spar and spanwise beam 2, no uniformity could be seen.

The failure mode of the large majority of shear ties involved a combination of tensile and shear forces. Figure 2 shows a typical shear tie mounting location, in this case on the lower chord of SWB 1. The shear tie bolts generally fractured in tension, either because of a reduction in the vertical dimension of the stiffener (crippling) or because of an expansion in the vertical dimension between the upper and lower tank skins. This was followed by a longitudinal (fore/aft) motion, deforming the shear tie bolt fragment in the respective direction and leaving drag marks on associated structure.

The shear tie failure pattern at the front spar supports the failure of the front spar stiffeners through crippling. The lower shear tie failures are consistent with the stiffener moving forward and rotating forward about the lower end. The upper shear tie failures are likewise consistent with the stiffener moving forward and rotating forward about the upper end. This indicates that the stiffeners had broken somewhere between the upper and lower ends, as indeed many had.

The shear tie failure pattern at SWB 3 is different. In this case, the lower shear ties failed while moving aft, and the upper shear ties failed while moving forward. This is consistent with a uniform rotation of the stiffener about a fulcrum point. A likely fulcrum location is the vertical flange of the beam's lower chord. Much of this flange was found intact and in place on the lower skin. The lower intercostal structures may have influenced this as well. It is probable that the flange "tripped" the lower end of the stiffeners as they tried to move forward. The resulting rotation displaced the lower shear ties aft. Thus, there is no indication of crippling on this beam. The stiffeners generally remained intact until striking the front spar, whereupon portions of the stiffeners fractured.

The exceptions to this are the stiffeners associated with tension fittings. Those SWB 3 stiffeners which resided under floor beams were equipped with single bolt tension fittings instead of shear ties. These stiffeners fractured several inches below the tension fittings in a fairly uniform manner (Figure 3). The fractures are consistent with in-plane tension loading and out-of-plane shear loading. The out-of-plane forces were applied to the aft side of the beam.

Very similar failures were observed in the case of spanwise beam 1, except that the beam failed aft. The same type of shear tie failures were observed, with the same "tripping" of the lower end occurring about the lower chord vertical flange. In this case, the upper shear ties moved aft, and the lower shear ties moved forward. The net result was the beam rotating aft and down. This failure pattern was not as well defined on the right side of the beam, but what failures could be interpreted were consistent with the pattern.

The mid spar and spanwise beam 2 left much less evidence regarding longitudinal motion. The minimal evidence that could be interpreted for SWB 2 generally indicates forward motion. The mid spar is a much heavier structure. Shear tie or tension fitting failures for the mid spar were not conclusive.

### 1.3 Flange Stub Nicking and Tension Fitting Deformation

The vertical flange of the upper chord associated with spanwise beam 3 exhibited witness marks. These marks resulted from the shear tie studs as they passed the vertical flange remnant which remained attached to the upper skin (Figure 4). The marks are remarkably uniform across the vertical flange remnant from left to right.

In addition, the portion of the upper chord which remained attached to the beam struck stringer 29, forward of the beam. The Sequencing Group identified and measured the vertical separation to be 0.9 inches at the center, becoming progessively less with distance outboard of center.

Many recovered shear ties or shear tie mounting locations on chord flanges exhibited unique drag marks or bent stud remnants (Figure 5). The nature of the drag marks is consistent with either a) the simultaneous withdrawal of the stud while moving longitudinally, or b) a partial withdrawal of the stud prior to longitudinal motion. Many of the shear tie studs are bent based on their longitudinal/lateral motion. Very few exhibit shear failures of the studs in the flange plane. It is likely that an increase in the distance between the upper and lower skin assisted in the withdrawal of shear tie studs, perhaps weakening the shear connections and allowing the studs to bend back and drag the skin as they withdrew rather than fracturing at the shear plane.

The vertical faces of the tension fittings associated with spanwise beam 3 and 1 exhibited vertical bolt hole elongations or vertical deformations of the bolt remnant (Figure 6). These elongations are consistent with the tension fitting moving upward relative to the beam web. This evidence is also consistent with an increase in the dimension between upper and lower skins.

### 1.4 SWB 1 Upper Chord Separation

A considerable portion of the upper chord at SWB 1 remained with the beam web and separated from the upper skin with minimal evidence of longitudinal motion. Many of the fasteners along the beam's upper chord failed in tension or pulled through the skin. The crack forming the forward boundaries of CW135 and CW221 follows these fastener holes. Figure 7 illustrates an area of the beam upper chord which lies to the left of centerline.

### 1.5 Upper Skin Soot at SWB Shear Tie Nuts

On the upper skin, along the line of SWB 3, the holes left by the shear tie bolts are marked by small soot tails oriented forward. In some cases, particularly on the left side, it is clear that the nut which retains the shear tie bolt was still present when this soot adhered. In other cases, this is not clear. It is not possible to determine the disposition of each nut after SWB 3 failed; however, the violence of that event would likely have displaced the nuts as the shear tie bolts fractured beneath them. Thus, the pattern of this soot suggests that it may have adhered prior to the failure of SWB 3 (fIgure 8).

It is possible that the nuts in question remained in place after the failure of SWB 3. However, at LBL 83, a globule of the polyurethane splatter associated with Deposit 1 on the upper skin adhered to the area where the nut would have been (Figure 9). So, at least in this case, the nut was present when the soot adhered, but had departed when the splatter arrived.

These patterns were studied in late 1996 and early 1997, and were documented by the F&E group. However, later study was not possible in the reconstruction due to the installation of the passenger seats in the reconstructed cabin. Even after moving the seats, the mesh supporting structure over the upper skin prevented further examination.

### 1.6 Lower Pressure Bulkhead Soot

This region of sooting, shown in Figure 10, involves the lap joint flange which runs laterally across the aircraft and which joins the front spar with the lower pressure bulkhead (the "smiley face"). The entire lap joint resides below the lower skin of the center fuel tank. From approximately BL 0 left to approximately LBL 25 (LF55D, LF55C), the sooting on the lap joint is particularly heavy (Fig 11). The fasteners exhibit tails indicating downward flow, including the fasteners which attach the LBL 17 stiffener to the bulkhead web. Farther outboard, some evidence of flow toward the left side-of-body is visible (Fig 12). There is very heavy soot built above the location of the LBL 9 angle chord which joins the left side of the keel beam to the bulkhead (Fig 13). The area directly beneath this location, which would be covered by the angle chord in the assembled state, exhibits a much lighter migration of soot to approximately the bolt hole plane.

The aft face of the lower pressure bulkhead web which resides beneath the angle chord at LBL 9 is completely free of soot with the exception of a gap at the upper end which is not protected by the angle chord . A very sharp gradient line of sooting is exhibited down the web to the left of the angle chord location. This clearly indicates that the soot accreted before the angle chord separated from the lower pressure bulkhead.

The fasteners which remain with the angle chord remnant on the keel beam exhibit soot tails in the downward direction as well as soot buildup on the upper circumferences of the fastener heads (Fig 14). This upper circumference buildup is visible on the smaller fastener heads along the left side web of the keel beam, extending back as far as approximately 90 inches from the lower pressure bulkhead.

In the assembled state, the lower skin stops short of the lower pressure bulkhead web. At the web, the only structure between the ACM bay and the dry bay above is the lower chord of the front spar (Fig 15). This chord fractured during the forward rotation of the front spar. The fracture line was through the vertical flange. The remnant of this chord attached to the lower skin exhibits soot accretion on the lower surface, but not on the forward surface. However, the portion of the bulkhead web against which the lower chord would butt does show some sooting, increasingly heavy towards the inboard area around LBL 9 (Fig 16).

## 1.7 Front Spar Soot, Aft and Cargo Sides

Very light soot was found on the aft face of the front spar. This surface is normally clean and dry, as it forms the forward boundary of the dry bay. The existence of some pre-event grime is possible, since the dry bay is open to the outside through two oval shaped access ports.

At the top of the front spar in the bay between BL 0 and RBL 11, soot tails are present. (Figure 17) These extend up the stiffener at BL 0 from about midheight, and they indicate upward flow. Also, some very light soot tails are present near the lower chord, above the keel beam. These indicate downward flow. All of this is associated with one piece, CW501. CW501 also includes the remnant of the lower lap joint at LBL 9 that was described as heavily sooted in paragraph 1.4 above.

On the forward face of the front spar, the F&E notes have stated that sooting is more predominant around the tears in the web which resulted from the impact of SWB3 with the web.

## 1.7 Splatter on CW504

The Splatter Group studied six deposit areas of a splattered substance which had adhered to structure. Of these six, five were identified as consistent with a polyurethane foam used to insulate an air conditioning duct which runs along the left side of the upper skin, beneath the floor boards. Deposit 1, mentioned in 1.3 above, is located between LBL 75 and 98 on the upper skin. Deposit 2 is located on the aft surfaces of pieces CW 504 and 515, which are part of the front spar. In order for this deposit to adhere to the aft side of the front spar, the spar had to have separated from the uper skin and moved forward. However, CW504 was possibly the first piece to leave the airplane. It landed very early in the debris field. Hence, this deposit had to have occurred very early in the sequence, although after the front spar failed.

1.8 SWB 3 Lower Shear Tie Nut Sooting

From approximately LBL 11 right to RBL 33, a consistent pattern of sooting is visible around the fastener nuts which retain the bolts attaching the lower shear ties to the stiffeners. This flow is distinctly downward. The pattern is uniform across pieces CW602, CW603, and CW604. It also appears uniform on both the left and right sides of the stiffeners depending on which side of the stiffener the retaining nuts are located on. The downward flow is also noted around fasteners attaching the lower chord to the web between these stiffeners. It is clear that this soot accreted prior to the fractures which separated these three pieces (Figures 18 through 20)

1.9 SWB 3 Fastener Soot Impingement Characteristics and Distribution

On the aft face of SWB3, considerable sooting is visible around the fasteners which attach the stiffener web flanges to the web. This is mapped graphically in Figure 21. From approximately LBL 33 to RBL 49, consistent downward flow is visible below approximately WL 170. Above this line, the flow is upward. Interestingly, at approximately the WL 170 point along the inboard flange of the stiffener at RBL 41, the change in flow direction is clearly visible (Fig 22). At fasteners below this WL, the flow is downward; above it is upward. At the one fastener in between, the flow bends around the fastener head from inboard to outboard, suggesting flow impingement from inboard of the stiffener at about this WL. This location is less than 10 inches outboard of the SWB2 access panel and at approximately same height as the upper edge of the panel.

CW607 and CW633 comprise the recovered lengths of the stiffener at RBL 75. Both exhibit soot flowing upward on both sides of the stiffener web (Fig 23). The stiffener at LBL 75 exhibits very similar flow (Fig 24).

1.10 CW703 Fastener Sooting

On the forward face of the SWB 2 access panel, CW703, several fasteners remain attached and retain the portion of beam web on the upper edge. These fasteners exhibit soot flow in an upward (panel intact) direction. With the exception of these fasteners, and two remaining near the lower edge, little soot accretion is notable around fastener holes. Those fastener holes in zone B do not exhibit any soot (Figure 25)

The upper fillet of the panel web exhibits considerable soot. This also would have to be accreted while flow was upward relative to the intact panel orientation.

## 2.0 Analysis

The analysis of the center tank failures is probably best understood in terms of pressure differentials and combustion byproducts. While neither of these phenomena will lead to a precise ignition location, both can assist in narrowing the field somewhat and perhaps in better understanding the nature of the combustion.

The Quarter Scale tests provide a very useful reference for the combustion and pressurization behavior of a multi-compartment tank. However, due to cost and mechanical feasibility constraints, the quarter scale tests were unable to actually simulate the behavior of the CWT during the TWA 800 event. ALPA believes the actual CWT experienced failures in the lower skin, and possibly the upper skin, within the beam failure sequence. Further, we believe spanwise beam 1 failed aft in the accident; the tests did not repeat this failure mode. Finally, we believe the maintenance panel in spanwise beam 2 failed forward prior to the failure of spanwise beam 3. The quarter scale tests did not model this failure; rather, the panel failed after spanwise beam 3 in the tests.

### 2.1 Upper/Lower Skin Expansion

The predominant structural response across the tank was an expansion of the distance between upper and lower skins. This vertical expansion is clearly evident at the upper chord of SWB 3 and also at the upper chord of SWB 1, as discussed in 1.4 above. It is likely that the tensile failures of the keel beam attach bolts at SWB 2 and the midspar, and the associated tensile separation of the SWB 2 lower chord, occurred as a result of this same vertical expansion event. This left both SWB 3 and 1 still attached to the lower skin, and large sections of SWB 2 and the midspar still attached to the upper skin.

During the early part of the vertical expansion, while the web of SWB 2 was still experiencing in-plane load (vertically parallel to the web), the Zone A fasteners in the maintenance panel failed in shear. Subsequently, the lower chord and keel beam attach bolts associated with this beam failed in tension.

### 2.2 Longitudinal Pressure Differentials

Longitudinal pressure differentials clearly existed across SWB 3 in the forward (Quarter-Scale positive) direction and across SWB 1 in the aft (Quarter-Scale negative) directions. The origin of the differential across SWB 3 is fairly obvious, since this beam forms the forward boundary of the fuel tank.

The differential across SWB 1 takes place within the fuel tank vessel itself. In this case, one might expect combustion on both sides of the beam. However, the quarter-scale tests demonstrated that internal pressure differentials can change sense and magnitude rapidly depending on the speed of combustion. This differential is interesting in that it first manifests itself by forcing gases through the maintenance panels on both sides of the BL 0 rib. When this happens, the beam must still be structurally sound and capable of resisting the pressure differential at the upper and lower ends. Subsequent to this venting through the maintenance panels, the beam loses its ability to resist out-of-plane (perpendicular to the beam web) loads. This is probably because the vertical expansion has failed the chord and shear tie fasteners in tension, and created a freedom of movement for the beam. At this point, the beam displaces in the aft direction, with the beam upper chord rotating downward.

During this process, any combustion which was underway in bays 5 and 6 was apparently unable to accelerate and balance or reverse the pressure differential.

Another positive differential is evident across SWB 2. This pressure differential resulted in the failure of the Zone B fasteners on the maintenance panel. There are two mechanisms by which this differential might develop. In one scenario, combustion generated pressure in bay1 might be sufficient to balance or exceed the pressures being developed in bay 2. At this point, the zone B fasteners have not failed, and the panel is not open. However, if SWB 3 then fails forward, it vents bay 1 pressure to the outside through the dry bay. When this happens, a large pressure differential develops across SWB 2, failing the zone B fasteners and drawing the panel forward. This is essentially the scenario modeled during the quarter scale tests.

However, the extensive pattern of soot tails mapped on the aft face of SWB 3 leaves open another possibility. The gas flow marked by these tails is generally upward above waterline 170 (about two-thirds of the way up from the floor) and downward below this waterline (see Figure 22) The soot flow indications are more or less symmetrical around the SWB 2 maintenance panel location. The point on the SWB 3 stiffener at RBL 41 where the soot tails change from upward to downward is approximately 10 inches to the right of the panel's right edge butt line and about even with the upper edge of the panel. The flow indicated by the fastener between those with upward tails and those with downward tails is from left to right. This is consistent with a gas jet from the maintenance panel.

This interpretation suggests that the pressure differential across SWB 2 existed before SWB 3 failed. This was probably the same pressure differential that was driving the vertical expansion, and the panel failed forward when a sufficient number of zone A fasteners had failed to overload the rest.

The maintenance panel would have to have blown open before SWB 3 had started to move. If the beam had assumed any angle other than vertical, a gas jet impinging on it from behind would deflect through the smallest angle. After the beam began to rotate forward, the smallest angle would be toward the top of the beam. In such a case, the downward soot flow which is quite visible would probably not have taken place.

As the lower inboard part of the panel rolled forward and upward, the gas jet from behind SWB 2 exited with an initial velocity vector oriented inboard and down. During the panel's motion, the gas flow velocity vector rotated up through the horizontal and rotated to the right as the last of the panel moved upward. This led to the distribution of upward and downward flowing soot across the mid section of SWB 3.

It is important to note that, as the chords of these beams separated from the upper and lower skin, equalization of these differentials would begin. Continued combustion could, as shown in the quarter scale tests, maintain a pressure differential despite a vent opening, but not for long. Generally speaking, once the upper or lower chords of the beams separated from the skin, the pressure across that beam would equalize pretty rapidly.

2.3 Weakening of the Beams

The expansion of the distance between the upper and lower skins, and the consequent failures of the upper and/or lower chords substantially weakened the ability of SWB 3 and SWB 1 to resist out-of-plane loads. Thus, the actual loading required to move the beams cannot be determined, except to say that it is likely to be substantially less than that required in the fully assembled state.

2.4 Beam Longitudinal Motion

In most locations along the upper chords of SWB 3 and SWB 1, evidence of vertical expansion coexists with evidence of longitudinal movement. In the case of SWB 3, this is forward; SWB 1 moved aft. These motions were driven by the respective pressure differentials across the beams, and began when vertical separation between the beams and the upper and/or lower skin had sufficiently reduced the shear strength of the beam connections to the skin. This motion left behind the bending of shear tie stubs, the nicking of the upper chord remnant, etc.

2.5 Rupture of Lower Skin

The only plausible origin of the soot accretions found on the aft side of the lower pressure bulkhead is the combustion in the center tank. Based on the condition of the air cycle machines, heat exchangers and lower body fairings, a fire external to the tank could not have occurred.

However, the impingement of soot on the aft face of the lower pressure bulkhead and adjacent keel beam undoubtedly took place before the failure of these structures. The localized nature of this soot suggests that a large opening would not be required. The impingement angle appears to be from left to right. Some soot was forced through the gap between the lower pressure bulkhead and the keel beam upper chord. Soot also was forced upward, against the exposed part of the front spar lower chord. In a couple of small areas, it appears that the front spar may have started to move while this soot was still accreting.

The first opening in the lower skin aft of the bulkhead is the lap joint failure at S-15. This joint failure is characterized by the Sequencing Group as a fore/aft shear failure. Actually, most of the joint failure appears to have been due to tensile loading of the fasteners resulting in the heads failing, followed by some dragging of the fastener stubs. Outboard there is a region of fasteners which failed predominantly in shear. Inboard, near and over the keel beam, the failure is characterized by numerous fasteners pushed up through the upper lap flange with the backing nut lifted into the tank, where they remain. This is consistent with other recontact damage seen on CW702 and elsewhere along the lower chord of SWB 2.

This failure mode extends outboard across a region of heavy blackening of the lower skin into an area which was not blackened, up to the region where the failure mode changes to shear. The evidence suggests that most, if not all, of the lap joint at S-15 remained attached until after the lower skin was blackened by soot; this would have been after the keel beam had departed.

Nonetheless, the failure at S-15 provides a convenient source for the gas flow which led to the soot on the lower pressure bulkhead. The failure mode might allow the skin aft of the joint to drop down, forming a slot with the correct orientation to exhaust soot forward to the lower pressure bulkhead. However, at least at the inboard section of this failure, the timing is not correct. Outboard, this is less clear, and the joint remains a possibility.

Immediately aft of the S-15 joint, alongside the keel beam, some soot tailing exists around some fastener heads. This indicates a forward flow direction, which would be consistent with impingement on the lower pressure bulkhead. Several candidate openings in the lower skin exist aft of S-15. With the exception of the crack at S-10, under the mid-spar, all of these openings lie under bay 5, behind SWB 1.

Venting from bay 5 is possible but does not seem likely. The pressure within bay 5 is lower than that in bay 3 at least as early as the soot venting through the maintenance panels. At that time, the beam is structurally capable. This pressure differential continues to predominate during the vertical separation of the upper and lower skins through the aft failure of SWB 1. The sequence of gas venting through the maintenance panels in both bay 3 and 4, followed by separation of the upper skin from SWB 1 indicates that this pressure differential did not develop due to a drop in pressure in bay 5, but rather due to an increase in pressure in bay 3. However, this is as far as one can go, and venting from bay 5 is still possible.

## 2.6 Rupture of Upper Skin

The uniformity of the soot tails noted on the upper skin associated with the SWB 3 shear tie bolt holes is unique. At the least, the bolt holes at LBL 41 and 49 show the soot accreting around the retaining nuts, indicating a source from behind this location.

The only single fracture line which opens the upper skin to all of the bays between floor beams is the fracture at S-8. This corresponds to the upper chord of SWB 1. This skin fracture predominantly follows the fastener holes left when the skin lifted off of the beam's upper chord.

The floor beams were probably still more or less intact when this soot accreted, and they would prevent lateral migration of soot. Instead, gas flow would be confined to the channels between the floor beams. It is this feature which requires a broad lateral opening in the skin in order to cause sooting across the width of the upper skin at SWB 3.

Conveniently, soot is known to have been present in bays 3 and 4 prior to the upper skin lifting off the SWB 1 upper chord (2.2 above). It is not clear what generated the flow from aft forward; this apears to be the same general flow which influenced the splatter in Deposit 1. It is possible that cabin depressurization had begun at this point. Certainly, before Deposit 2 could arrive at the aft side of CW504, there could no longer be a barrier between the top side of the upper skin and the dry bay, and this alone would open the cabin to the outside atmosphere.

The presence of fastener nuts at LBL 41 and 49 may indicate that this soot accreted before SWB 3 failed. However, other holes are much more ambiguous; the presence of other nuts cannot be determined from the available photos. In order to generate the soot tails, however, some object must have been in place; there would be no aerodynamic reason for the recirculation flow which leaves the soot to occur without an obstruction. At LBL 83, it appears that the nuts were in place; what is clear at LBL 83 is that splatter was deposited after the sooting and after the retaining nuts had departed.

## 2.2 State of Combustion

The quarter scale tests were not designed to look specifically at the combustion characteristics of jet fuel; rather, they were intended to investigate the flame propagation behavior of a multi-compartmented tank. In order to make this relavent to the TWA 800 investigation, the simulant fuel was chosen to closely emulate the energy release behavior expected from jet fuel.

However, the inclusion of liquid jet fuel for the purpose of examining liquid lofting behavior adds a useful element to the understanding of the actual event.

The presence of considerable soot within the actual center tank, specifically in locations which indicate its existence prior to structural failures, provides some definition to the combustion event. Either the premixed flame was quite rich and produced some soot, or some type of diffusion flame developed very early. This may have been the result of liquid lofting or residual fuel retained behind tank structure. Lofting clearly contributed to the combustion in the quarter scale tests and left a soot residue. In at least one test conducted without a liquid layer, orange flame and soot were thought to have originated from jet fuel retained by the tank structure from a previous test.

In the later round of quarter scale tests, several jet fuel only tests were conducted for validation purposes. No record has been published regarding the character of the combustion in the vapor only tests. However, although possible, it is not likely that a premixed flame would produce large quantities of soot. It is more likely to have resulted from some type of diffusion flame.

The quarter scale tests which examined liquid lofting reported that the liquid combustion did not occur until late in the combustion event, and probably did not contribute to the overall pressure rise. The presence of liquid may accelerate the development of pressure. Thus, if liquid fuel lofted within the CWT during the accident event, it was likely to ignite late in the progress of the flame.

The specific origins of the soot noted within the 800 CWT are therefore of interest. The tank had been loaded for the flight to New York from Athens. Thus, all wetted surfaces were eligible to retain some thin film of liquid fuel; which surfaces actually did cannot be known.

However it is interesting that several areas can be seen in which the soot had a specific flow direction, indicating a pressure differential. This is particularly interesting when flow from one bay to another is indicated by the soot adhesion. In bay1, the soot accretions associated with the red zone pieces exhibit flow directions and are not accompanied by a noticeable general sooting.

This really cannot be said of any other bay. However, it is interesting that the soot accreted between the fasteners on the aft face of the SWB 1 access panels does not appear to be accompanied by additional general sooting around the fasteners themselves.

## 2.3 Conclusions

Because much of the structure remained with the aircraft after the initial combustion and was exposed to later fires, it is difficult if not impossible to determine very much about the early event in the aft bays. Further, the quarter scale testing demonstrated the ability of the flame and pressure in the ignition bay to be rapidly outpaced by the propagated, turbulent flame in adjacent bays. However, several things can be said.

a) At an early point in time, the pressure differential across SWB 1 became negative.

b) Before SWB 1 lost its ability to resist out-of-plane loads, the combustion in bays 3 and 4 had become sooty. This is demonstrated by the soot flow through the gaps in the access doors in SWB 1.

c) It is likely that the combustion in bays 5 and 6, if any, was not producing soot during the period in which the access doors gapped. This is not a foregone conclusion; however, the structure around the doors exhibits soot adhesion in a pattern flowing out from the door's flange gaps. The same structure does not exhibit any other distinct soot pattern, such as flow tails or soot buildup on one side of the fasteners. Since this structure's ability to accept soot and retain it is demonstrated, it is likely that little soot was being produced by the combustion in those bays.

d) From the time that the SWB 1 differential became negative, it remained negative until the beam failed aft.

e) At an early point in the event, the pressure differential across SWB 2 became positive.

f) The combustion in bay 1 was not able to accelerate and reverse the SWB 2 pressure differential before the access panel failed forward.

g) The combustion in bay 1 was probably not producing appreciable soot prior to the failure of the SWB 2 access panel.

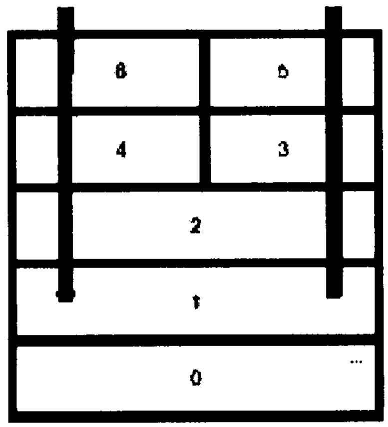
h) At some point after the SWB 2 access panel failed forward, SWB 3 failed forward. The fractures of the stiffeners below the tension fittings give evidence of substantial load applied both in-plane and out-of-plane. Thus, it is likely that the bay experienced substantial pressure after the access panel failed. This may be an indication of pressure piling induced by combustion after the panel failed.

i) The lower skin failed at some point during the event. This failure took place in a bay that was producing soot at the time; the soot exhausted forward, impinging on the lower pressure bulkhead.

j) The lower skin failure took place early enough to allow soot to impinge on the lower pressure bulkhead and keel beam before that structure experienced significant failure.

k) The absence of soot accretion on the parts of the lower pressure bulkhead and surrounding structure that was exposed by structural separation resulting from the front spar failure may indicate that the pressure differential which was venting the soot through the lower skin prior to the front spar failure had dissipated by the time the lower pressure bulkhead structure began to separate.

l) The upper skin also failed during the initial event, probably at the SWB 1 fracture. This allowed some soot to vent into the area between the floor and upper skin. This soot preceded the splatter in passing FS 1040 (SWB 3).




Map of Tank Bay Designations
from Quarter Scale Test Report

(bay designations used in this document
are the same)

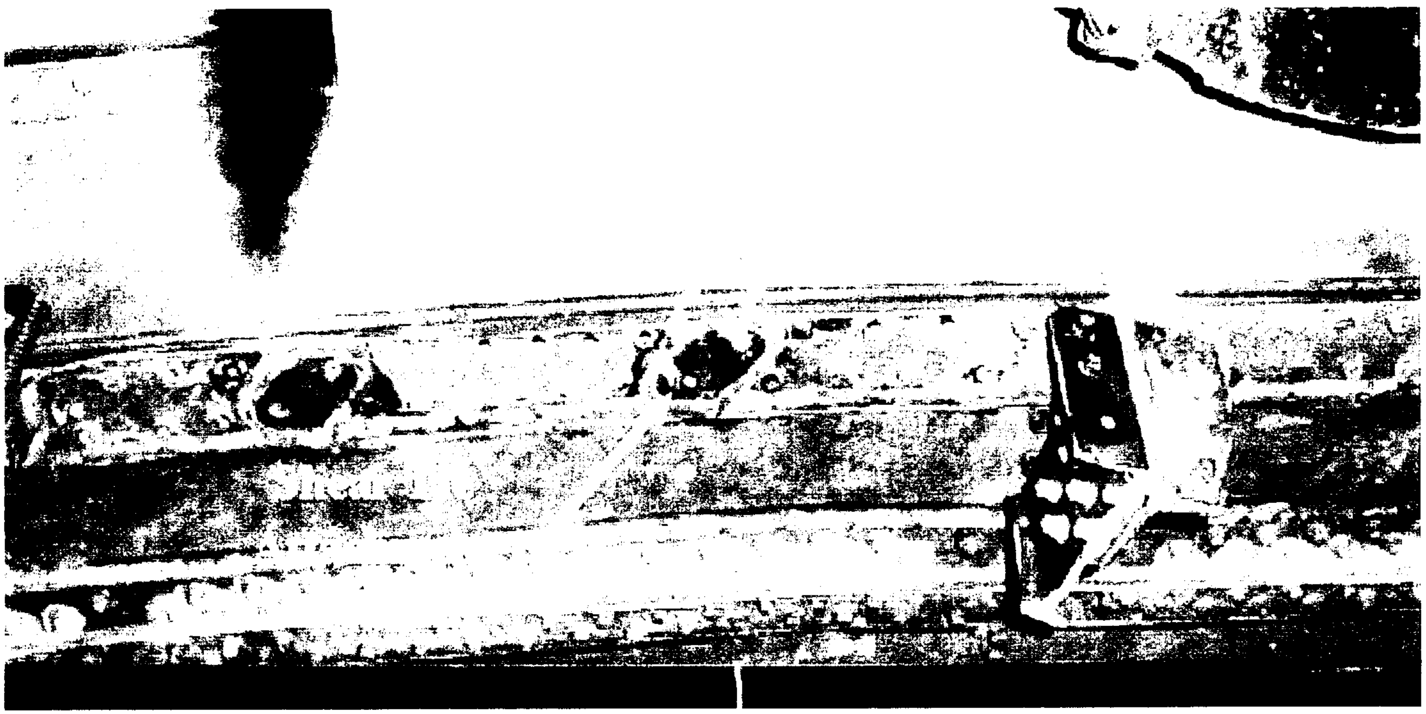
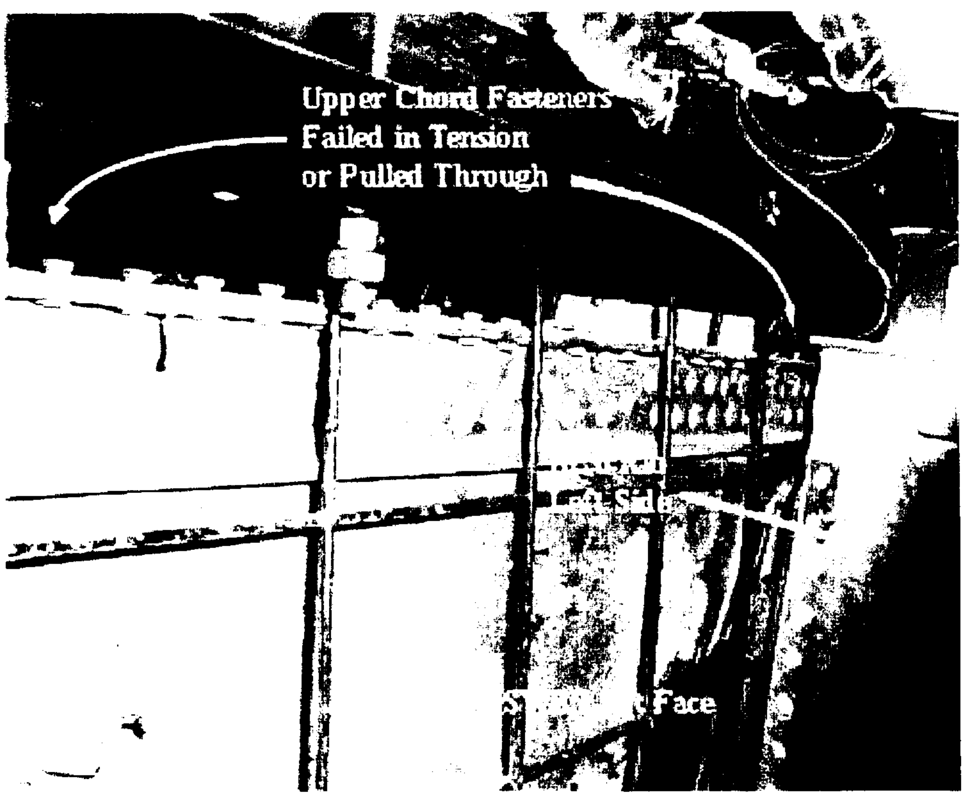


Figure 4


Figure 5


Figure 6

Figure 7



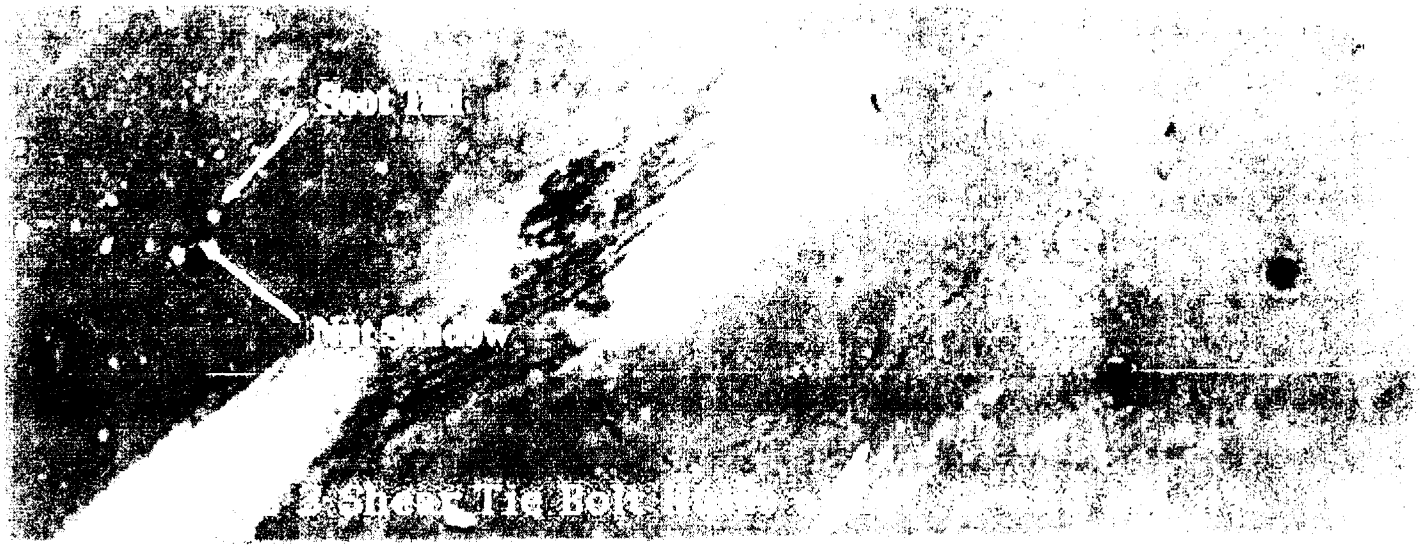
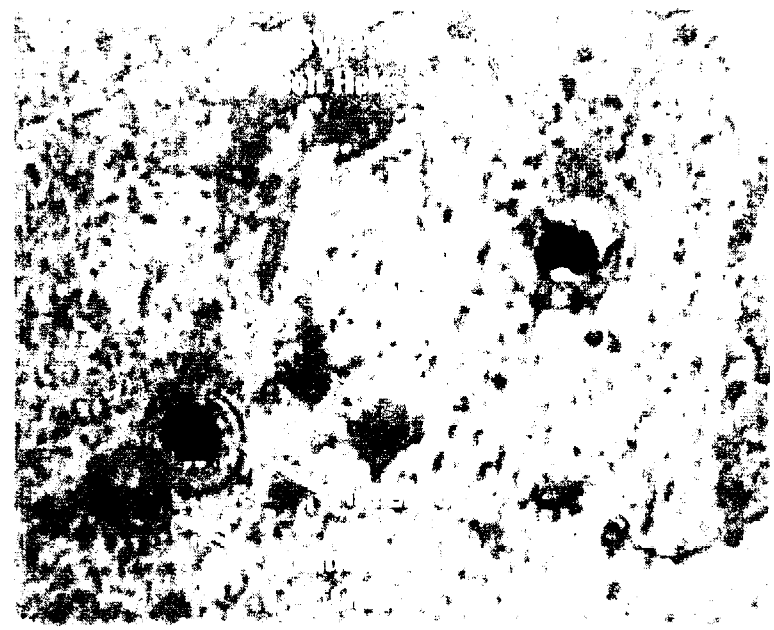


Figure 8

Figure 9



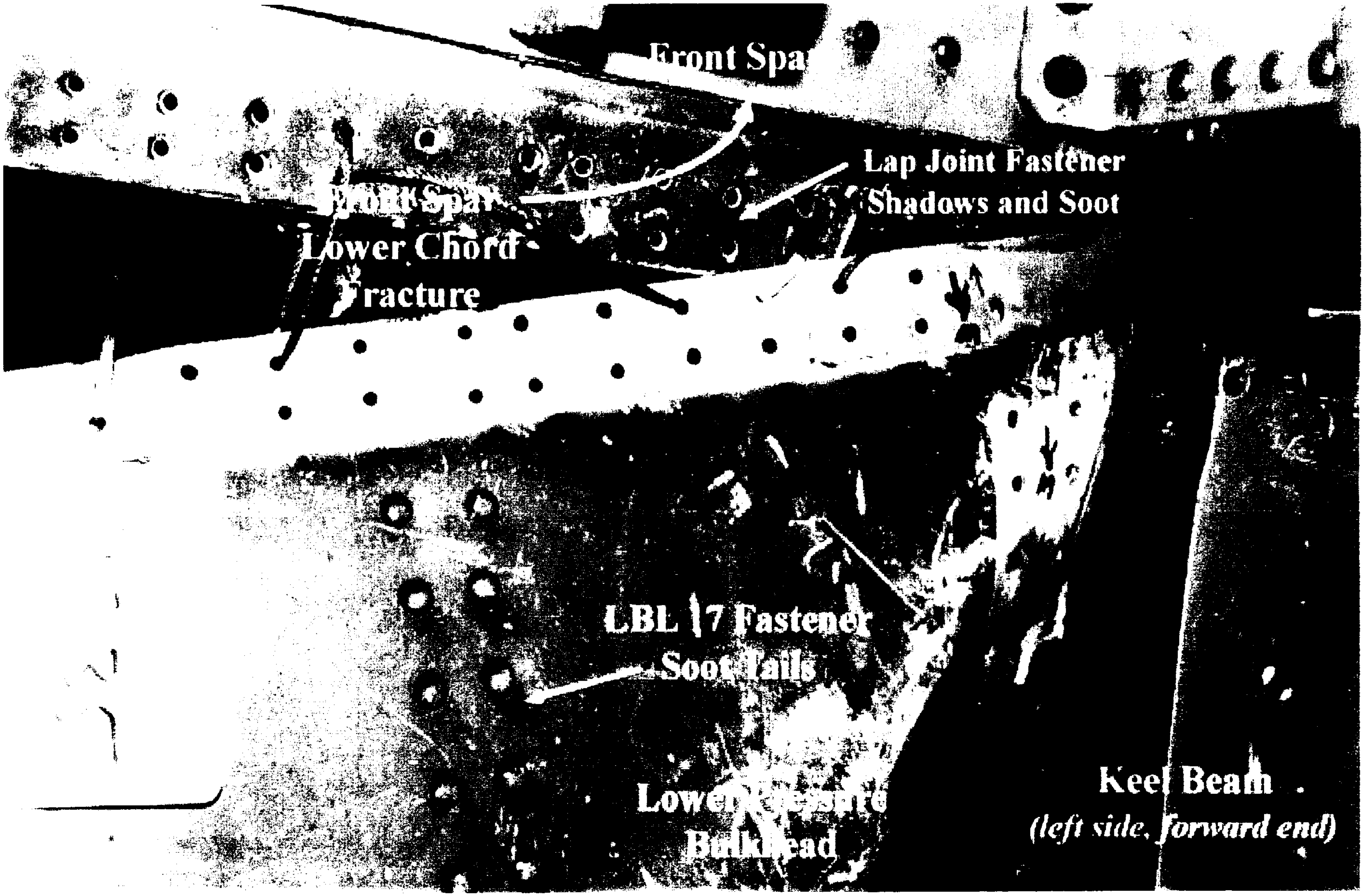

Lap Joint Fastener
Shadows and Soot
Keel Beam
(left side, forward end)

Figure 10

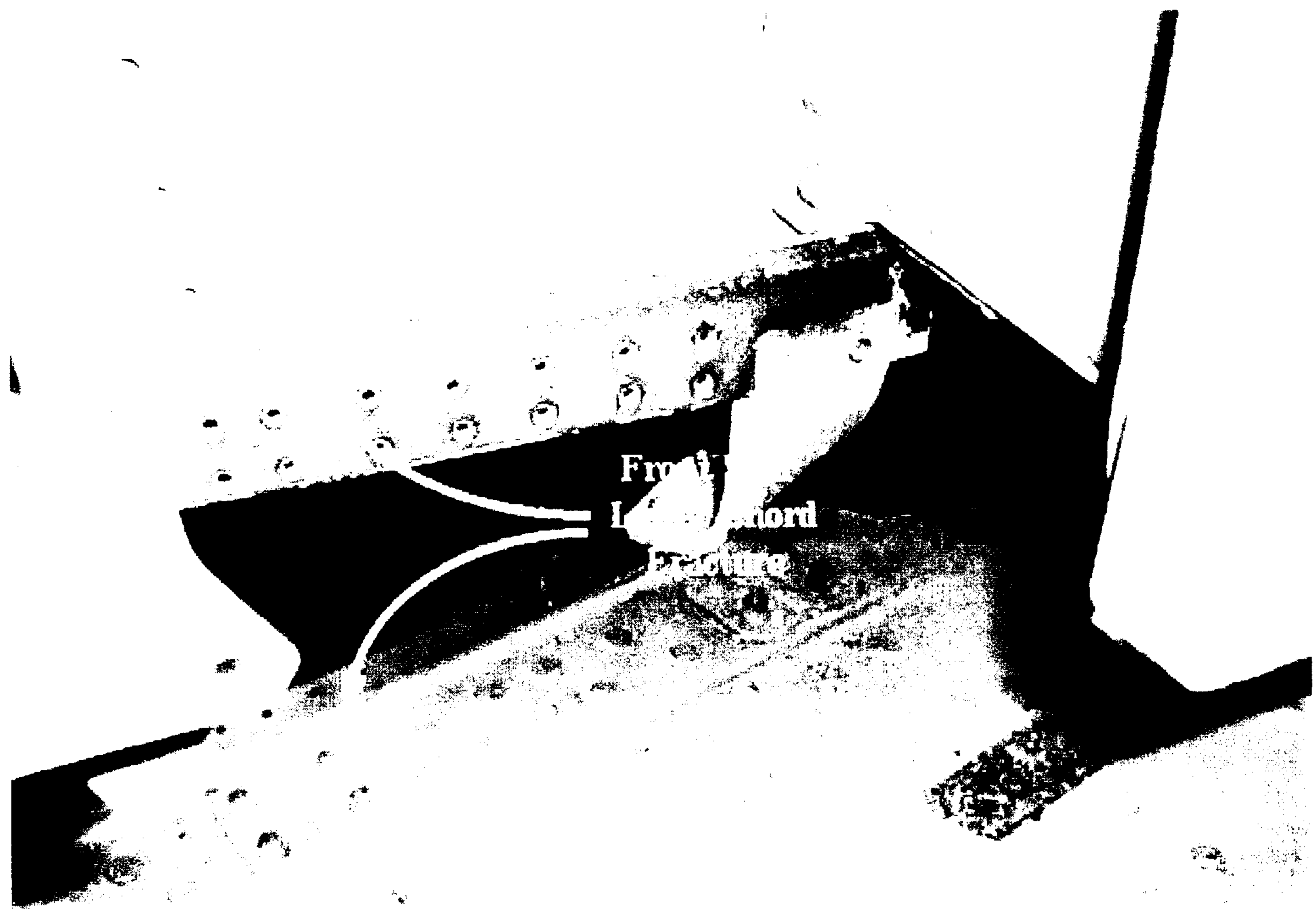


Figure 11


Figure 12

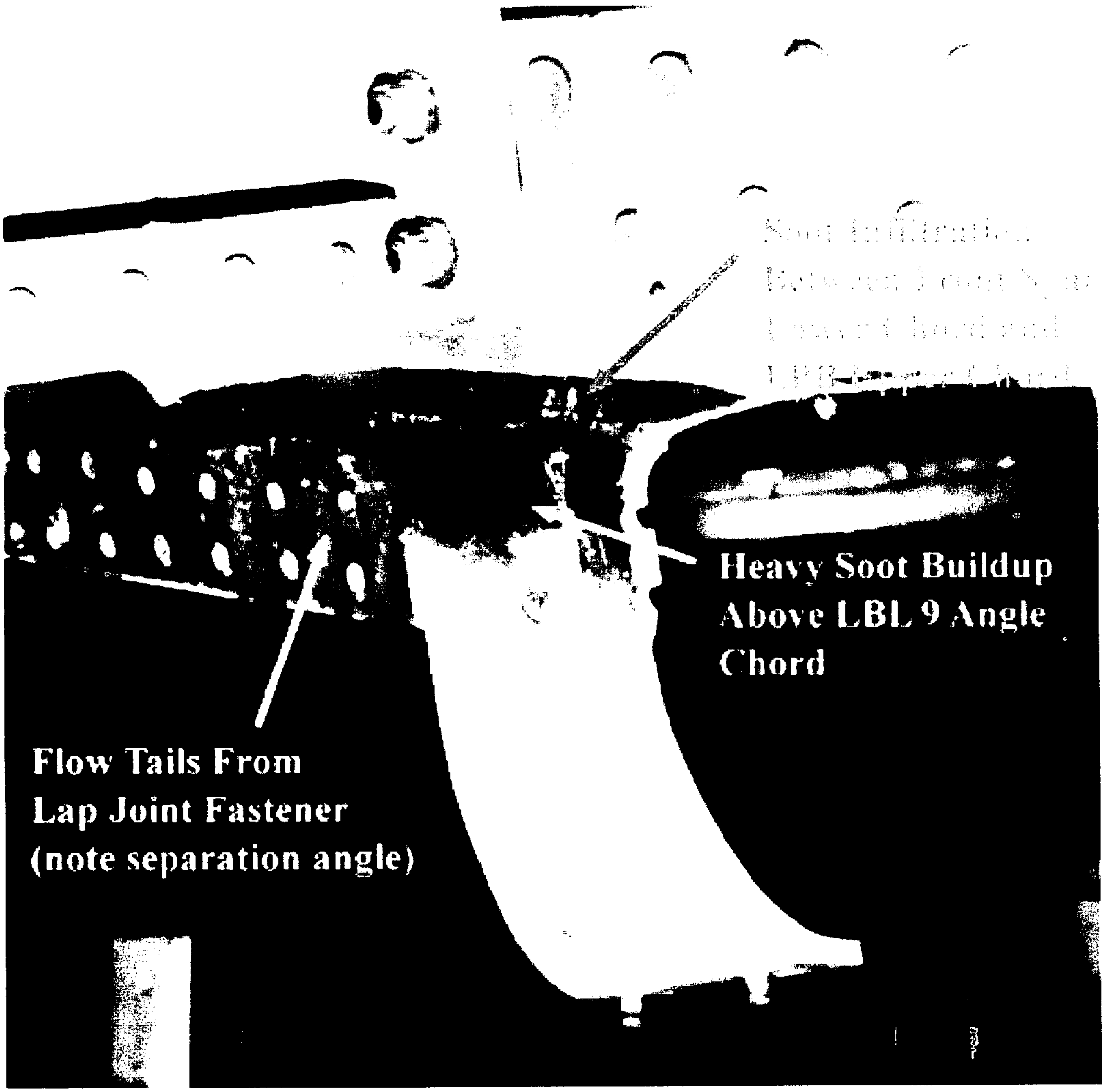

Heavy Soot Buildup Above LBL 9 Angle Chord
Flow Tails From Lap Joint Fastener (note separation angle)

Figure 13

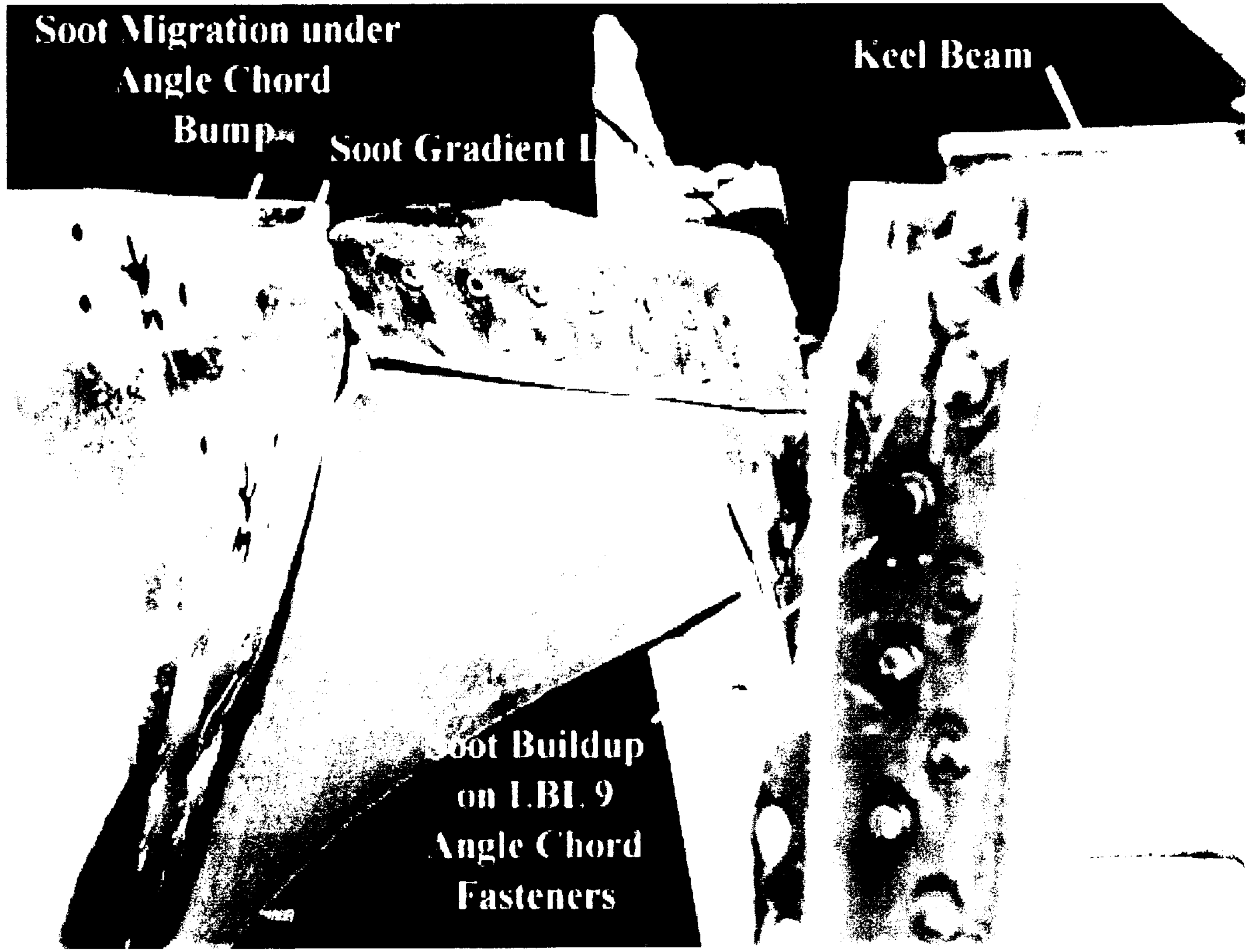

Soot Migration under
Angle Chord
Bump
Soot Gradient
Keel Beam
oot Buildup
on LBL 9
Angle Chord
Fasteners

Figure 14

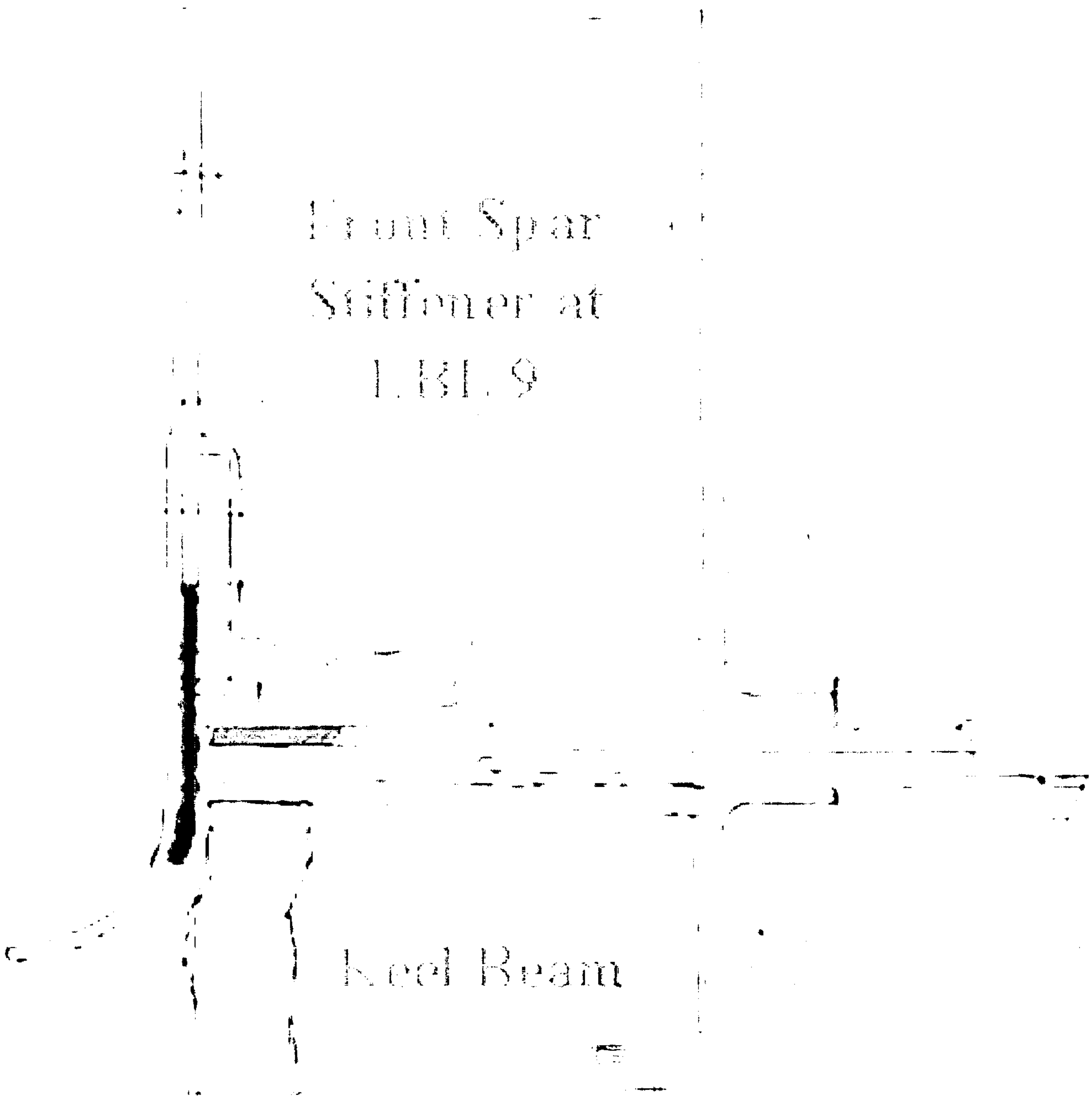



Figure 15

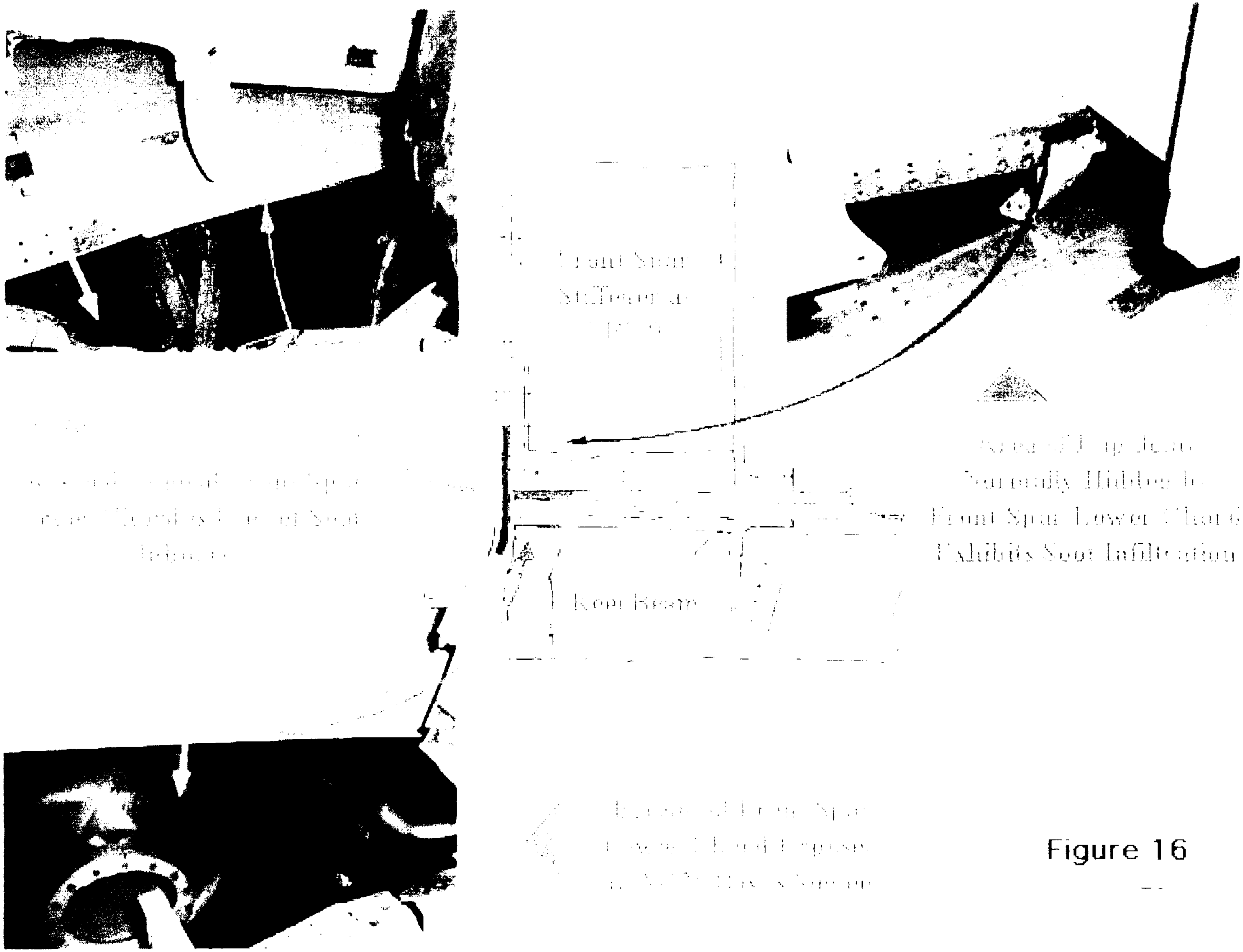

Normally Hidden
Front Spar Lower Chord
Exhibits Soot Infiltration
Keel Beam

Figure 16

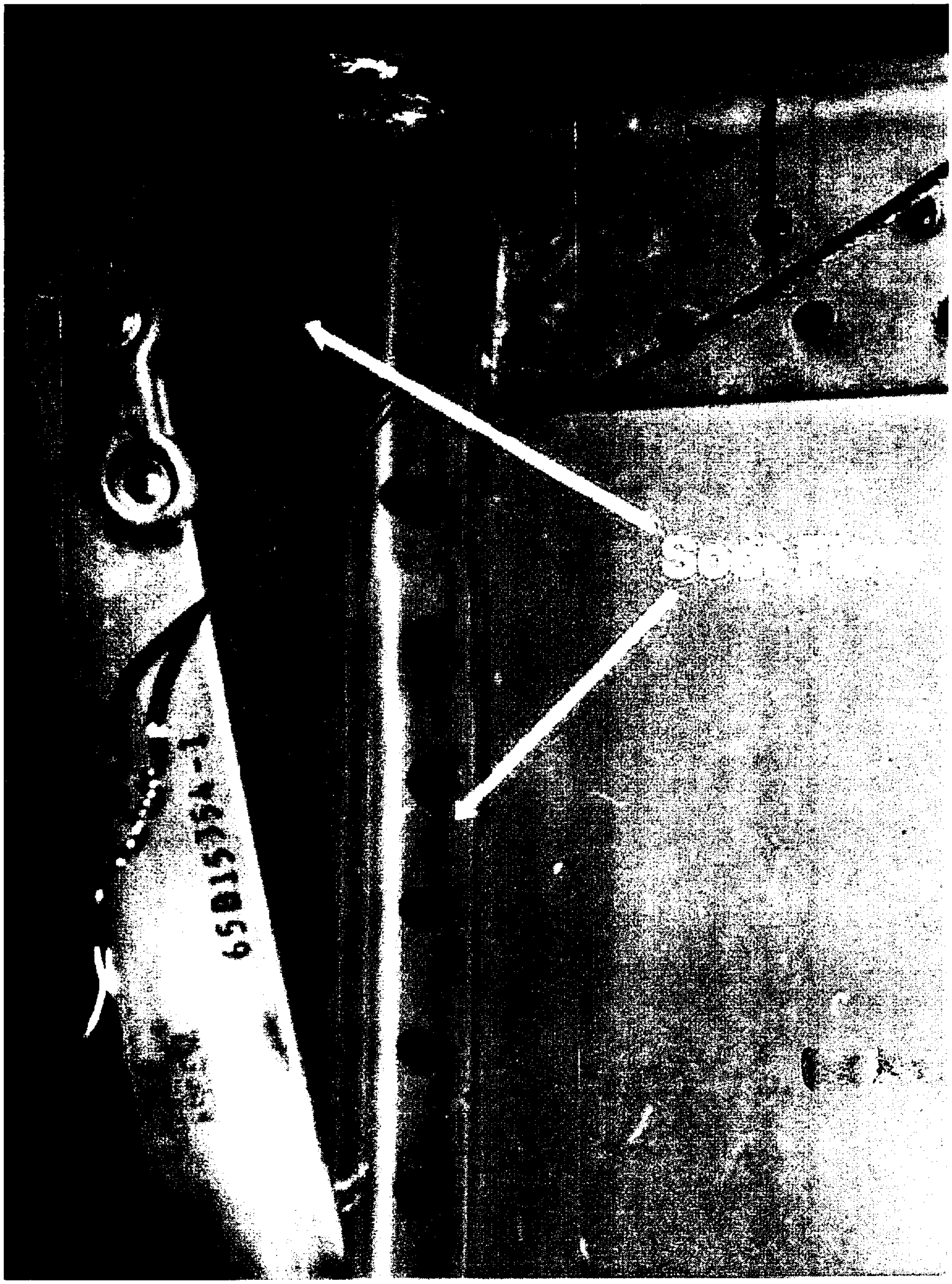


Figure 17

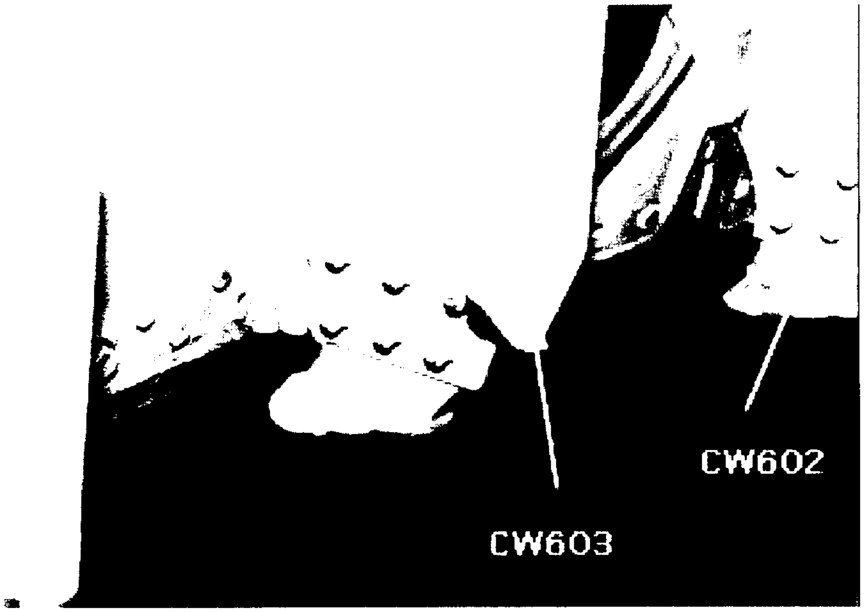


Figure 18

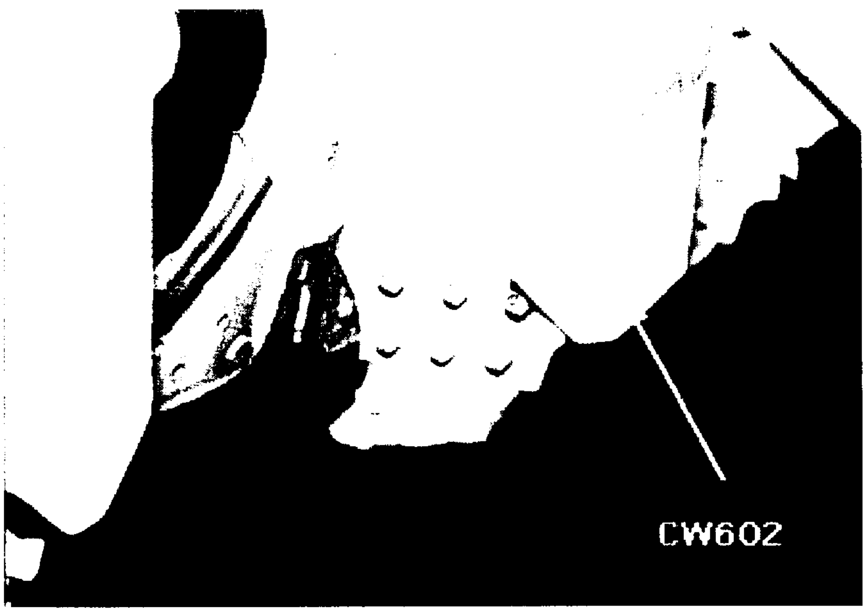


Figure 19


Figure 20

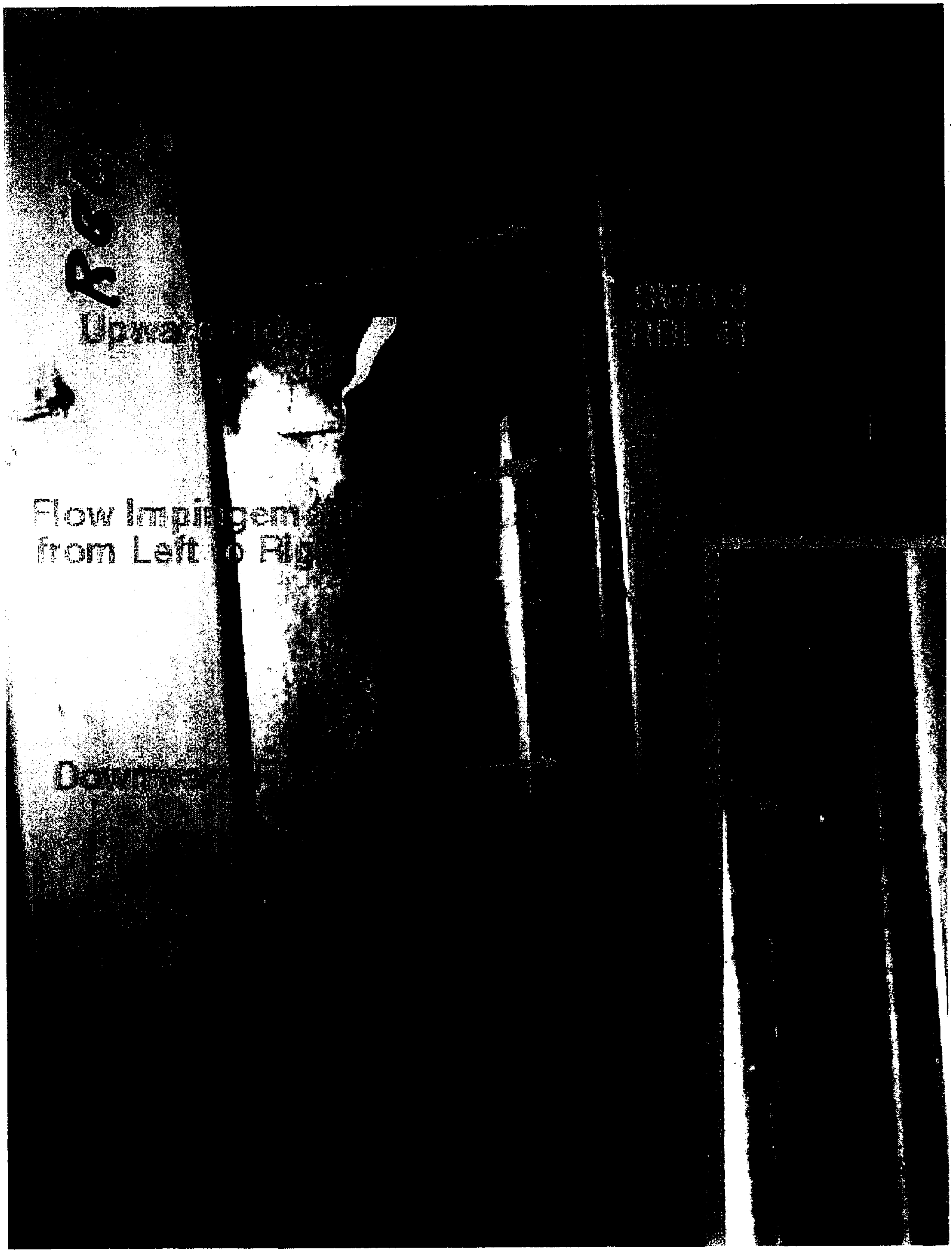



Figure 22

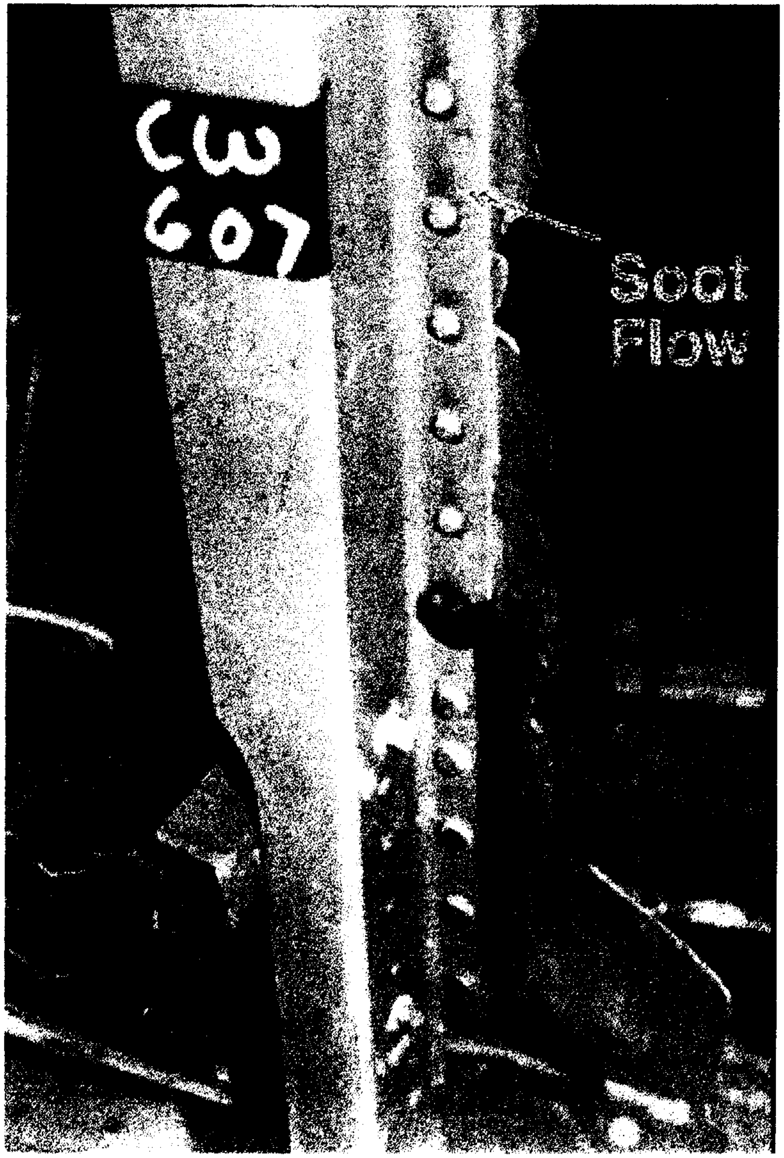


Figure 23

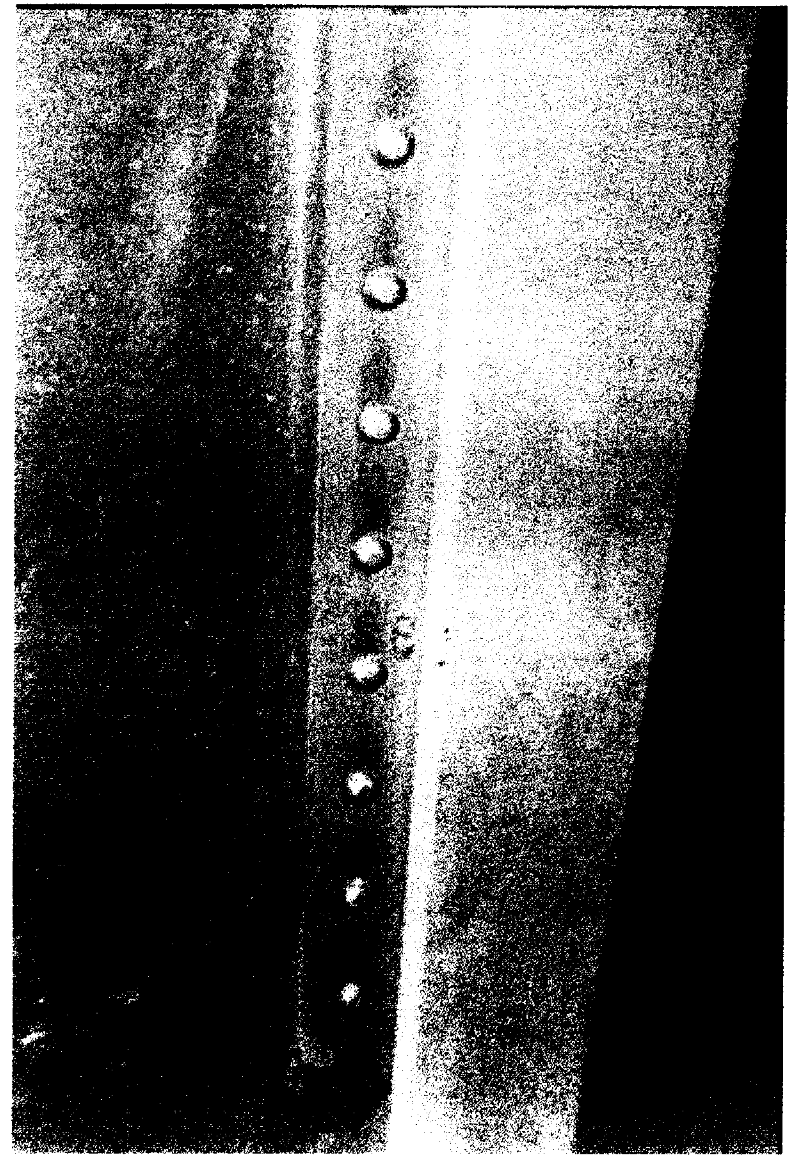


Figure 24

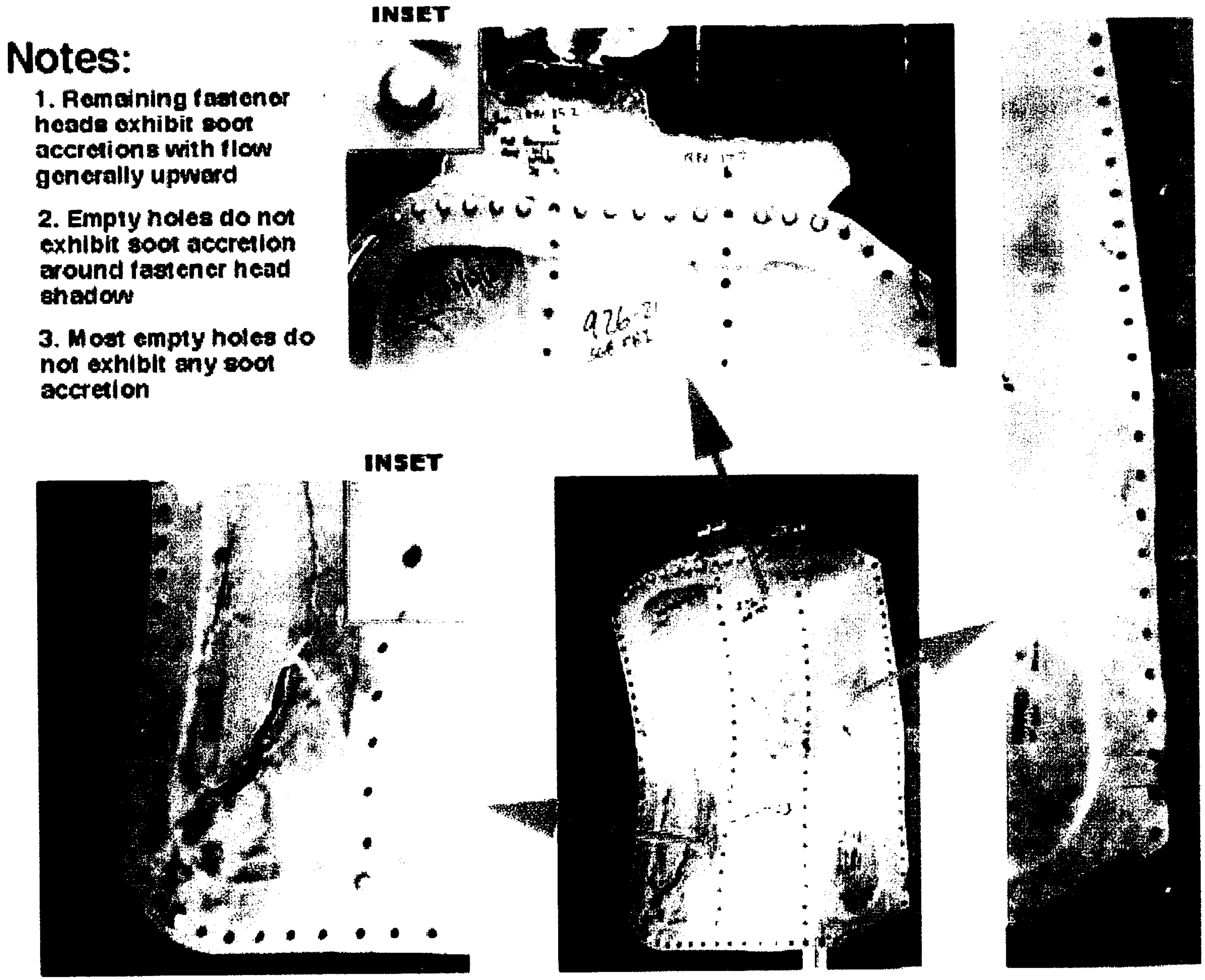

Notes:
1. Remaining fastener heads exhibit soot accretions with flow generally upward
2. Empty holes do not exhibit soot accretion around fastener head shadow
3. Most empty holes do not exhibit any soot accretion
INSET
INSET

Figure 25

# APPENDIX C

# DATABASE DESIGN and IMPLEMENTATION*

## Databases

To many people, databases are the embodiment of information technology. Ideally, all the necessary information is neatly packaged, categorized and compartmented, waiting only for the correct button to be pushed in order to generate "the answer." The reality, as every investigator and engineer knows, is far different from this ideal. A brief examination of this subject should clarify the capabilities and limitations associated with using databases for accident investigation.

The ready availability of extremely capable database software should make it no surprise that accident investigators have adopted this tool. In their purest form, databases excel for data organization, storage and retrieval, simply because that is what they are designed to do. Ideally, the data is collected, categorized and stored, and then retrieved and manipulated when and as required. The data in question can be numeric (e.g. FDR, radar, part numbers), text (e.g. part descriptions, accident history), graphic (e.g. landforms, charts, weather) or any combination thereof.

During the field phase of an investigation, databases are typically used in one of two ways. They are repositories for the facts being developed, and they are a source of additional ideas, leads, and considerations for steering the investigation. When data is being collected for a database, there is a built in checking effect due to the fact that the collector is attempting to "fill boxes", and any omissions generally become apparent. This characteristic aids the investigator by helping to ensure that a complete set of facts is gathered. During the field phase, investigators can also access existing databases for similar events in order to uncover information that could prove useful in guiding the conduct of the present investigation. Examples of this would include the Service Difficulty Report (SDR) database, or a particular aircraft or airport accident history.

During the analysis phase, these same two types of applications would pertain. One difference here might be that for the database-building scenario, the data that had been collected during the field phase would now be sorted and reduced in order to catalogue and enter it into a database. In other words, although the data was not originally collected with the explicit intent of loading it into a database, it was subsequently decided that it would be useful to assemble it into a database. Databases, whether preexisting or created specifically for or from the individual accident data, lend themselves particularly well to the manipulation and presentation of information for the analysis (and eventually report) phase.

These applications seem straightforward enough, and usually are. However, the regimentation that makes the databases so useful can also work to the detriment of the investigator or analyst. As anyone who has ever worked with a database knows, the utility is only as good as the database design itself. Foremost on the list of potential database problem areas is the quality of the parameter list. Missing parameters are the most apparent deficiency. But there can also be ill-defined, overlapping, and useless or meaningless categories. Ideally, the database should be comprised of sufficient, clearly defined parameters that are mutually exclusive.

* Excerpted from ISASI Paper "Information Technology in a Large Scale Aircraft Accident Investigation", C. Baum & M. Huhn, October 1997

danger of making categories that favor or require analytical entries, which then taints the subsequent analysis. In a recent accident investigation, the absence, presence and sequence of fire was a critical factor in developing the progression of events, and eventually the root cause. In constructing and filling in the database, the investigators needed to be extremely diligent in recording their *raw* observations, rather than interpretations of their observations.

For example, when trying to determine whether a component was exposed to fire or smoke prior to or subsequent to fracture, one of the pertinent facts would be sooting of the fracture faces. However, since these fracture faces had been exposed to salt water and then air for several months prior to the investigators' observations, the task became much more difficult. Merely by visually inspecting a fracture, the investigator would not be able to discern between soot and corrosion. While a clean fracture face would clearly not be sooted, a blackened face could be either. The observation would most accurately be recorded as "blackened", not "sooted" or "corroded." An investigator recording "sooted", when in fact the face was corroded, could lead to incorrect analysis, conclusions and understanding of the accident. In the worst case, this could hinder or deny prevention of future accidents. Thus, it becomes important to have a database category that requires the investigator to record the condition of the piece in the rawest possible form, not his or her field analysis of the reason for that condition. In some applications, use of high-resolution photography may avoid some pitfalls of using a textual description. If so, the database will either have to be technologically sophisticated enough to actually include the photographs as data, or a database field will be necessary to link photographs with parts.

In a large-scale investigation, there may be several investigators working in shifts performing the same task. In this case, both the database itself and the procedures for entering information must be designed to ensure standardization of the data entered. If, for example, a data field exists to record a location, the database should specify exactly what parameter should be recorded. Otherwise, one group of investigators may record latitude and longitude while another records distance from a reference point. A well-designed database will not only prevent entry of improperly formatted data, but will prompt the investigator to enter the proper information.

Even assuming the database is well designed in terms of the parameters or categories, there are additional potential problem areas. Much of the population subscribes to the tenet that "computer generated," necessarily means "accurate and complete." This mindset is so well entrenched that it is virtually impossible to defeat, even when the flaws of the analysis are readily detectable. Unfortunately, those who have experience with computer generated data are also well acquainted with the phrase "garbage in, garbage out" (GIGO). What appears to be inconsistency in data that requires a new hypothesis or further study may simply be an error in the way data was entered or retrieved. In cases such as this, it is the medium itself that creates the communication barrier via the potential to misrepresent or completely obscure the truth behind the cloak of "computer generated." Errors, with their *appearance* of accuracy, may become more acute as the information moves further from the source, up the organizational hierarchy from technical personnel to senior management levels.

Finally, there is the issue of software compatibility. Different parties will frequently have different software suites, which downgrades or prevents cross utilization and communication. Such incompatibility can affect the investigators' efforts to utilize other databases and other applications, including word processing and plotting programs. Furthermore, even if one software company succeeds in completely taking over the industry, there is the question of version compatibility. Often, but not always, newer versions of a particular program will be able to utilize files generated by a previous version. Problems arise more frequently when the reverse is the case; the file was created by the newer software version, and cannot be read by the older version. When compatibility is not addressed and assured, regardless of the reason, communication is crippled.

The lessons to be learned here are few, but they are vitally important, and can all be summed up in the recurring message of "plan ahead." The well-designed database should be comprised of a sufficient quantity of parameters or categories to fully contain and describe the subject of interest. These parameters must be clearly defined in order to ensure that the entries are correct and factual. Hardware and software compatibility should be assured to the extent possible. Finally, efforts must be made to bring the liveware into the loop early, and educate them as to the specifics and nuances of the data collection activity.

"Clearly defined" can be thought of as the optimum balance between an over-specified category and an under-specified one. If in doubt, it is usually better to over-specify, but keep in mind this will generally necessitate a greater number of parameters. A simplified example of this could be the parameter "size". In the under-specified case, the data collector input values of length, but what was really intended and required was volume. In the over specified case, "volume" could be a derived parameter by collecting the dimensions of height, width, and length.

Unfortunately, the failures of the parameter list are often not recognized until the database is being used for analysis purposes. Frequently, the needed data has been irretrievably lost. Thus, the requirement for a well thought out parameter list is crucial. Even if it costs extra days in the field, gathering too much information is almost always superior to not obtaining enough.

Ideally, the entries supplied in the database will be congruent with the information expected by the designer(s) of the database, and satisfy the requirements of the investigation. A good example of this is an underwater wreckage recovery database. Such a database might be thought of as simply a means to account for what parts have been recovered. In this case, it might only be necessary to record a part number and a yes/no value for "recovered." However, if the intent is to create a wreckage diagram, a new set of variables comes into play. Just as on land, the exact location of each piece must be logged. For the underwater recovery effort, though, limitations on the process may preclude recording the exact location. The best data available may be only an approximation of the position of the piece based on the position of a recovery vessel. Thus, a measure of uncertainty may become a critical parameter to be determined and recorded for each piece. That degree of uncertainty must be communicated to those in charge of the investigation. Even with this limitation, though, if the officials in charge of the recovery coordinate their efforts with the investigators, the utility of the data that *can* be obtained can be maximized.

For underwater recovery, the individuals managing the investigation must keep in mind that the personnel doing the actual recovery are experts in salvage, not in aircraft part identification. Since it will be impractical to have an "airplane person" work with every diver, an alternate means of identifying pieces must be employed, and the database design must include parameters to track that information. A photograph, or a diver's description, subsequently interpreted and modified by an accident investigator, may need to be incorporated into the database. Hundreds of hours of videotapes taken during the recovery effort may need to be indexed and cross-referenced with recovered parts to aid in detailing the initial wreckage distribution. Clearly, these requirements add to the complexity of the database.

Additionally, the time of recovery may be more than just an item of passing interest. The sea floor is a dynamic environment. When used in combination with known ocean currents, the time of recovery may prove to be a vital element in deriving initial impact location. In general, the investigators must decide in advance what information *should* be obtained. The capabilities and limitations of the recovery effort must be evaluated, and the recovery effort must be tailored to maximize the obtainable information.

Databases are compendiums that are typically assumed to contain factual, as opposed to analytical, information. The database "facts" are used to conduct the analysis. There is the

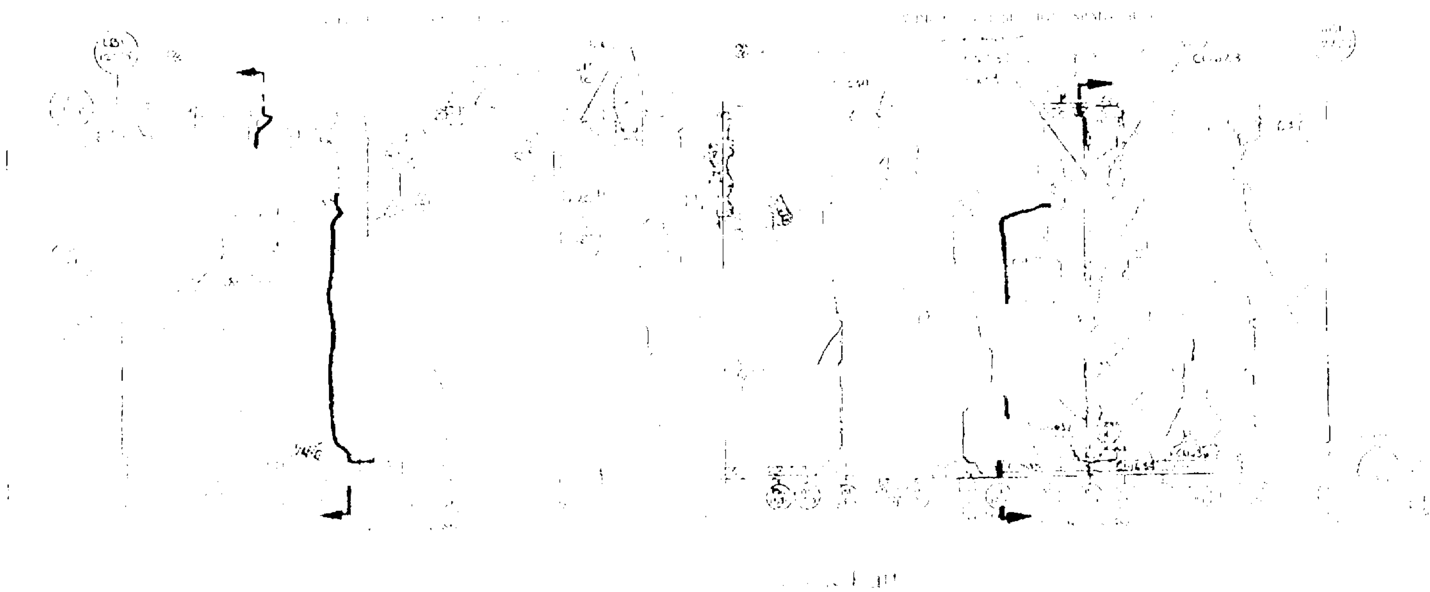


Figure 2-1

SUBMISSION OF THE

AIR LINE PILOTS ASSOCIATION

TO THE

NATIONAL TRANSPORTATION SAFETY BOARD

REGARDING THE ACCIDENT INVOLVING

# TRANS WORLD AIRLINES FLIGHT 800

OFF LONG ISLAND, NEW YORK

ON JULY 17, 1996