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Editorial and Business Office:
c/o Editor, ISASI forum
4507 Wakefield Drive
Annandale, VA 22003
(703) 978-2944

CHANGE OF ADDRESS:

isasi
West Building, Room 259
Washington National Airport
Washington, DC 20001
U.S.A.

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The 1980 International Seminar of the
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Mail to:
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At the time of his retirement in 1979 he was the Deputy Director of the Bureau of Accident Investigation of the United States National Transportation Safety Board. Mr. Bruggink has published numerous technical papers on accident investigation, passing on to other investigators his great wealth of understanding of the process of investigation and of the lessons learned through investigation that have made air transportation safer for all members of the public.

The Australian Air Safety Incident Reporting System

G. V. Hughes
10 Rhodes Drive
Victoria, Australia Glenwaverly 3150

The Australian Air Safety Incident Reporting System is possibly unique, in that it is basically a mandatory system. It is administered by the Air Safety Investigation Branch of the Department of Transport. Currently, some 6000 reports are received each year and each one is examined by a professional air safety investigator.

The majority of our incident reports concern General Aviation operations. Over the past three years, for example, our records comprise 71 per cent involving General Aviation aircraft, 21 per cent Airline aircraft, and 8 per cent in other categories such as gliding and sport aviation.

A broad breakdown of factors shows that about 50 per cent of reported incidents are found to involve personnel factors, 35 per cent aircraft factors, and 30 per cent other factors. Obviously, on many occasions, a report contains factors relating to more than one of these areas.

Background

It is first necessary to place the Air Safety Incident Reporting system into its proper perspective. It is only one of several safety performance monitoring systems which the Secretary to the Department of Transport administers in discharging his statutory responsibilities for the safe, orderly and expeditious operation of civil aircraft in Australia and Australian aircraft outside Australia. Other complementary systems are the Accident Notification and Investigation system, the Major Defect Reporting and Investigation system and the

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Further, the Australian aviation safety monitoring systems are concerned with what happens both in Australia and in other countries. Allied with the function of operating our Incident Reporting system is liaison with overseas aviation authorities for the exchange of safety information, such as accident/incident investigation reports, safety studies and aviation safety recommendations. Information received is carefully examined for its relevance to the Australian aviation environment.

Objectives

It is important for any safety monitoring system to have a clearly defined and properly expressed objective. In the case of the Air Safety Incident Reporting system, its fundamental purpose is to establish the circumstances, the sequence of events, and the contributory factors leading to any occurrence prejudicial to air safety and to use that data as the basis for an effective accident prevention program. This objective acknowledges the concept that any circumstances which come together to cause an aircraft accident will almost certainly have occurred previously, perhaps many times, and that these circumstances are capable of being identified and remedied, given a suitable organisation and the means for doing so.

What is Reported

The question as to what is to be reported is sometimes misunderstood by the aviation industry, possibly because the word "incident" has, unfortunately, come to be associated by the industry with errors, mistakes or misdemeanours. This has the undesirable effect of reducing the number of reports submitted. Currently, our Air Navigation Regulations define certain specific occurrences as incidents requiring mandatory report. The guidance material in the Aeronautical Information Publication, however, encourages the use of a much broader interpretation. For practical purposes, the system advocates and accepts any occurrence or circumstance which anyone in the industry believes to be undesirable or hazardous.

The obligation to report incidents rests not only with pilots but also with aircraft owners, operators and air traffic control personnel. It is not unusual therefore to receive reports in respect of a specific incident from more than one source throughout the industry.

How an Incident Report Is Lodged

There is no exclusive method for notifying an incident. The Department has long held the view that the notification process must be kept simple, so that potential users of the system are not discouraged by complex procedures. A form, well known throughout the industry as " 225", which has been around, deliberately largely unchanged, for over 25 years is one means of notification. This form covers such items as location, date and time, aircraft type and registration, pilots name, owner/operator, flight conditions, type of operation and route, and provides space for the originator to set down a narrative account of the circumstances of the incident. The use of the form is not mandatory and it is quite usual and acceptable for reports to be made by letter.

The primary method of submitting an incident report is to lodge it at any Departmental unit or office, either personally or by post. Additionally, some operators have arranged for reports to be lodged through their internal systems for onforwarding. This arrangement is accepted in the interest of keeping the reporting system simple. It is emphasized, however, that the direct reporting method is the primary one and is available to all in the industry.

The Central Office of the Air Safety Investigation Branch is currently located at Melbourne but it is likely to be transferred to Canberra in the next year or two. Additionally, Regional Branches are located at Perth, Adelaide, Brisbane, Sydney and Melbourne. An air safety investigator is rostered 24 hours a day, 7 days a week in each Region and in Central Office to process notifications and to initiate investigations of accidents and incidents. All notifications are referred in the first instance to the Region of occurrence, where they are examined by experienced investigators.

Air safety investigators are employed solely on air safety investigation work and are quite distinct from, and have no responsibility in, the regulatory and surveillance areas of the Department. Similarly, the Assistant Secretary, Air Safety Investigation, reports directly to the Secretary to the Department and is independent from the rest of the management structure.

The regional investigator determines the scope of the investigation to be made in each instance. He has access to all of the material and documentary evidence affecting the aircraft at the time of the occurrence. The first step is to ascertain the facts and the circumstances. Until this is done, the impact of the occurrence on safety cannot be properly assessed. In some cases, the initial notification provides all of the necessary information; but 30 years experience with the system has shown that this tends to be the exception rather than the rule. To some extent this is because the notification procedures have deliberately been kept simple and can be discharged by the provision of only basic information. However, it also occurs because, mostly, there are two sides to the story and the originator of the report is familiar with only one.

Follow-up action to obtain elaboration of the report presents no difficulty, because the notification procedures call for the originator to be identified. In many cases, a telephone call to him will obtain all of the information required. On the other hand, the investigation of an incident may become a very complex affair involving interviews with pilots and other personnel, specialist technical examinations, examination of flight recorders and communications recordings and much investigative probing in order to establish all the facts and circumstances surrounding the occurrence. Anonymous reports are accepted into the system but very few are received. They are investigated as far as possible but such investigations are severely inhibited by the inability to obtain follow-up information.

Acknowledgement of Reports

The notification form provides for the originator to indicate that he wishes to have an acknowledgement of his report. In such circumstances, receipt of the report is acknowledged and the originator is informed of the results of the investigation when it is completed. Irrespective of whether or not the originator indicates his desire for acknowledgement of a report, consideration is always given to the question of advising the results of an investigation and any remedial action being taken. The decision as to whether such advice is despatched has regard to the nature of the report, but it is provided in all instances where the circumstances described suggest the need for a reply, where it is in the interests of encouraging reporting, is good public relations or where it has educational value.

Remedial Action Arising from Incident Investigation

Once the facts are obtained, the Investigator assesses the occurrence for its safety hazard potential. If remedial action is to be recommended, the matter is referred to the appropriate regulatory area as soon as the need to do so is identified. Recommendations for remedial action are made as the need becomes apparent and do not await the conclusion of the investigation.

All investigation reports, on completion, are forwarded to the Department's Central Office where the investigation and the remedial recommendations are reviewed against the background of national experience and available international information. Experience indicates that, while individual investigations in some instances lead to remedial action, this is the exception rather than the rule. A productive source of information for safety promotion is more likely to come from analysis of occurrences as a group, particularly where the groups have common features about circumstances leading to the occurrences. To provide for this process, all factual data from Incident Reports is recorded in a comprehensive, especially developed computer-based statistical system located in the Department's Central Office. This statistical system is the same one which is used for storage of data from accident investigation.

Irrespective of whether a recommendation is derived from an individual investigation or from analysis of a large number of occurrences, it is, in the first instance, directed to the area within the Department with the functional responsibility for the particular aspect of aviation operations. The resultant remedial action may take the form of a procedural amendment, an information circular, a directive or some similar action. Additional benefit from the investigation arises when it is possible to convey the lessons learnt from the investigation directly to those in the industry with a responsiblity for the safe operation of aircraft. For this purpose the Department publishes the Aviation Safety Digest, an periodical with which some of you may be familiar.

Effectiveness of the System

In establishing the incident reporting system in the first place, the Department was conscious that, for it to be fully effective, industry cooperation was essential, so that all occurrences with a possible impact upon aviation safety would be reported. In discussing this general theme through the Aviation Safety Digest in 1960, a policy was declared that, to ensure optimum reporting, no punitive measures would be imposed by the Department upon the originator of an incident report for any of his actions in an incident which is brought to notice only by his submission of such a report. This declaration did not imply that the report would not be investigated to establish the facts and circumstances of the occurrence. Clearly, such investigation is essential in order to enable a proper consideration to be made of the need for remedial action. The only exception to this policy is where the investigation reveals beyond doubt that persons or property were exposed to danger because of either a contemptuous disregard of the law or a dereliction of duty amounting to culpable negligence.

These "immunity provisons", as they came to be known, were repeated in the Aviation Safety Digest in 1968, and were extended in 1972 to cover pilots calling for assistance from the ground organisation when encountering navigational or other difficulties.

Notwithstanding the measures described above, it is valid to ask how many occurrences still remain unreported? There are no means of establishing precise figures for this. The simple wide-ranging notification system is such that it is unlikely that occurrences which are known to several people remain unreported. In particular, there is reason to believe that the Department hears about the occurrences where one component of the industry is critical of the performance of another. There is also reason to believe that the Department hears about most of the comments and criticisms on its facilities, standards, procedures and practices. These types of reports are particularly valuable as they are often based upon the considered experience of senior members of the industry.

Yet, clearly, there are reports which affect safety, probably directly, which are not presently brought to notice through the incident reporting system. One reason for this is believed to be that the pilot fraternity often shows a reluctance to put pen to paper about a safety issue after a flight has been successfully concluded, though at the time the pilot felt concern. Another is believed to be the natural reluctance of people to reveal occurrences which they feel could be interpreted by their peer groups as showing inadequate or unacceptable performance. A further one could be that, despite all the assurances given by the Department in the form of immunity provisions, there is no such constraint on an employer if he sees the occurrence as a transgression of a company operating practice or procedure.

In the course of accident and incident investigation and through the Aviation Safety Digest, the Department has been encouraging the industry to report occurrences, emphasising the accident prevention aspect of the total system as well as the immunity provisions. Within the Department, officers with regulatory responsibilities are provided with guidance to ensure that the role of the incident reporting system is property understood. Generally, the industry has responded well, which is pleasing in,itself and indicative of the overall faith there is in the system.

Further Developments

What is to be the future of the system? In the first place, it is to make effective use of all of the data available in the system on the circumstances leading to incidents and accidents and, in so doing, to come closer to the prime objective of the system — the prevention of aircraft accidents. In the second place, it is to increase the feedback to the industry of the information available in the system and to encourage the industry's use of the information so that maximum benefit can be derived by all concerned.

There has already been substantial movement in these two directions. In respect of the first, a computerised accident/incident data recording system has been developed. Additionally, arrangements have been made for the exchange of information regarding accidents with the United States, Federal Republic of Germany, New Zealand and Papua New Guinea. Australia also participates in the ADREP system, developed by ICAO on behalf of its member States for recording accident/incident data on large aircraft.

By the abovementioned measures, Australia has access to a great amount of data on aviation safety occurrences throughout the world. At the present time the records in our system stand at over 50,000 accidents world-wide, together with over 60,000 Australian incidents. To use this large amount of information the Department has developed computer based extraction and analysis programmes and is experimenting with new methodology, aimed at correlating accident/incident factors and having accident prediction ability, thereby pointing up "soft areas". These analyses were made regularly and the results are circulated widely within the Department and to other organisations in the industry with an interest in aviation safety. Additionally, special analyses are made from time to time in response to specific enquiries about the history of safety issues in Australia and overseas. The information derived from these special analyses is examined, in conjunction with the information available from other sources, in the process of determining the need for revising policies and standards in a wide range of the areas for which the Department has a responsibility for safety matters.

The foregoing leads to one final comment. Any air safety incident reporting system is only as good as the information in it is complete. If the system does not reveal that a specific problem has a history, then that problem is much less likely to be drawn to attention through an analysis than one which has a history.

A Low Cost Constraint-Based Incident Reporting System

Richard C. Bartel M02062
Human Factors Engineer
Box 153, Station H
Montreal, PQ, Canada H3G 2K7

Introduction

The question as to what is and what is not an "incident" has been the subject of considerable debate and the source of serious problems in the reliability of current incident reporting systems. Generally this question has been left to the interpretation of an administrative unit which collects reports; there is evidence that, as a result, the threshold criteria for an "incident" have been more sensitive to the immediate administrative workload and biases of the report receiver than to the actual criticality of the event.

In addition the scope of current incident reporting systems has generally been limited to flight operations (takeoff, departure, enroute, approach, and landing) without regard to those activities occurring before and after flight which may "predispose" the actual activity (flight) to certain sequences or combinations of events which, as a whole, become a hazard to flight safety.

Therefore in this paper I hope to suggest an incident reporting system which is sensitive to criticality and has sufficient scope to identify the activity elements which "predispose" a flight to critical events. At the same time it is hoped that the proposed system will assist in the continuous and iterative modification of activity constraints (deletion, change of level, modification, addition), as well as serving as an instrument to assess the impact of such changes.

The Constraint Base

The basic contention of this proposed system is that the constraints of an activity, other than "common sense", are sufficient in scope to address and index almost every operating procedure, recommended practice, regulation, statute (law), advisory, or other prescribed element. It is generally believed that some if not most activity constraints may exceed their most effective scope and depth. This is evidenced by the recent debate between "deregulation" and "regulatory reform."

In aviation the constraints take many overlapping forms. These include legislative acts, implementing regulations and orders, and recommended practices and advisories. Within industrial organizations these levels are identified by bylaws, operating procedures, internal directives, and other forms of recommended practice. In almost every case the prescription of such constraints, whether in government or industry, are identified numerically or in some other indexed manner. Generally each subdivision and division of such indicies is addressed to (and originally generated by a specific problem in) a standard or operational/procedural activity.

The incident reporting system proposed by this paper is designed with existing constraint indicies as the "backbone" and central variable for analysis. Since many other administrative, enforcement, and statistical data are related to the indexed constraints of an activity, the data acquired from this incident system can be effectively and appropriately utilized for decision making throughout all levels, from administration to customer (passenger, participant).

The Reports

It is essential to the validity of this proposed system that reports be simple, effortless, easy to mail, and be available throughout the activity (i.e., airports, schools, ATC facilities, government offices, etc.).

In order to achieve simplicity, ease of completion, and ease of analysis it is suggested that a post-paid single-page card be supplied for data entry. The card and entries should be processable by computer without significant preparation. A standard computer card, which contains columns for coded information, would be ideal; however, any format which increases simplicity and readability would suffice. The data field of the proposed system should contain at least:

a) Status of the Observer/Reporter
e.g., Pilot, Flight Engineer, Maintenance Technician, Air Traffic Controller, Dispatcher, Designated Examiner, Engineer, Airport personnel, Avionics repairman, operator management, Test Pilot, Dealer, Analyst, Investigator, etc.

b) Date of Event

c) Time of Event (GMT)

d) Location of Event
i.e., Coded from location identifiers directory to nearest coded fix or airport. (Example KDCA).

e) Altitude of Event (if applicable)

f) Constraint Identification (Level)
i.e., related Statute, Regulation, etc. coded, for example as follows:

1. Inviolatable Constraint — Statute of Law — Bylaw

2. Implementing Constraint — Regulation or Operating Specification
3. Recommended Constraint — Advisory or Recommended Practice
4. "Operating Practice" — not prescribed but traditional

Specific implementing documents could be coded here such as Air Navigation Orders, Advisory Circulars, internal "Orders", etc., tailored to the activity scope.

g) Constraint Identification (Specific)
FAR 91.170(a) would simply be coded "091.170.a", or ORDER 8110.65, para. 201 would simply be coded "8110.65.201". The procedure of a specific operator would be identified by Operator, Manual, and paragraph.

h) Criticality of Event:
This item should be coded as follows:

1. Unusual or abnormal event which has been or could be related to the sequence of events leading to an accident or incident but generally would be considered a nuisance;
2. An event which could have led to damage or injury had not specific action been taken;
3. An event which was involved by itself or as part of a sequence of events leading to damage or injury not classified as an accident;
4. An event which was involved by itself or as a part of a sequence of events leading to an accident;
5. An event which led directly to an accident and without which the accident would not have occurred.

Other scales could be devised; however, it is essential that once a scale is established the criteria not be significantly changed.

i) Suggested remedy:

1. modification or change of specified constraint;
2. deletion of specified constraint;
3. addition of a constraint (a second digit here could relate to a suggested level of constraint addition from codes in item f and/or g);
4. no constraint change suggested, however specific training or education could have enhanced the human judgment involved;
5. change of a constraint from one level to another (see f) (again second digit could refer to appropriate level);
6. remedy exists outside constraint system, such as management practices and attitudes, and failures where no performance standard could have predicted or prevented the occurrence;
7. enforcement of constraint.

Other data fields could be included such as aircraft identification by type (if applicable), equipment make/model, or applicability of other standards such as SAE and ANSI, or ISO. In addition a random code could be entered by the reporter so as to facilitate easy retrieval at the reporter's option. Optional information such as a telephone number for additional information, etc., could be included.

Sample Report

For sample purposes suppose that an aircraft incident occurs on February 15, 1980 at 0230 involving an air taxi pilot who falls asleep at the controls due to long flight or duty hours and loses control until awakening and recovering the aircraft at 2000 feet. The incident could be reported by the pilot in the following format:

1/2-15-80/0230/KJST/5000/2/135.0261.a/2/7

a/ b / c / d / e /f/ g /h/ i

The pilot has identified his status (pilot), the date (2-15-80), time (0230), location (i.e., Johnstown, PA. USA), altitude (5000), constraint level (Regulation), constraint (14 CFR 135.261(a)), criticality (could have led to damage or injury had not action been taken), and suggested remedy (enforcement of flight and duty time limitations).

A second sample follows: Suppose that an electric servoed altimeter (non-reverting) is found to have failed in flight under IFR without displaying a warning flag (voltage was between 4 and 16 volts). As a result the aircraft slowly descends below the assigned altitude and experienced a near miss with another aircraft at 4,200 feet on May 3, 1980 at 3:55 pm near the EXPOS intersection, Canada. Such a report, filed by a flight engineer, would be simply as follows:

2/5-3-80/1555/EXPOS/5000/2/037.0120/2/1

The engineer has identified his status (flight engineer), the date (5-3-80), time (1555), location (EXPOS, from standard location codes), altitude (5000, at which the primary event occurred), level of applicable constraint (Regulation), Specific constraint (altimeter TSO, FAR 37.120), criticality (an event which could have led to damage or injury had not action been taken), and suggested remedy (modify TSO to assure reliable operation of electrically servoed non-reverting altimeters).

Additional data could be incorporated into the reports if a field of 72 columns per report card are fully utilized.

The samples utilized above involve actual flight operations; however, it can easily be seen that such reports could be extended to quality control in manufacturing, air traffic control equipment and procedures, operator practices, and the activities of regulatory or service agencies simply by reference to the appropriate level of constraint and its index.

Use and Correlation of Incident Data

This proposed system is designed to identify areas for further study by government or industry administrators. Once specific constraints have been identified by the system as related to incidents thought to be critical to the safety of flight, administrators have several options to narrow in on specific remedies.

First, managers could devise a more detailed incident system (independent of the overall system) which has a scope of indicies limited to the areas(s) previously identified. For example, if the basic system identifies problems in the area of automated ATC traffic systems, the manager could index the equipment and operational characteristics of the automated systems involved, narrowing the sensitivity of the reports to useful details.

Second, specific suggested changes could be solicited from the public pertaining to specific constraints which have been identified as problem areas by the basic incident system. For example, if the basic system is receiving significant reports concerning failures of repair work by mechanics, then a review of FAR 43.13 may be appropriate.

It is hoped that management will identify those areas where the deletion of a constraint may improve flight safety, as well as identifying where change or modification would be beneficial. This system is designed to make such identification and decision-making a continuous process of assessment, change, and re-assessment of the consequences of change.

Correlations of incident data will serve to identify specific problem areas. For example, one could sort incidents by criticality, location, and/or any other criteria or combination thereof. The selection of correlates and sequence of sorting would be critical to the implications derived therefrom. The first sorts should be those of the most important factors relating to the decision(s) sought.

Within air traffic control a sort by location (fix) and/or altitude could indicate a need for re-evaluation of procedures or route structures. Incidents could be normalized to traffic statistics for a further clarification of occurrence rates.

Within flight operations a sorting by rule or procedure can be correlated with criticality and location so as to identify problems which may be specific to one area, district, region, or state. Management could compare incidents and traffic statistics at specific airports to identify local problems and compare rates with other aerodromes after normalization.

In addition to identifying and narrowing-in on problem areas it is suggested that this system, after establishing historical trends, can be utilized to assess the impacts on safety of changes to operational procedure or other constraints. If a change in procedure or rule does not result in a favorable change in incidence rates (over a period of time), then it is likely that the change was futile or that the constraint itself has little or no effect on enhancing flight safety (and therefore should be eliminated or changed further). Where a constraint and the various changes thereto cannot show an enhancement in safety (lower incidence rates) management should opt for deletion. If deletion does not result in higher incidence rates then management has taken an important step in eliminating unnecessary or ineffective constraints.

It is my opinion that continuous publication of correlated compilations of reports can in itself act to serve as an advisory and enhance awareness and therefore safety overall. In addition such compilations on a periodic basis can serve to set priorities for enforcement of those rules which have been shown to be appropriate and effective.

The Investigator's Role

An accident investigators we all are aware that the line between a critical incident and an accident may be a matter of chance in some cases. However the data collected from accidents can be useful in accident prevention, even though it may be only a limited view of critical activity. We must acknowledge that critical events do occur in "accident-free" operations, and that this data is just as important to the development of accident prevention methods as that collected under official circumstances.

As investigators we have dedicated ourselves to "promote that part of the aeronautical endeavor wherein lies the moral obligation of the Air Safety Investigator to the public." One contribution we can make, in my estimation, is the active encouragement of incident reporting by making the process open to everyone involved, assuring that the reports are simple and easy to submit, and assuring that the scope of any reporting system is as broad as possible. A narrow scope can only serve to bias efforts with ineffective or inappropriate remedies, and can become the instrument of political manipulation. Such problems could only serve to discredit any accident prevention efforts.

In addition to actively supporting incident reporting the investigator should submit individual reports whenever possible. If an incident report is submitted which relates to an accident investigation, the incident report should be submitted *after* the investigation is completed. If a series of incidents are involved in an accident sequence, then each event should be reported separately with the appropriate criticality code.

Summary

I believe that the proposed incident reporting system is simple, low cost, expanded in scope, and is indexed to one of the very systems to which reform is addressed. This proposal places the judgment of criticality in the hands of those most directly involved in and affected by the hazards. This should serve to determine the appropriateness of an activity's constraints, improving those with demonstrated effectiveness and eliminating those with demonstrated ineffectiveness or no effect.

Management should benefit directly by increased confidence in accident prevention efforts derived from incident data and the availability of an instrument to test the effectiveness of prevention efforts and regulatory change. In addition the system could be applied selectively in identified problem areas to further define necessary corrective action, particularly within complex activities.

INCIDENT ANALYSIS AS A KEY TO ACCIDENT PREVENTION

John B. Galipault
Aviation Safety Institute
P. O. Box 304
Worthington, Ohio 43085

and

Ira J. Rimson, P.E. *M00851*
System Safety Associates Ltd.
P. O. Box 1015
Springfield, Virginia 22151

At each of the past two ISASI seminars we have been reminded of continuing patterns of recurrence of aircraft accidents.(1,2) Both Captain McDonald and Professor Parker stressed the fact that accident investigations, even when determining causes with accuracy, have had little effect on prevention. There is simply no meaningful process for implementing the corrective actions which are obvious from the lessons we should have learned. The current relationship between accident investigation and accident prevention reminds me of a comment made to me a few years ago by a prominent aviation litigation attorney: "I don't know a thing about how to design an aircraft; but after several hundred lawsuits I can tell you a hell of a lot about how *not* to design one."

His point should form the conceptual basis for anyone who plans to take a stand for accident prevention. The cheapest insurance you can find is the lesson you learn from someone else's mistake. It's free, it's usually accurate and it's realistic. The reason the concept has not been widely accepted is that, to do so, most people would have to change their attitude that accidents are unique events — departures from "normal" situations.

Flying has been characterized for many years as "hours and hours of boredom punctuated by moments of stark terror." As a result, we believe that the "moments of stark terror" have come to be accepted as a routine part of normal operations, and the dividing line between "normal" and "abnormal" is the occurrence of an accident. This "anything-short-of-an-accident-is-O.K." attitude is nurtured by such quasi-official bodies as the National Safety Council when it publicizes the motto: "Safety is No Accident." Gerry Bruggink identified the fallacy of that saying by translating it into the equation: "Safety = No Accident."(3) However, equations must retain their validity when transposed; or, "Safety = No Accident" should be identical to "No Accident = Safety". We all know that is absolutely untrue.

I think everyone here is aware of the three major forms of untruth — lies, damned lies and statistics. Statisticians have contributed greatly to the current oversimplification of safety data. Zero equals zero, and despite exposure rates there is no statistical difference between not having one accident and not having a hundred. As a result of current practices in data reduction and analysis, aviation industry groups indulge in congratulatory backpatting by citing the relative safety of air operations in comparison with other modes of transportation. However, if we compared aviation's safety record as it is, against an aviation safety record as it could have been had we taken action against known potential accident cause factors, our record would appear sorry indeed.

McDonald and Parker spoke of lessons learned and ignored from accidents. Today we would like to address a cheaper source of learning — aircraft incidents and aviation system errors. We say cheaper because, by definition, the consequences of incidents and errors are far less costly both to the vehicles and the human participants involved than are the consequences of accidents. In fact, most incidents and errors cost nothing except for the damaged pride and confidence of the participants. That may be a clue to why incidents and errors are rarely reported, and receive so little attention when they are.

If we are truly interested in accident prevention we must first accept that an incident or system error is not merely one of the acceptable "moments of stark terror," but is an event which could have caused an accident and didn't. In one way or another the chain of events leading to the accident was broken. If we examine an incident or series of incidents under that concept, they can afford us the opportunity to discover why accidents *don't* happen as well as identifying potential breakdowns within the routine process which can facilitate accidental occurrences. Let me cite a recent example with which most of you are probably aware: On April 5, 1979, a TWA B727 was cruising at 39,000 feet when suddenly, and without warning, it departed balanced flight. The aircraft rolled into a tight diving spiral from which the crew finally managed to regain control — at 5000 feet. Airspeed during the dive approached 500 knots with a rate of descent in excess of 20,000 feet-per-minute. Investigators from the National Transportation Safety Board (NTSB) subsequently determined that the most probable cause of this potentially catastrophic event was the extension of the #7 leading edge slat on the right wing. During the descent the slat broke off because of excessive air loads, which probably was the reason the crew was able to recover. The NTSB Investigator-in-Charge has been quoted publicly as believing that recurrence of the event is unlikely because "...we can't find...any way to get it (the slat) out there without at least a double failure of some sort, unless it was deliberately extended."(4) Curiously enough he did admit that a similar slat extension occurred in late 1978 aboard an Eastern Air Lines B727 cruising at 25,000 feet. However, that occurrence has been attributed by the NTSB to "pilot error."

It is now almost six months since the TWA incident and neither the NTSB nor the FAA has publicized any facts which could be used by B727 operators to prevent a recurrence. Various bits and pieces of information have, of course, been released to the press and an enterprising safety analyst could develop guidance from the news releases. What has *not* been publicized, except by the little-known Aviation Safety Institute, is that the NTSB's investigation failed to probe deeply enough to discover that the B727 has had a history of reported slat malfunctions significantly more prevalent than any other air carrier transport aircraft. ASI extracted data from the FAA's Service Difficulty Report files for an exemplary two-year period which revealed 59 reported slat malfunctions for the B727. The next-most-frequent was the B707 with nineteen. Least frequent were the B737 and the DC-9 with four reports each. Weighted by hours flown per model aircraft, the B727 retained its lead with a frequency of 1.5/100,000 flight hours, half-again more frequent than the B707 at 1.1/100,000 flight hours and almost an order-of-magnitude more frequent than the DC-9's 2/million flight hours. We wonder if the NTSB's Investigator-in-Charge was aware of these data when he expressed such strong disbelief in the likelihood of recurrence.

Researching the incident data base sometimes reveals unexpected information. For instance, while researching the FAA's SDR data for reports relating to engine mounts (ATA Code 7120) subsequent to the Chicago DC-10 accident in May, we discovered that the DC-9 had suffered engine mount cracks or failures six times more frequently than any other air carrier transport (weighted for exposure). Two reports, both dealing with aircraft having about 20,000 flight hours (and both operated by the same carrier) were almost identical: "During walk-around inspection, noted left engine drooping. Found aft mount broken. Failure attributed to fatigue."(5) We wonder if the supervisors at the FAA Data Center in Oklahoma City ever bothered to pass this knowledge along to DC-9 operators for use in adding a special note to their inspection procedures.

With the exception of the air carriers' in-house reporting and publication procedures, U.S. civil aviation has shown little interest either in reporting or analyzing incidents. The Flight Safety Foundation routinely publishes a monthly periodical, *Flight Safety Facts and Reports,* which includes about a dozen selected accident and incident briefs in each of five general areas: Air Carrier, Air Taxi/Commuter, Corporate/Executive, Rotorcraft, and Other General Aviation. Distribution is limited to subscribers. The populous general aviation community is probably the group most needful of help, and the most ignored. The only avenues of communication available are through the manufacturer (who has always been loath to publicize any problems with his product) or through the FAA Service Difficulty Report system (to which reporting is not mandatory, and from which data is made available only on demand). The FAA's excellent publication, *Inspection Notes,* was cancelled several years ago, apparently because its continuation was not considered "cost-effective" by the deskbound bureaucracy.

Thus far we have examined incident and error analyses only in relation to mechanical problems. If we attempt to analyze the human factors implications we must face two major problem areas: first, the inherent reluctance of people to admit their errors; and second, the lack of a suitable forum for encouraging such admissions, filtering them to prevent retribution against the reporters, and finally extracting and publicizing the information which would be significant in an accident prevention program. The military services have had success in motivating human factors reporting by dealing with the *mea culpa* issue as a matter of professional integrity, and the retribution issue by administrative regulation. Unfortunately their attempt at publicizing relevant prevention information to the field operators has been less complete than it might be. Both the Army and the Air Force feed back less than half the information received. The Navy, having cancelled its excellent *Crossfeed* series of analytical publications (ostensibly because of inadequate funding) currently has no routine feedback system whatever.

I suspect that many of you do not know that an independent, anonymous reporting system has been in effect within the United States for almost seven years, devoted to collecting, analyzing and communicating incident and error information for the purpose of accident prevention. Nearly four years before the FAA and NASA began their collaboration in the Aviation Safety Reporting System, the Aviation Safety Institute was in operation accomplishing similar tasks. ASI has identified more than 35,000 specific hazards as a result of reports by pilots, controllers, passengers, mechanics, cabin attendants and dispatchers. As a direct result of its follow-up efforts, ASI has influenced resolution of about 2% of these hazards. However, by making its information available to any and all users it has enabled many of its participants to institute hazard avoidance procedures where hazard elimination was impractical.

ASI's system is derived from established safety theory tempered by practical experience with the aviation environment and a great deal of patience. Acknowledging that chance has a large role in determining the effectiveness of a safety program, ASI's analytic process accepts chance in the same way that pure mathematics accepts probability. Any accident may be analyzed on the basis of three parts: the error(s) leading up to it, the accident event and the severity. Most accident analyses with which we are familiar concentrate on the event and the severity, relegating the precedent errors to an historical litany which often undervalues their importance. Errors cause accidents, and very often many errors must occur before an accident can happen. Obviously if potentially critical errors can be prevented there will be far fewer accidents. Yet we do not adjust the depth of investigation according to the number and relevance of the errors. We devote the majority of our time to investigating the spectacular accidents at the expense of lesser, but potentially more productive ones. Yet accident investigations are difficult, expensive and tedious affairs. Some investigations extend for years, only to end with conjectures about "probable" causes. In many others the evidence required for accurate analyses is destroyed in the course of the accident or, worse yet, and unfortunately just as frequently, during the course of the investigation. In his book *Industrial Accident Prevention*, published more than forty years ago, H. W. Heinrich stated "...in basing accident prevention work upon the cause-analysis of major injuries alone, not only is the importance of the accidents that produce them overestimated, and the field of research thus limited, but the resulting data alone also are seriously misleading when used to determine the proper corrective action to be taken." The resources required to perform intensive investigation of accidents drain those organizations attempting to accomplish a competent job. By coming in after the fact they are in a perpetual state of trying to catch up with problems forever elusive.

The Aviation Safety Institute program is called the Error Analysis Rating System (EARS) which, by concentrating on the errors which precede an accident, we believe to be a much more potent prevention tool. The EARS concept starts with the assumption that each error carries its own level of risk — or odds that will contribute to an accident. There is a great range of odds among various kinds of errors. Two additional assumptions expand the breadth of application to the entire universe of accident causation. First, we assume that errors which may contribute to accidents can be made by anyone involved in the design, construction, use or regulation of a product. Once an error has been made it will continue to cause risk until it has been identified and corrected. Some errors may lie latent for years prior to discovery; for example, the designer who trims too much metal from a part in order to save weight. Years may pass before the part fails prior to its design lifetime. Errors may also compound with other errors, some additive, others cancelling previous effects.

The second assumption is based on our analysis of accident prevention theories. Heinrich developed a set of ratios relating accidents to injuries in which he theorized that about 0.3% of all accidents produce major injury and about 9% of all accidents produce minor injuries. The significant point is that more than 90% of accidents in no injury at all. In his theory Heinrich used only verifiable evidence of human error, which in fact had a much higher frequency of injury than machine-caused accidents. However, EARS includes all modes of error. For example, if because of ignorance or misunderstanding a pilot merely planned to fly an aircraft in a way which could have resulted in an unsafe event, ASI would include the planning error in its data base. Even though the pilot may have corrected the error before any overt act was committed, the error was real, and so the potential for accident. So we ask: What caused the error? What injury potential does this type error have? How often does this error occur? Under what conditions? What can be done to prevent it? All these questions can be answered without waiting for an accident to occur.

ASI believes that the more events which are included in a statistical data base the sounder it will be. This derives in part from a postulate that frequency is a much more valuable indicator of safety performance than severity, since chance usually plays a greater part in determining how frequently accidental injuries occur.

The difference between EARS and current systems is that a much greater range of data is considered, including greatly expanded incident reporting by crew members, controllers, maintenance personnel and, for that matter, any interested person; broader maintenance and operational data; supplemental pilot/crew interviews; field inspection of fleet and fixed-base operators; inputs from human factors research; data from in-flight recorders, and ground and in-flight simulators.

In a 1963 study by an ASI associate (then at Ohio State University) in conjunction with the Air National Guard, a compendium of errors was developed. Pilots contributed to a total of more than 300 possible errors. The research team then extracted the 40 most frequently mentioned for analysis by operational survey. Pilots reported that, on average, five of the forty errors occurred *on each flight*. The relative risk levels and interactions of these errors were rated and scored weekly, so that trends and deviations could be detected by quality control techniques. Of significance were the surprising frequency of unexpected errors uncovered by the OSU study and subsequently by the ASI Anonymous Incident Reporting System, which is still in use today. We still believe that there is no better way to determine what is really going on in the real world.

ASI's Error Analysis Rating System is based on the statistical premise that some errors will cause an accident every time; others will almost never contribute directly to an accident. By establishing relative risk levels for various aspects of error in relation to various phases of the aviation spectrum, we can provide not only a more accurate means of analyzing safety performance, but the derived data can be used as an effective predictor. Thus, if a known procedure carries a risk factor of X, you can reduce the factor to Y by instituting selected changes. By sampling various types of errors an index can be developed which provides relative risk factors for known errors, and is flexible enough to permit continuing refinement as more raw data is generated and included in the base.

In summary, the difference between a viable prevention system as currently in effect at ASI and our traditional accident investigation-based practices is in acknowledgement of Heinrich's 40-year-old dictum: "The importance of any individual accident lies in its *potential* for creating injury and not in the fact that it actually does or does not so result."

Prevent the accident, and the severity takes care of itself.

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Techniques to Improve the Effectiveness of the Capable Investigator

Dr. Ted S. Ferry CH0136
Institute of Safety and Systems Management
University of Southern California
Los Angeles, CA 90007

The maturity and wisdom of the International Society of Air Safety Investigators is apparent in this year's Seminar theme: "The Investigator's Role in Accident Prevention." While our organizational objectives may be directed at assuring the best possible aircraft accident investigation, our end goal cannot be anything but accident prevention. I present for your consideration two tried and proven techniques that can improve the accident prevention effectiveness of an accident investigator; even a very good investigator.

The greatest single improvement to be made in accident prevention, assuming a good investigation, is a systematic search to find where management has failed in allowing the accident cause factors to exist. Management here means all levels of management above first line supervision and the associated staff.

The approach calls for recognizing that all accidents and hazards are indicators of management failures, and that these failures are causing many other losses, near accidents and plain goof-ups that have not been identified as accidents. This is simply because they do not fit the accident definition. Here is a hypothesis: "In the investigation of any accident, there can always be found some degree of management involvement or activity (or lack of it) that might in some way have prevented the accident."

I ask you to arbitrarily assume that management will, in some way, be responsible for the causes of every accident as well as the existence of every hazard.

Accident investigators, by their nature, tend to be largely materialistic in their search for accident cause factors. If the investigation is broadened to include management failures, the true purpose of investigation, prevention, can be better served.

We usually seek to prevent recurrence of a cause factor involved in an accident through simple corrective action of the discrepancy. If, however, we sought the management oversights that allowed the discrepancy or fault to exist, we could prevent other discrepancies, errors, oversights, and omissions. This would not only prevent similar accidents from happening, but improve general operating efficiency with a good dollar return, making investigation a viable, profitable venture.

The main thing required in this particular line of investigation is concurrently and consistently seeking the answer to the question: "Where did management fail?" There is solid reason to believe that management failure, sometimes several management failures, exist in most every accident or incident. Uncovering the management failures that led to the cause factor offers the most potential for future prevention, and at an affordable price.

Every time we uncover an identifiable cause factor, we simply ask one question: "Where did management fail?" We keep on asking that question until it is not longer feasible to take corrective action on what we find.

Let me summarize this discussion so far with some simplified illustrations.

1. A multi-engine aircraft crashes at a critical time in the performance envelope and is largely destroyed by fire. A diligent investigation reveals that the number one engine was at little or no power, but due to the extensive fire damage, it is believed that the cause cannot be determined. In a classic case of investigative determination, one investigator cannot let loose and finally spots something mysterious about the fuel strainer. Alas it is the wrong type and he duly turn in his report with the case solved. Solved, that is until a high level safety type is reviewing the report and wonders why this thing was in the system. He was not satisfied with the cursory recommendation to be certain to use the right type of strainer. Lo and behold, he finds that the culprit had been banned and taken out of the system years ago, but had found its way back into use. At that stage, asking the question: "Where did management fail?", he not only found out where management failed, but found a way that numerous culprits could get back into the system and had indeed brought about dangerous situations in several locations, all of which could result in accidents. He also found that several aircraft similar to the one involved in the accident had the old strainer installed and were accidents just waiting to happen. True, these errant strainers, once identified, could have been found through inspection but the management factors that allowed it to happen would not have been corrected if the question had not been asked; "Where did management fail?"

2. A responsible individual is on a local carrier one night when it makes four approaches to a small airport before landing in the fog. Glad to be alive, he is determined to find out what kind of an operator would go along with this. Despite "stonewalling" at every turn, he soon finds that lax management and contradictory, unwritten policies at every level encouraged the pilots to use a maximum of personal judgement instead of the written company manual and the FAR's. Unfortunately he was not in a position to secure the

corrective action needed in the management aspects of the airline and two accident, one with many fatalities occurred. It took a complete change of management and several years before the operating procedures of the airline approached those that allow us as passengers to feel comfortable.

3. If we want to be in a position to take positive, specific corrective action as a result of an investigation, the investigator must come up with solid, specific cause factors. In a recent review of a public-interest, non-aviation accident, I waded through two and one-half inches of accident reports without finding a single specific cause factor, and as a result, not a single specific piece of corrective action. What was apparent at every turn was gross mismanagement at each level of policy, procedures, and performance. The major unanswered question was: "Where did management fail?"

Let me show you how an investigation that consistently seeks factual information on management failures improves on the usual method of investigation (See Figures 1, 2, and 3).

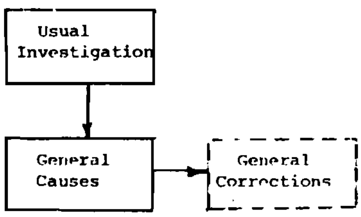

Fig. 1. The Usual Investigation

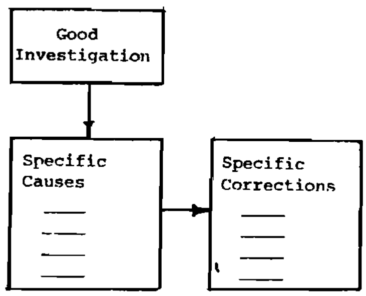

Fig. 2. The Good Investigation

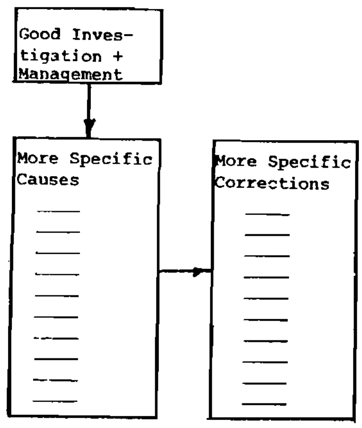

Fig. 3. The Good Investigation Plus Management Factors

At the start of this presentation, we said that the single greatest improvement of investigation techniques for accident prevention purposes involved a systematic search for failures of management. There is another way to greatly improve our investigative efficiency that will be referred to as the "multiple review system."

In spite of the fact that we pride ourselves on "dealing only in facts" during an investigation, you have probably considered that if there were another equally skilled investigation effort of the same accident there might be new or at least different facts uncovered. This is usually impossible due to constraints of resources, time, and availability of the wreckage. It would simply be too expensive and impractical. Consider, however, that we tend to see things differently even when given the same facts.

Every one of us have interviewed a series of witnesses who have seen the same event at the same time, but we have come to quite different conclusions. We know the story of the blind men feeling their way around the elephant and "seeing" everything from a snake to a barn door. We may all read the same factual account of an event in the newspaper, yet come to different conclusions based on the facts given us. When the evidence is not highly visible, as is often the case in our investigations, we come to different conclusions. Who is to say that our conclusions are better or worse than those of the next person? My point is that while it may not be practical to find more cause factors through multiple investigations, it is practical to conduct multiple investigations, it is practical to conduct multiple reviews of the investigations we do make, to uncover more cause factors and thus more accident prevention corrective actions.

We have found that given the exact same facts uncovered in the course of a good investigation, different reviewers or reviewing groups come to different conclusions and different recommendations for corrective action, all of them valid.

Over a period of seven years, I have given around one thousand safety professionals an accident situation with all the uncovered facts presented on a 27' film. They are then given a list of sixty-six types of operational errors. They choose from this list those errors that seem involved in the film. Since they operate in groups of four to six persons, there is ample opportunity for discussion on each point and they arrive at their conclusions by consensus. Never do the groups agree completely on the conclusions as to the operational errors involved. Each group usually comes up with eight to ten cause factors. With four or five groups doing this at the same time, they rarely have as much as twenty-five percent agreement, all based on exactly the same factual information. Sometimes there is no agreement at all. While that rarely happens, the groups may only agree on one out of the eight or ten cause factors each selects.

Let me repeat what happens. Through the medium of a good, well done film, we present all the facts uncovered by an investigation. A roomful of twenty-five to thirty safety professionals are divided into four to six review groups or inquiry boards. The groups or boards rarely reach the same conclusions on as much as twenty-five percent of the cause factors involved. This tells me that given all the facts uncovered through expert investigation, the critical action may be the proper assessment and corrective action coming out of these facts.

More specifically then, for a relatively small cost, we can increase our accident investigation leverage tremendously through a multiple review of the facts. Of course it cannot end at that point. Further action then involves a positive recommendation on each cause factor involved and a corrective action for each recommendation. Here (Figure 4) is a diagram that shows how this increases our effectiveness.

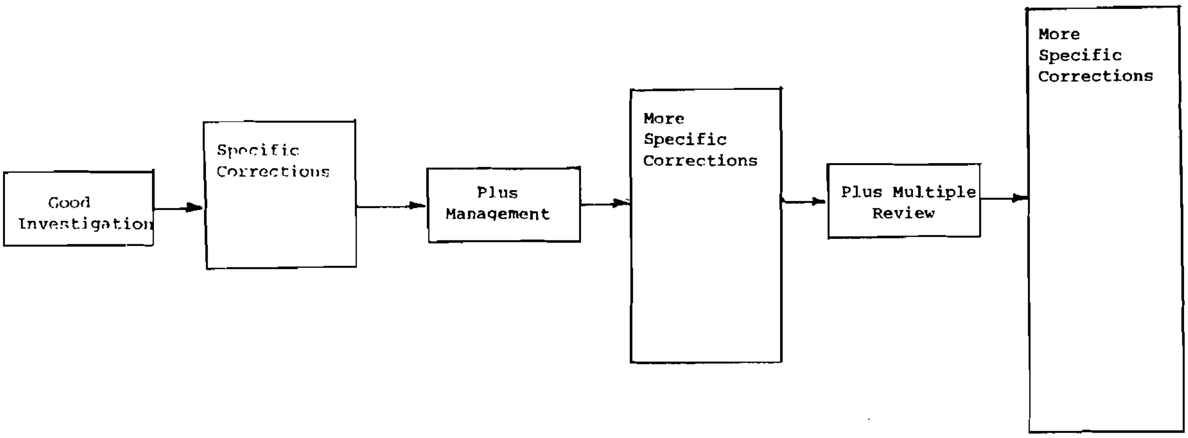

Fig. 4. Added Specific Preventive Correction Action When Management Factors And Multiple Review Are Added

Our great dream to increase the effectiveness of accident investigation by an order of magnitude or more to the point, to cut our accidental losses to a tenth of what they presently are, could be greatly facilitated by two specific actions:

1. Continually and critically seeking the answer to one more question: "Where did management fail?", and

2. Having independent multiple reviews of all the facts uncovered through investigation.

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The Limitations of an Accident Investigator in Preventing Military Aircraft Accidents: The Canadian Forces Experience

Colonel J. R. Chisholm
Director of Flight Safety
Canadian Armed Forces

The Canadian Forces have experienced a remarkable decline in both numbers of accidents and accident rate over the past 25 years. In 1954 there were 111 aircraft written off with 96 fatalities while in 1978 the figures were 10 write-offs with only 4 fatalities. The reduction in flying hours over that period was approximately 60 percent. This parallels the experience of other air forces and is due to improvements in equipment and training as well as to dedicated efforts in the field of accident investigation and prevention. Over the past few years, however, the accident rate appears to have levelled off and in the view of some has reached an acceptable level for a military flying operation. I don't share this view. It is suggested that any further reduction would call for measures which would actually inhibit our operational capability and would likely be prohibitively expensive. Besides, in these days of limited finances safety measures have to compete for funds like everything else.

Let me illustrate the nature of the problem in the military.

First, I will show you a film illustrating the actual inflight structural failure of one of our Snowbird aerobatic team aircraft last year. The cause was a fatigue crack in this attachment fitting in the vertical tail fin — easily identified and quickly rectified.

Now consider this accident in 1977 involving a fighter pilot in a CF5 aircraft who was engaged in low level air combat manoeuvers and who was unable to recover from a dive before hitting the ground. He was an experienced pilot who exceeded the aircraft's operating envelope.

A similar accident occurred this year at the same base with the same type of aircraft under very similar circumstances. This time the pilot recognized his critical situation in time and ejected successfully.

The point of all of this is that the second aircraft need not have crashed if the lessons of the first accident had been learned correctly.

If we examine the causes of Canadian Forces flying accidents over a recent ten year period (1966-76) it is apparent that pilot error as a percentage of all cause factors has been steadily increasing. This was during a period in which there were no drastic changes in role, equipment or training methods. Since most accidents have multiple causes, it is likely that the number of pilot errors was relatively constant while other factors, particularly materiel ones, declined. One might also conclude that our accident prevention efforts have been more effective in the area of technical defects than that of human error. In which case it seems logical to examine the role and methods of the Canadian Forces accident investigation and prevention organization — the Directorate of Flight Safety (DFS).

Without going into the whole organizational structure of the Canadian Forces it suffices to say that DFS is a relatively independent agency outside the normal chain of command which reports to the Chief of the Defence staff through the Vice Chief. Its primary role is to investigate accidents or selected occurrences and to make recommendations on all flight safety matters to the appropriate staff or commander. In simple terms DFS is required to identify hazards and to pass this information to everyone from the most senior commander or to the lowest private as appropriate. The degree of success which is possible with this type of system depends upon the validity and timeliness of the information and the manner in which it is utilized by those in positions of responsibility. It is apparent that our success in recent years has been due to a tendency to concentrate our accident prevention efforts in the area of technical deficiencies. This in turn enhances the role of the specialist accident investigator. For reasons which I will explain later this is a weakness in our accident prevention system.

Obviously our low accident rate and the decline over the years mean that the Canadian Forces are doing something right in the field of aircraft accident prevention. There are two features of this system worth discussing. The first principle of accident prevention in the Canadian Forces is that the commander at every level is responsible for the safety of his operation. To assist him in this endeavour we have established full time flight safety officers, usually pilots, who are responsible for advising each commander on safety matters. Their function is to be totally familiar with the role and operating environment of their organization and to identify hazards. This includes the reporting and investigation of minor occurrences. From these the Canadian Forces can detect trends and devise prevention measures.

Aircraft accidents in the Canadian Forces are investigated by Boards of Inquiry appointed by the Operational Commander who controls the aircraft. The Board consists of the usual mix of experienced pilots who are familiar with the aircraft and its role, technical experts, medical personnel and other specialists. They will all be selected from units other than the one involved in the accident. These people are *not* trained accident investigators and they normally have only two weeks to complete their report. Needless to say in some cases they won't get all of the answers in that time frame and they will make mistakes. Recognizing this, specialist accident investigators from DFS are sent to each accident site to advise and assist the Board and to carry out an independent investigation. The DFS investigator prepares a separate report and arranges for all follow-on investigation, such as engine strips, to be conducted under his supervision.

Perhaps this duplication of effort seems wasteful to you. I would suggest that we have the best of both worlds in this system — an investigation conducted by those who actually operate the aircraft and also by an independent specialist. If we relied solely on the former, we wouldn't get all of the right answers, and on the latter; a highly specialized point of view. Even if the specialist is totally correct his criticism of an organization may not be accepted. If there is anything good about an accident, it is the fact that it forces management to review the strengths and weaknesses of an organization. Thus, a Board of Inquiry which is totally familiar with an operation inevitably uncovers deficiencies which tend to be accepted by the appropriate level of command. Usually, a Board does not limit its findings strictly to the causes of the accident itself. The next step in the process is for each level of command to devise and implement corrective measures which are within its areas of responsibility. This tends to be much more effective than prevention measures which are imposed from above.

The final phase of the accident investigation process occurs when the report of the Board of Inquiry reaches DFS after progressing up the chain of command. At this point the DFS investigator is able to compare his findings to those of the Board to ensure that they are valid. Once all of the preventive measures are identified a closing action report is completed. This is signed by the Vice Chief of the Defence Staff and directs those responsible to carry out whatever preventive measures are still required. It's a good system which makes use of specialized accident investigators but it doesn't prevent enough of our recurring human factor accidents.

The root of the problem lies in our operational military flying role and an apparent confliction with the peacetime demands of flight safety or accident prevention. Success for a military pilot is defined in terms of how well he can overcome equipment and environment restrictions to complete his mission. The purpose of any military flying organization in peacetime is to be operationally ready for war and to provide aviation support in a civil emergency. In either case there is a recognized element of risk which is accepted. Unfortunately this fosters an attitude among military aviators and their leaders which is contrary to the aims of flight safety. Peer pressure encourages the military aviator to bend the rules or to take chances in order to achieve success. Leaders may overlook or even encourage this tendency since their own success is measured by the performance of their organization. This is not a problem unique to the military, I might add. Given the nature of the military role, particularly with tactical aircraft, it becomes very easy for the organization to accept the fact that there will be human error accidents because in some situations there isn't much margin for error. The attitude is that realistic training is necessary and that accidents are an inevitable price that has to be paid.

Consider the role of the fighter pilot, which is a uniquely military aviation activity. How can he be motivated to be safety conscious when his domain of high speed, low level operations is so fraught with danger? He probably considers that just being there is a violation of the basic concepts of flight safety. Our problem in military accident prevention is not just to develop safe procedures for tactical air operations but to somehow convince the whole system that the safe way is the best way. Let me reinforce my point by describing a CF104 accident in Germany.

The pilot's mission was to do a simulated bomb run on a bridge in a river valley. He was given limited information about the target by an airborne controller and was unaware that there was a 300-foot hill behind the target. This would not have been a problem had he not violated all of the criteria for a safe weapons delivery. This film shows what happened. Was this simply one man's mistake? Not if the organization he belonged to condoned bending the rules to achieve success.

Now let's come back to the methods of accident prevention used in the military and how that relates to the role of the accident investigator.

Dr. Zeller from the U.S. Air Force Directorate of Aerospace Safety presented a paper last year examining the USAF efforts to reduce human error accidents over a thirty year period. One of his contentions was that "accident prevention...involves the development of attitudes which accept the importance not only of the mission but also of the need for safety if it is to continue in a satisfactory manner." I suggest that this is the essence of the problem in the military. It is also apparent to me that the accident investigator will have great difficulty in changing attitudes if he is viewed as an outside expert.

Over the years as accident investigation methods have become more sophisticated this activity has also become a highly specialized field involving pilots, engineers, doctors and experts in many previously unrelated fields. Greater emphasis has been placed on matters such as human engineering, psychology, and system safety. The results are obvious. The accident investigator has become an acknowledged expert as well. The problem is that this role inhibits his ability to communicate effectively with operational personnel or even senior management. Safety, or accident prevention, thus becomes more the responsibility of the expert than of the organizational hierarchy. In the military, role confliction makes the situation even worse.

The traditional methods of accident prevention based on communication and leadership seem to be giving way to the scientific method. At what point do we stop changing procedures, modifying equipment and designing sophisticated aircraft to protect man from himself? Even that can be counterproductive because safety considerations may conflict with the role of the aircraft. Consider the philosophy of the designers of the F16 fighter who built a small, single-engined aircraft with the engine, fuel system and vital components all grouped together to make the aircraft less vulnerable to battle damage. Conversely, the F15 designers had system safety in mind when they did not put the fuel tanks around the engines. Which is right for a military aircraft?

When the Canadian Forces set up the Directorate of Flight Safety many years ago, it was meant to investigate and prevent accidents. It is clear to me now that DFS has fallen into the trap of becoming the safety branch for the whole air operational organization which depends on the DFS investigators to "look after" safety. Accident prevention becomes the responsibility of the safety expert and management will react to his proposals if it doesn't conflict too much with the operational role. In fact, although almost all of the DFS investigators were operationally qualified pilots they quickly become technical experts who concern themselves with specific aircraft types. In an effort to reverse this trend DFS was reorganized last year into operational and technical sections to try to direct the activities of some investigators towards the purely operational causes of accidents. Progress has been slow.

My contention is that accident investigation has to be simply one task of the flight safety officer. It is a highly specialized field which demands the talents of experts from many disciplines. I am convinced that a small organization like the Canadian Forces cannot afford the degree of specialization which has developed in our primary accident prevention organization — DFS. Perhaps even the term "flight safety" should be changed to "operational safety" to reorient the direction of our activities. Until accident prevention becomes an integral part of the operational role we will continue to experience the same accidents over and over again. We don't need any more evidence from accident investigations to embark on a better prevention programme.

The Investigator's Role in Accident Prevention: A Viewpoint from the Private Sector

John L. McWhorter M00378
John L. McWhorter & Associates, Inc.
1454 S. W. First Street
Miami, Fl. 33135

This presentation is directed primarily to the present policy and practice in aircraft accident investigations in the United States. Other countries may or may not have similar policy or procedures.

The role of the aircraft accident investigator is, of course, to determine the cause of an accident. The determination of the cause of the accident permits action to prevent similar accidents in the future. Basically, this is the job of the aircraft accident investigator employed by a governmental agency. The U.S. investigator operates under the Federal Aviation Act of 1958 as set forth in Title 7 where it states:

> Sec 701 "It shall be the duty of the Board to (1) make rules... (2) investigate such accidents...report facts conditions...the probable cause... (3) make recommendations...to prevent similar accidents in the future."

Of interest is the provision of 701(b) which permits the engagement for temporary service persons outside government.

Nowhere in the provisions of Title 7 is there any prohibition against the participation or use of any class or type of independent or private investigator. To the contrary, the Board is empowered to use any person other than an employee or officer of the U.S. and to pay for his services.

Aircraft accident investigators come in many different uniforms. The investigator may be from the government agency or department vested with the authority to investigate aircraft accidents or he may be from the staff of a large aircraft or engine or component manufacturer, an airline union, airline management or a number of other sources. In major aircraft accident investigations in the U.S. there is one uniform you will not see. That is one from Insurance or the plaintiff's attorney. Early on in this presentation I would like to tell you that I feel this discrimination is not in the best interest of the aviation industry nor is it in the public interest. The policy set forth in Sec 102 and Sec 103 of the Federal Aviation Act of 1958 state the Board and the Administrator shall encourage, promote and regulate aviation and their efforts shall be in the public interest. A number of years ago in Washington the Civil Aeronautics Board (now the National Transportation Safety Board) conducted its investigations and its formal boards of inquiry with a high level of expertise and staffed with a broad spectrum of experts in all the various aspects of aviation. They conducted their hearings with a definite set of rules and each hearing was almost a carbon copy of the last, except for a slight change in details such as type of aircraft, location of accident, etc. At that time only Board panel questioned the various witnesses, representatives from the airlines, experts, crew members, ground witnesses, etc. They conducted the hearing without any participation by "outsiders." The proceedings were such that even copies of the various reports were not available to the press or to any other interested parties at the Hearing. This, of course, was really not in the public interest and certainly did not result in the production of evidence or assist in determination of cause and the prevention of accidents in the future. Various people on meeting with the Board finally convinced them that either the procedures would be changed voluntarily by the Board or subsequently by the U.S. Courts. A number of prominent plaintiff's lawyers in the aviation field had considerable to do with this change in the regulations and gradually things improved. No one could ask a question under the old procedure. Later people with questions could submit them in writing and *if* the panel decided to ask the question, they would then do so. Later the Board broadened the participation of persons and groups and permitted questions from the designated representative of each participating party. Current procedure is known to all and needs no review.

Meanwhile out in the boondocks, things haven't changed very much at all. Currently, the NTSB leaves the designation of and participation of parties in a field office accident investigation up to the investigator in charge. Since there are some 90 investigators in the NTSB, each of whom is an individual with a slightly different viewpoint, the investigations are all run differently with different expertise, at different speed and, of course, different results. Investigations by personnel from the same Field Office are often extremely different.

Some of you may not know that the "private sector" has many well qualified aviation investigators. This classification of investigator certainly exceeds at least tenfold the number of all those involved in aircraft investigation within the government agencies or large aircraft manufacturing companies. This vast labor force is virtually ignored and obviously misunderstood by the NTSB.

To clarify the investigator's role in accident prevention which is the theme of this seminar, we should point out the different investigators that exist in the United States.

First we have the official U. S. Government investigator. He is from the National Transportation Safety Board. Also, in an official government capacity is the Federal Aviation Agency investigators who participate in most of the U.S. accidents.

Next are the group of investigators who are actually technically qualified employees of manufacturers. These may be engineers or otherwise qualified experts from the airframe manufacturer, engine manufacturer, radio, instrument, propeller manufacturer or any other component that is installed on the aircraft that could be involved in causing or contributing to an accident. A sub-category is noted under the Insurance class referred to hereafter.

Now we have the insurance companies. These are divided into several sub-categories. There are the large aviation insurance companies who have in-house aviation investigators and aviation adjusters. A second sub-category is the accident investigation company which is owned by an insurance company and operates quietly under a non-insurance name. These may actually be insurance company owned, oriented and concerned with the insurance risk rather than the manufacturing position. The NTSB has permitted some of these to participate in their investigations. A third sub-category is a private investigator who is primarily interested in the liability aspects of the accident and who appears at the scene stating he is an investigator from the *X* Aircraft Company, the manufacturer of the airplane or product involved. This is the category referred to in the previous paragraph.

The next category is that of the private aircraft accident investigator. He works for a number of different people. He may work on one accident for an aircraft manufacturer, on the next he may work for the aircraft owner or operator or for an insurance company that does not have its own investigation staff. He is sometimes permitted to participate in field investigations. The independent investigator working for an insurance company on a particular accident is often permitted to participate only when funds are needed to move wreckage or do certain testing.

Another category, is the aircraft accident investigator who is working solely for the plaintiff's attorney and whose main interest is to recover a monetary award for his client. He is always *persona non grata* at the investigation but many of these are highly qualified people who could contribute to the investigation and their exclusion *per se* is not warranted in the public interest.

The government investigatory agencies at least in the U.S. are hesitant to accept the fact that there is an established court system which is designated to permit recovery of monetary damages in aircraft accidents in accordance with the Federal or State law. The attitude within government on this point is understandable to a degree, but little if anything has been done regulation-wise or procedurally to adjust to the increased involvement of attorneys and litigation in almost all aircraft accidents. This is due in part because the FAA at least is frequently a defendant in the litigation arising from an accident. The first real warning of things to come may be heard in the now infamous DC-10 matter. The U.S. Federal Courts may well take away much of the authority now vested in or exercised by government agencies, such as the NTSB and FAA.

Each of the different categories of investigators, wearing a different hat, has a slightly different viewpoint and a slightly different goal. The bottom line should only be that there is but one viewpoint and there is but one goal in aircraft accident investigation. That is the determination of the actual cause of the accident and the prevention of any similar accidents in the future if possible. The agency and personnel within that agency should direct the investigation using all sources of assistance and control the conduct of the investigation so as to achieve the proper result. We have some real problems in the overall accident investigation/prevention business. This is true to some extent in most countries but is, I believe, a significant problem in the United States where almost every aviation accident results in litigation.

Some of the problems result from a too quick investigation by the government and a policy or attitude of accomplishing a fast investigation, send in the report and probable cause and wait for the next accident. This is sometimes called the numbers game. Which office handles the most investigations and how long does it take one office to do a job compared to another? This I submit is not the way to do it and certainly the Federal Aviation Act does not direct or even imply such action. It is, I believe, to the contrary. The NTSB, as are other agencies, is subject to scrutiny by the government as to its efficiency, its productivity, etc. If permitted a constructive criticism, I would advocate they work for more equipment, more investigators, more funds and consequently better investigations rather than a continuous attempt to handle an increasing work load with the same or fewer people. Today a non-scheduled cargo operation usually involves not a C-47 or C-46, but a DC-6 or more often a 707, CV-880 or a DC-8. As I understand it, the Federal Guidelines on "work units" gives the same unit value to a Cherokee 6 as to a B-707. Funds, employees and equipment are based in most part on these "work units." The problem is obvious. It is therefore understandable that we the private sector see what happens to be a continued gradual decline in the involvement and effectiveness of the NTSB in all but major accident investigations.

The problems we face today can best be illustrated by reference to actual aircraft accidents.

One aircraft accident several years ago which is still in litigation today, has developed six or more different viewpoints. This accident involved a private, twin engine airplane with several fatalities. Each of the persons or manufacturers who is a defendant in the personal injury litigation resulting from that accident has a different viewpoint. It is rather disappointing to see that each attorney is possibly more interested in protecting their client's name, their money and their pride in their work product than they are in publishing the real cause of the accident and preventing a similar accident in the future.

Part of this presentation will be consideration of things that were developed in aircraft accident investigations by the private sector investigator which were not found or noted by the government investigator. If found by any other investigators representing manufacturers or companies it certainly was not made known. I do not think such an end result is acceptable. It defeats the real purpose of our profession.

Why do these things happen? Well, it is a very complex situation. Over the years we have observed that many aircraft manufacturers and aircraft component manufacturers, have a tremendous pride in their product. They want to advertise they make the best propeller, the best engine or the best airplane in the world. Some of what they say, of course, is true. On the other hand, some of it is not and some is just a product of the sales department. One must sell, of course, to stay in business. The pride of authorship problem comes in two different forms. One is a management positive thinking viewpoint that their product is infallible, that it did not fail, it did not cause the accident and that all accidents are basically "pilot error." The other form in which this pride manifests itself is through the loyalty and protection of the company name on the part of the employees. There are instances in accident investigation where an employee propounds the most favorable position with respect to the company's product. We cannot condone a right or left of center position by anyone with respect to aircraft accident investigation but nevertheless, such does exist. Over the years it has been noted and passed on to the NTSB the fact that the amount of investigative research and test work done by the private sector of investigation greatly exceeds that done by the government agency even though the government may have designated a number of parties to participate in the investigation. A large number of accidents go on into prolonged civil litigation. When they go into this stage the investigation continues on in considerable depth using experts and resources which usually greatly exceed that which the government can or has utilized. The significant thing that results from these investigations is oftentimes the discovery of new evidence and a different cause for the accident than that published by the government agency. One change that would be of definite help would be for the government investigators to be required to read the depositions, testimony of the expert witnesses, look at exhibits, photographs and other information that results from the investigation/litigation of aircraft accidents. The government investigators might learn something. They could learn of new techniques, of different applications for existing techniques and perhaps most important of all, be able to analyze the viewpoint of a number of qualified persons and achieve a better understanding of an accident, its cause and how to prevent another such accident.

Several years ago there was a major four engine jet crash. Some of the investigators never were really satisfied with the investigation or the probable cause that resulted. It was commendable, however, that the cause attributed to the accident did prevent a number of other accidents of a somewhat similar type. We were, however, considerably surprised to find out later of a totally different cause for the accident. The aircraft in question had undergone major repair, some time prior to the accident, and the work had been done in concert by the manufacturer of the aircraft and the operator of the aircraft in a joint effort to get the airplane back in the air as soon as possible to avoid loss of revenue. The aircraft manufacturer and the operator agreed not to discuss the adequacy of the repair in any way but to argue vehemently against each other on entirely different grounds. The argument based on pilot error versus aircraft design was very heated and overpowered the entire investigation, public hearing and later litigation. What some investigators considered to be the real cause of the accident was hardly mentioned. This took place several years ago. The actions of the parties and the manner in which this litigation was defended was apparently due to the fear of both manufacturer and operator of evidence or information which would later lead to a verdict or award based on punitive damages.

In another major aircraft accident attributed to pilot error, the so called private sector, after several years of investigation and litigation, determined that the accident was not pilot error as issued. The official report indicated the pilot feathered the wrong engine after an engine failure and had he not feathered the wrong engine the flight could have continued. Subsequent investigation, however, showed that the engine which the pilot feathered had, in fact, failed. A bent intake valve caused backfiring and resulted in an induction system fire. There was no question that the second engine failed, however, the pilot did not feather this engine as it was producing some power.

Another accident involving a large four engine aircraft was determined to have been caused by pilot error and distraction of the pilot by a fire in an engine. The subsequent investigation and civil litigation continued for several years. It proved conclusively that there was no fire in the engine as stated in the government report. The only fire was a ground fire. This was evidenced by the lack of in-flight type burn damage that would have been noted on the engine accessories, clamps, wiring and other components. The fire in question was of very short duration and occurred on the ground after impact. The accident took place in a marsh area and the crater served as a container for fuel from ruptured wing tanks. The subsequent seepage into the crater by ground water and rainfall misled some investigators as to the possible existence of a ground fire. The fire failed to burn any insulation off wiring, to burn any of the neoprene rubber liner in Adel clamps and the failure of the fire to burn in a typical pattern usually seen when the fire was in flight and lasts for a period of time. This plus the lack of any radio conversation from the crew regarding a fire disproved the fire in flight theory. Subsequent litigation showed that the accident occurred from loss of control. The aircraft had been vectored into a severe thunderstorm cell. This cell, however, did not appear on the information provided by Air Traffic Control for the official investigation. The controllers stated there was no photo equipment in operation for the radar weather display at the time of the accident. They emphatically stated there was no cell and drew maps of the existing cells from memory. The existence of the cell which resulted in the accident, was, however, recorded by the U.S. Weather Bureau Radar and photographs were obtained from the U.S. Weather Bureau. These showed conclusively that the accident site was at the exact position of this cell which was otherwise "non-existent."

Unfortunately, there are many more examples of this same result. There are cases where the official investigation did not correctly determine the cause of the accident either due to lack of time, lack of expertise, or whatever the reason. Subsequent private investigation, however, determined the true cause of the accident. The disturbing thing about this has been the governmental agency position which basically is they do not wish to consider any information from an outside source after they have concluded their investigation and determined the cause of the accident. They will not consider anything in the nature of an opinion or conclusion from outside sources. Their position is they will only accept and evaluate ***new evidence***. Unfortunately, oftentimes they don't consider "new evidence." In the fire distraction case the failure of the fire to burn insulation from wiring, rubber from Adel clamps, etc. was not noted, mentioned or otherwise commented on in the official report. When presented, they did not consider this information to be new evidence. They considered it to be a request to change the probable cause which they declined to do. Perhaps one of the problems is time. The private sector investigation may not be completed or litigation (with qualified expert's testimony and exhibits) completed for several years after an accident. By then the government has lost all interest in the accident. Ironically, the private sector investigator who found the new evidence that was presented to the Board in that case had been the Chief of the involved division in the agency prior to his retirement. He had considerably more qualifications and experience than the person who did the investigation.

In that particular case, the failure of the Board to recognize the new evidence did not cause any real problems. The litigation was successful in showing that among other things an in flight fire did not occur. There was nothing lost, therefore, in the way of information or data that would have prevented another accident since there had been no in flight fire. One has to be concerned, however, about the attitude of the governmental investigator or his agency when they evidence the same "pride of authorship" that we have seen expressed by the manufacturer of an aircraft or components.

This paper will be a success if we are able to accomplish even one instance where the private sector investigator is officially permitted to participate in a field investigation or if in only one case, new evidence, data or information produced by the private sector is considered and accepted by the governmental agency. One must hope, however, such will not be limited to a single case. We hope that all those involved will take another look at the private sector and not feel that *per se* they are unacceptable.

In actuality the aircraft manufacturer or components manufacturer has just as much at stake and just as much reason for bias or prejudice with respect to the outcome of an accident investigation as does the representative of any insurance company. A well known attorney representing an aircraft manufacturer has publicly stated the greatest single contribution to aviation safety has been the plaintiff's bar. I would respectfully request the NTSB at least to consider the advisability of a policy of utilizing any person or persons in their investigation who are qualified and can contribute to the investigation of an aircraft accident. This would certainly be in the public interest and assist in discharging the duty of the Board in ascertaining the facts, conditions and circumstances of and the determination of the probable cause of an accident.

The Challenge of Digital Flight Data Recorder Read-Out and Analysis

B. Caiger
National Aeronautical Establishment
National Research Council
Ottawa, Ontario, Canada

1. INTRODUCTION

It is now ten years since digital flight data recorders were first fitted to civil transport aircraft in Canada following the promulgation of the first Canadian requirement for recorders in 1968. The digital systems were an almost inevitable choice in view of the 18 to 22 parameters that were required to be monitored.

Since that time, the Flight Research Laboratory of the National Aeronautical Establishment, a division of the National Research Council in Ottawa, has been the Federal Government's central agency for read-out and analysis of the data. In 1972, we set up our own Flight Recorder Playback Centre, sponsored by Transport Canada and the Department of National Defence, to handle all flight data recorders and cockpit voice recorders installed in Canadian civil and military transport aircraft. Whilst the civil playbacks are normally confined to the investigation of accidents and incidents, regular playbacks are made of the military systems to aid in their routine maintenance.

In this paper, I do not propose to dwell on the audio playback side, though this is an important area of our activities, nor do I intend to cover the older data recorders using stylus marking on metal foil. We do have a number of the latter type in service on turbo-prop aircraft and have developed our own read-out and computer conversion system for them.

As far as the digital data systems are concerned, in case anyone imagines that the data recovery is just a matter of routine, I propose to highlight a few of the problems that we have encountered. It should be remembered that, with the early introduction of comprehensive data recording requirements in Canada, most of our experience has been with first generation systems and we hope to see fewer problems as time progresses.

It must be admitted that, right from the start of the Playback Centre, we took a pessimistic view of the task and set about making as many provisions as we could envisage to handle damaged recorders and poor quality data. In the event, our pessimism has been more than justified and all the techniques that we developed have been used to advantage.

2. DESCRIPTION OF THE DIGITAL SYSTEMS

In our present digital systems, all parameters are sequentially sampled, digitised and combined into a single electrical signal. This signal is then recorded on a wire or one track of a magnetic tape, the tape either being of the conventional type with an oxide coating on a plastic base or of metallic material. On the tapes, the signal is sequentially recorded on several tracks in order to achieve the required 25 hour duration with the minimum tape length. The complete cycle of recording is continually repeated, the tape either forming a loop or reversing at each end with appropriate track switching.

The location of the digital numbers for each parameter in the data stream are identified by their positions relative to a particular synchronization pattern of 11 or 12 bits that occurs once per second. During playback, the computer searches for this pattern. There is a small chance that an identical pattern may be found buried in the data stream and, if the data are constant, that it may repeat at the correct interval. In order to avoid the possibility that this may be incorrectly identified as the true synchronization pattern, that pattern is changed, either in alternate seconds or through a cycle that repeats every four seconds.

If the computer locates a synchronization pattern and then finds the appropriate following pattern separated from it by the correct number of bits, one can be reasonably confident that the data in between are being correctly decoded. If only one bit in the data sequence of anywhere between 288 and 768 bits is mis-read, all the following measurements will be incorrect until good synchronization has again been achieved.

The data format used is known as Harvard bi-phase and is illustrated in figure 1. The signal switches between equal positive and negative levels that are arranged to give saturation recording with the polarity in one direction or the other along the tape or wire as illustrated. It contains regularly spaced clock transitions that separate each digital bit. The presence or lack of an additional transition midway between the clock transitions indicates whether the recorded bit is a zero or a one. Each parameter measurement uses eight or twelve bits depending on the system involved.

3. RECOVERY OF THE SERIAL DIGITAL SIGNAL

The first problem in the data recovery is that, by the time the original square wave has been converted into a magnetic pattern on the medium and then subsequently sensed by a playback head, it is considerably distorted as typified in figure 1. The signal has to be reshaped into a square wave before it can be fed to the computer for processing. This task is straightforward when the quality of the recorded signal is good.

Unfortunately, there are many possible reasons for degradation of the signal. Most of these are induced by mechanical problems in the recorder. In our experience, the mechanical operation of the recorder is the weakest link in the data monitoring system. The development of suitable solid-state memories with no moving parts to replace the recorders would eliminate all these problems.

One of the problems that we have encountered a number of times is poor tracking of the tape over the heads. Figure 2 is a photograph of the magnetic pattern on one tape made visible with Soundcraft Magnasee. The Magnasee consists of fine magnetic particles in suspension in a rapidly-evaporating spirit into which the tape is normally dipped.

With digital data recording on the more conventional oxide coated tapes, the level of the digital signal being recorded is designed to saturate the tape. This eliminates the need for an erase head to remove old data prior to recording new data.

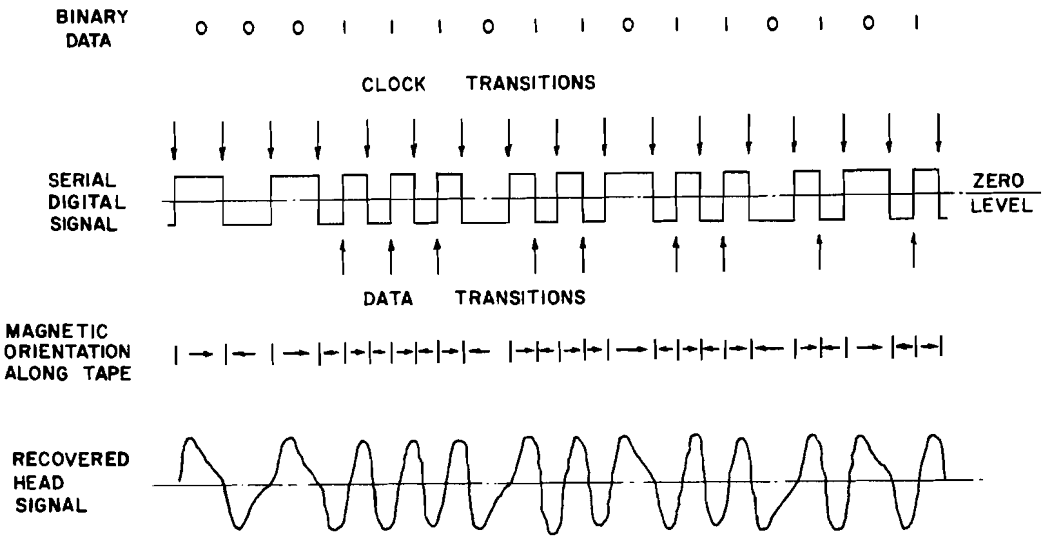


FIG. 1: BIT FORMAT AND DISTORTION IN THE RECORDING PROCESS

Bearing this in mind, figure 2 indicates that the path of the tape across the tape head has changed 0.15 mm (0.006 in.) at some time, leaving the residual edge of old tracks of data in the gaps between the tracks where they cannot be erased. If a playback head was not accurately aligned with a track from which data were being recovered, it would sense the residual data as noise on the head signal that could result in false transitions in the reconstituted square wave.

In order to minimize the effects of this problem, we have provided adjustable tape guides on our tape decks that control the position of the tape on the head during playback.

Another common problem in the recorders is that the tape does not move smoothly over the record head. When the tape is replayed at constant speed, the recovered signal has a variable data rate or "wow". Referring back to figure 1, the data are decoded by searching for the regular clock transitions and by checking the signal again about three-quarters of a bit length later to see if there has been a data transition. If the data rate is fluctuating significantly, the following clock transition may be misinterpreted as a data transition and bit synchronization is lost.

To overcome this problem with longer-term wow on the recorders, we have developed a special computer interface that sets the three-quarter bit period to a time based on the average length of the previous two bits.

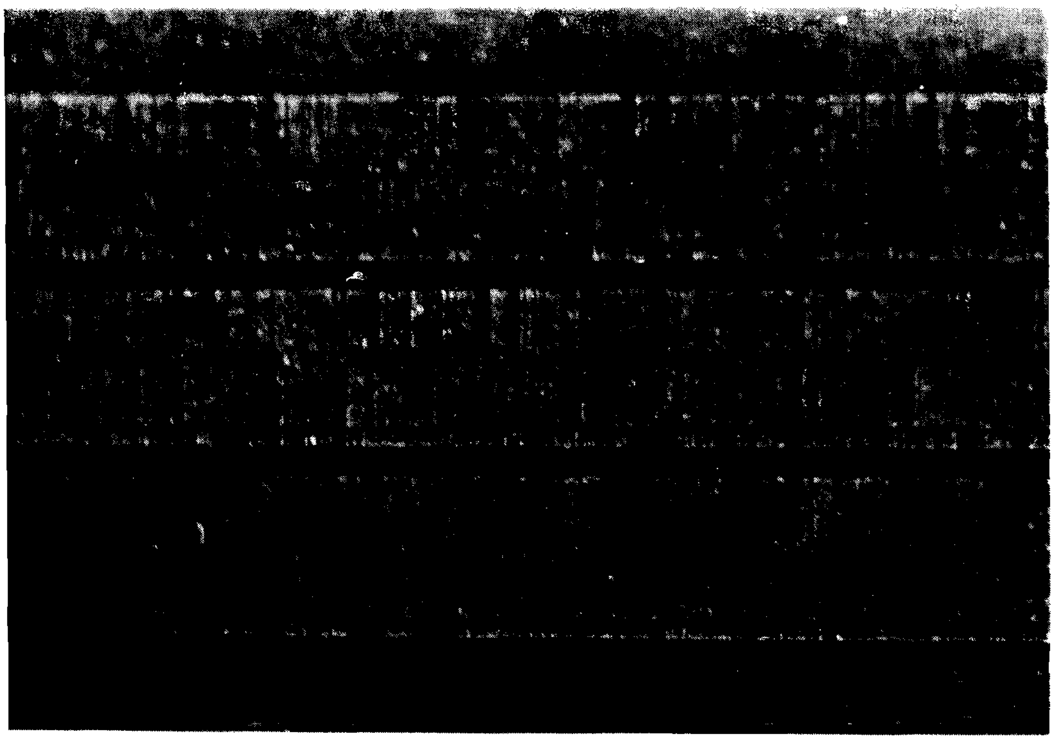


FIG. 2: MAGNASEE PATTERN ON MIS-ALIGNED TAPE

Mis-reading of even one bit can cause a loss in data synchronization that results in drop-outs or erroneous measurements until synchronization is re-established. This may take up to 2 seconds after the fault ends. The majority of the lost data could be recovered if the signal was also processed in the reverse direction. We have not automated this procedure but achieve it when necessary by hand from an oscillographic record of the playback head signal.

Alternatively, from a careful study of the recovered data we can determine whether some small number of bits have been missed or added to the data. We then have a comprehensive editing routine that not only allows us to change any bit or word but also to move the apparent erroneous digital stream by the desired number of bits in the appropriate direction.

4. RECOVERY OF DATA FROM TAPES DAMAGED BY HEAT

Another difficulty that occasionally arises is that the tape may have been damaged by heat. Whilst the insulation provided inside the armoured containment of the civil aircraft recorders is adequate to prevent damage from quite severe fires, prolonged immersion in the hot environment that may result with accidents in remote or inaccessible areas can still destroy a conventional tape.

One example of a recent fire-damaged recorder is shown in figures 3 and 4. This is a cockpit voice recorder that was installed in a turbo-prop aircraft that was being used to ferry fuel. There was an explosion in the fully loaded aircraft as the engines were being started. The aircraft was almost totally consumed in the ensuing fire. The recorder was installed in

FIG. 3: INSULATION PACKAGE OF HEAT-DAMAGED COCKPIT VOICE RECORDER

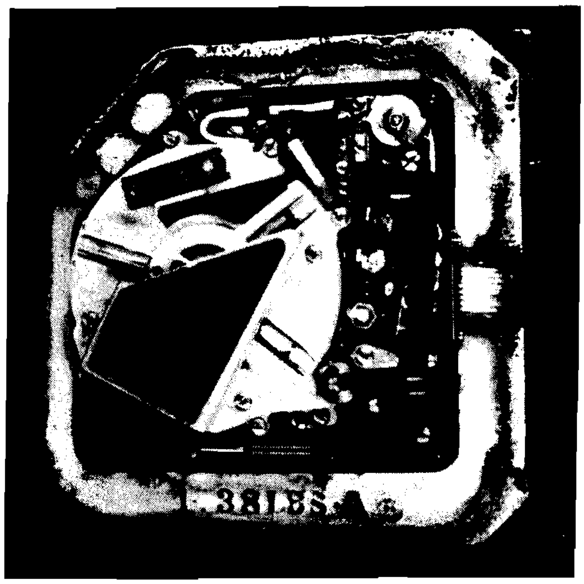


FIG. 4: TAPE TRANSPORT OF HEAT-DAMAGED COCKPIT VOICE RECORDER

the tail cone aft of the pressurized bulkhead. The tape, though stiffened in parts by the heat, was still replayed in the normal manner, indicating that the water-filled insulation had just been adequate for the situation.

To aid in replaying tapes damaged in this manner, we have provided adjustable tape tension on our playback machine and made provision for a co-belt to aid in maintaining good contact between the tape and playback head. The co-belt is a loop of the same width as the tape that can be separately tensioned and is arranged to run with the tape past the head.

Figure 5 shows a worse example of fire damage that occurred to a mechanically similar unit to the one previously described. This unit was being used as a digital data recorder. It was installed in the rear part of the pressure cabin of a jet transport involved in a major accident and was not removed from the burnt wreckage until about 20 hours later. It is interesting to note that if the unit had been installed aft of the pressure bulkhead as in the previous case, it would have been almost undamaged.

Figure 6 shows a close-up of the tape remnants left in the unit when the cover was removed. We initially declared the unit to be totally destroyed. However, following good investigation practice, we carefully retained the evidence and, upon finding with Magnasee that magnetic patterns were still evident on the charred remains of the tape, commenced a hasty research programme on possible ways to recover the data.

From figure 5, it can be seen that the plastic turntable on which the reel of tape normally sits had melted together with the cover that fits over it. The tape itself had a Mylar backing that melts at 260°C. We estimated that the tape transport reached a temperature of 450°C.

With the advice of the Chemistry Division at the National Research Council, we tried various techniques to soften and strengthen the remains

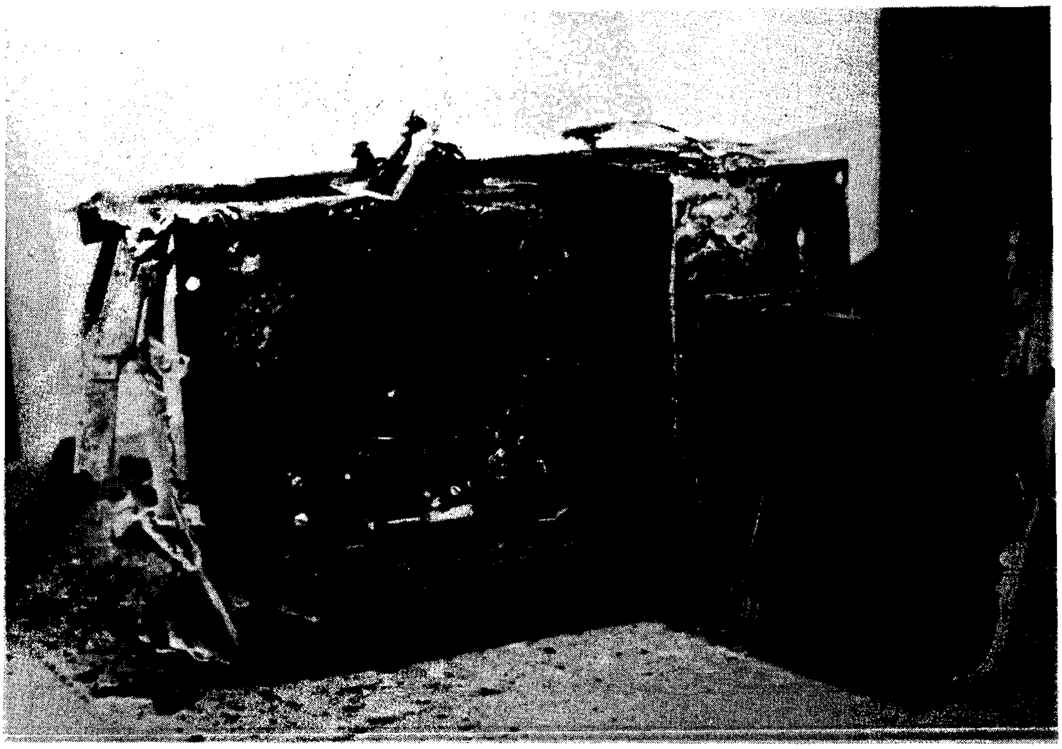


FIG. 5: SEVERELY HEAT DAMAGED DIGITAL FLIGHT DATA RECORDER

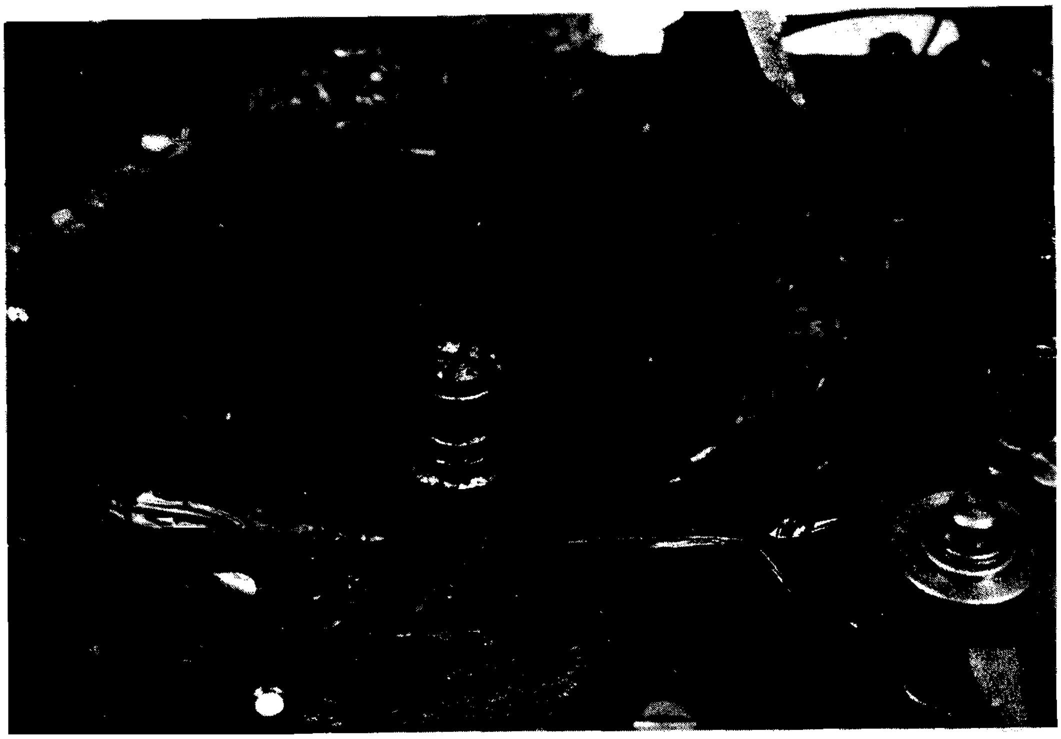


FIG. 6: CHARRED TAPE IN DIGITAL FLIGHT DATA RECORDER

of the tape, but without success. In the end, we resorted to the simple technique of making the pattern visible with Magnasee and reading it with the aid of a microscope. This technique was feasible because of the relatively low packing density of the data on the tape, with only 384 bits per inch.

From subsequent research, we think that this technique could be utilized with packing densities up to 1,000 bits per inch. Unfortunately, the two most popular digital recorders now in service have packing densities of 1786 and 2076 bits per inch. We are investigating other techniques for these tapes.

FIG. 7: MAGNASEE PATTERN OF DATA ON CHARRED TAPE

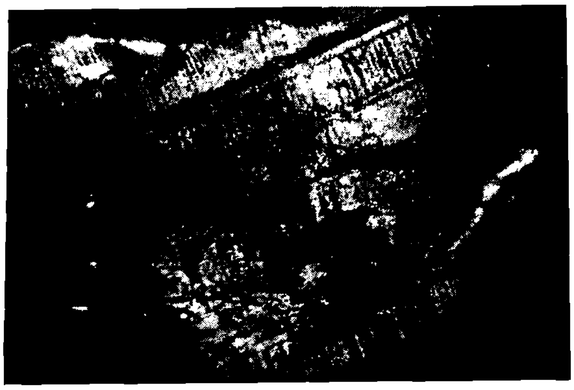


FIG. 8: TYPICAL DEPOSITS ON CHARRED TAPE

Figure 7 shows some of the clearest patterns found on the accident tape. Again, tape alignment problems are evident from the residual data between the tracks. In this case, they were found useful as a signature from which to identify the tracks on the curled-up sections of the tape.

On other sections, such as in figure 8, charred material was bonded to the surface partially obscuring the pattern. Sometimes we found that the bit pattern was only evident whilst the Magnasee was wet. We applied spirits that evaporated more slowly than that used in the Magnasee, and agitated the particles with a fine brush that was ultimately reduced to a single bristle. Even so, the tape broke a number of times during the reading process. It was also necessary to break away the last section of tape, fragment by fragment, after it had been read to enable some earlier critical data to be recovered from the layer underneath.

We were fortunate that the last data were being recorded on one of the two centre-most tracks of the eight on the ¼ inch tape as these were the only tracks that were always visible on the rolled-up sections of the tape seen in figure 6. Also, from figure 7, it is evident that the spacing of the transitions in the data signal in alternate tracks was only about half of that in the others. It would appear that only either positive or negative going transitions were being recorded due to an unidentified fault. It was found that the choice of positive or negative going transitions was continually fluctuating such that no useful data could be recovered. Again, we were fortunate that the track in use at the time of the accident was not suffering from this defect.

After three weeks of poring over the microscope, we recovered about 5,000 digital bits. These would normally have been detected by the playback system in about two seconds. The reading was aided by the presence of a parity bit at the end of each word that allowed parity checks to be made as the data were read. This feature is not included in the ARINC 573 data format now most generally used.

The final results obtained are illustrated in figure 9. I do not propose to discuss the accident in detail. The aircraft touched down in marginal visibility conditions whilst a snow-sweeper was still clearing it. An overshoot was rapidly initiated. The aircraft cleared the obstructing vehicle but subsequently crashed after the partially closed thrust reversers on the left engine re-extended under air loads. The recovered data shown in figure 9 covered part of the final approach, the initiation of the overshoot, and the last six seconds before impact.

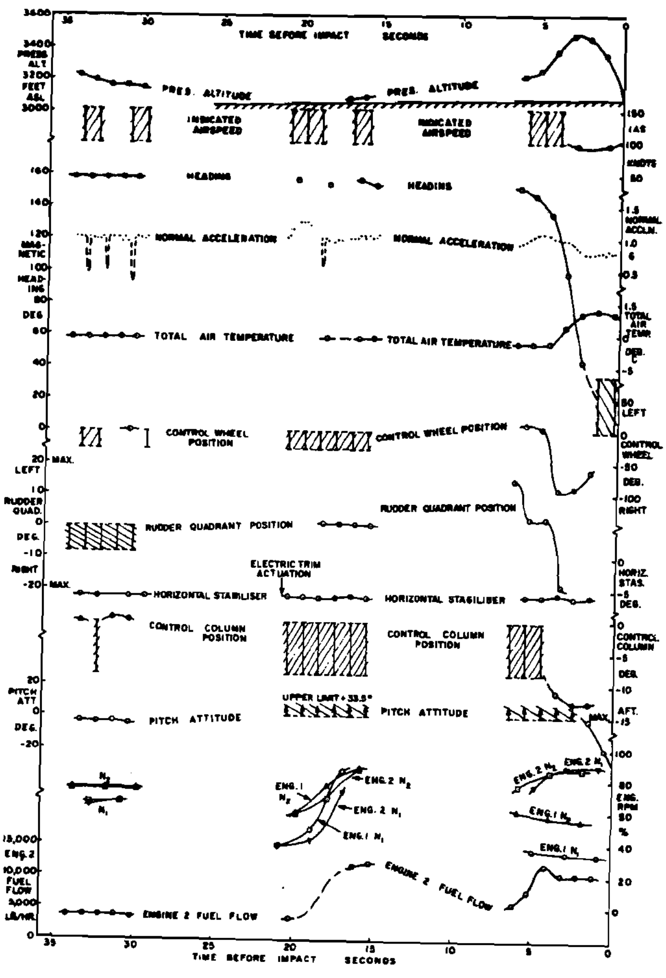


FIG. 9: DATA RECOVERED FROM CHARRED TAPE

The data recovery problems did not end with the recovery of the digital data stream. We found that parameters measured by synchros had an unusually high proportion of zero digital numbers. With the eight digital bits per measurement, the decimal values should have ranged between 0 and 255. For the synchros, the upper limit never exceeded 232. We concluded that there was a fault in the recorder electronics unit circuit that converted the three-wire synchro signals into D.C. voltages, and were able to estimate a correction factor utilizing the difference between the runway direction and the apparent heading on the approach.

When the correction was applied to the pressure altitude, the measured altitude on the ground was in good agreement with the airfield level after due allowance for the relevant altimeter setting. The correction implied that all the zero decimal numbers actually corresponded to points within specified limits. These have been indicated as vertical lines in figure 9 instead of the normal circled points. It was unfortunate that the indeterminate range of airspeed was between 100 and 153 knots as this bracketed the speeds involved except for the last two points.

During the investigation, it was apparent that the one measurement of left rudder pedal position six seconds before impact was extremely critical. The synchro monitoring this movement was installed such that the 0° to 360° transition point of the synchro corresponded to the neutral pedal position. With the synchro conversion circuit used, a narrow band of the order of $\pm 1^{\circ}$ of synchro angle either side of the neutral position could produce a random output that could fall anywhere across the full range of digital counts. Thus, any individual measurement could either be correct or represent a random output from the transition point of the synchro i.e. when the pedal is in the neutral position. More careful design could have easily eliminated or at least reduced the risk of ambiguity.

5. PROBLEMS WITH FAULTY SERIAL DIGITAL DATA FORMATS

Having progressed from discussion of data recovery from badly damaged tapes to problems in certain parameter measurements, I should retrace my steps a little to mention other problems that we have encountered after a "good" serial digital signal has been reconstructed from the head output. I am using "good" here only in the sense that the reconstructed signal is identical to the original data signal that was fed to the recorder.

In some cases when the computer could not make sense of the data, we have found that the synchronization codes in the bit stream were incorrect. In one case, the code was at least self-consistent and we were able to edit the data, again using our comprehensive editing routine, to correct the defect. Even then, the data that we recovered showed some unusual variations, and it took some time to discover that the four most significant bits were intermittently reverting to a fixed pattern. Through a careful comparison of the various parameters, we were still able to recover the altitude, airspeed, heading, vertical acceleration, and pitch attitude with a high degree of reliability.

In another case, when an attempt was made to recover the data, the apparent garbage that was obtained showed some systematic though non-standard variations. The system was designed to record 64 words per second. It was eventually found that, although the words were being recorded at the correct rate, there were a number of additional words of zero value interspersed in the format such that the synchronization patterns appeared every 78 words instead of every 64 words. Again, a time-consuming editing of the data eventually produced excellent results. Such is the task of the flight recorder playback specialists.

6. CONVERSION OF DATA INTO ENGINEERING UNITS

Having recovered the raw data i.e. the digital numbers that were recorded on the tape, the next step is to convert these numbers into engineering units. For this purpose, we keep a library of information ready for insertion into our computer that ultimately will cover all Canadian registered transport aircraft systems. This information is based on the standard calibrations for each fleet of aircraft. Where necessary, these can be replaced with special calibrations appropriate to the particular aircraft or transducer involved. The engineering data obtained are then stored in floating-point format on a computer tape together with the names of all the parameters and the calibration conversions used. These data can then be printed or plotted as desired.

7. VALIDATION OF THE RECOVERED DATA

The next step is the validation of the significant measurements. If the aircraft is undamaged, relevant parameters may be re-calibrated. In more severe accidents, the extent to which the validation may be achieved can vary considerably between parameters.

Pressure altitudes may be checked against specified flight levels and airfield elevations, headings against runway directions, and the vertical accelerations for 1.0 g in level conditions. Airspeed, often the most critical parameter, presents a more difficult task. If a post-accident calibration is impossible, it may be necessary to check speeds from a number of previous flights to see that they are reasonable. Frequent calibration checks are the only other means of increasing confidence when a transducer separate from the air data computer is used.

As the number of parameters monitored increases, a greater degree of redundancy starts to appear and cross-checks between the parameters becomes feasible. On several occasions, we have used the difference between radio and pressure altitude to obtain a time history of the terrain during an approach that was cross-checked with contour maps to give ground position. ILS glideslope data provided a good check of the results when it was available.

There can, of course, be a number of iterations in the process of producing the data and validating them. We tend to produce preliminary results based on standard calibrations as rapidly as possible after an accident with the proviso that the results will be refined at a later date. This gives the investigators something to assist them in determining where to concentrate their efforts at an early stage.

8. DATA PRESENTATION

Having hopefully recovered some reliable recorder data, the final step in the process is to find meaningful ways to present the results. At our Playback Centre, we started with digital print-outs of the results, but I heaved a sigh of relief when we progressed on to automated plotting of the results on our Tektronix 1014 CRT display that can be converted into hard copies as in figure 10. I have therefore been somewhat non-plussed to find that a number of pilots, when presented with such graphs, expressed a preference for the digital print-outs. Obviously, both methods have their advantages.

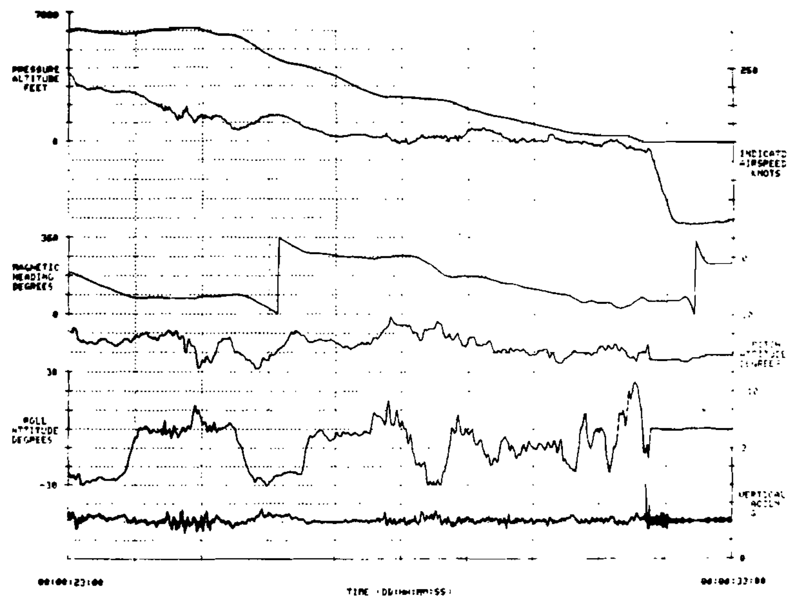


FIG. 10: TYPICAL TIME HISTORY FROM CRT DISPLAY

Of course, when one is trying to visualize aircraft motions, both methods suffer from severe limitations. As part of the data analysis, we have developed software that enables us to derive the time history of the flight path coordinates from the recorder data and the best wind information available, with the assumption of zero sideslip. We therefore developed a programme using these coordinates in conjunction with the aircraft attitudes that will produce perspective views of a simplified aircraft on the CRT as seen from any selected position in space. One example is shown in figure 11. The display includes a horizontal grid, and when required, can also outline runways or similar ground areas.

As a further extension of the motion visualization and, upon realizing how often the timing of the events was critical, we also developed a technique to recreate the aircraft instrument layout on the CRT and to feed the serial digital recorder data to this display in real time. We have also added symbolic displays of the pilot's control inputs. One example is shown in figure 12.

When this presentation is combined with the cockpit audio recordings, a useful simulation of the flight deck environment is created. With the civil aircraft, the use of separate voice and data recorders necessitates some careful synchronization of the audio and serial digital signals before they can be combined on to one tape. The serial digital signal is also normally recovered at a much higher speed than it was recorded. In order to be able to recover the data reliably at the recorded speed, it is often necessary to regenerate a higher quality copy of the signal from the raw data computer tape. Unwanted drop-outs may also be edited out during this process.

With our military transport aircraft, that use a light-weight combined audio and data recorder mounted in an ejectable emergency locator beacon, the combined audio and data display can be generated directly from the recorder.

From a number of accident investigations, we have found this display to be a powerful method of presenting the recorder information to pilots.

9. ACKNOWLEDGEMENTS

The work described has been a joint effort of a number of the staff at the Flight Research Laboratory. In particular, Mr. M.G. Renton has been responsible for the assembly and maintenance of the equipment, whilst Mr. S. Zurawski has developed and run all the CRT display and editing software.

The assistance of Mr. H.N.C. Lyster in developing the routines to process the serial digital signal into engineering units and of Mr. D.F. Daw in selecting and acquiring the necessary equipment is acknowledged.

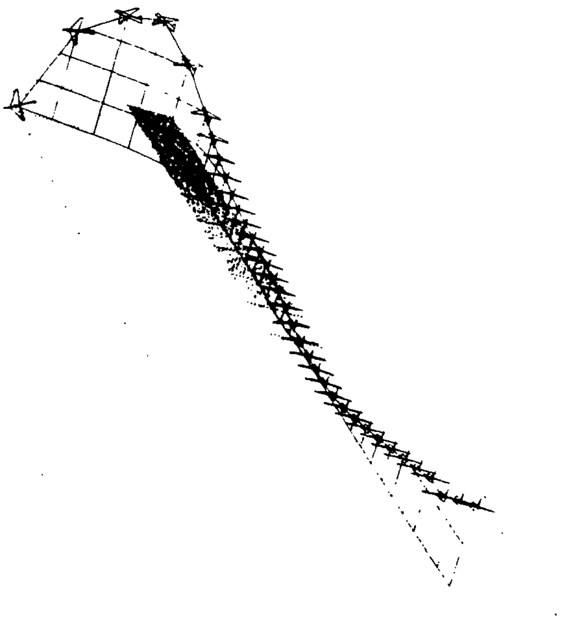


FIG. 11: TYPICAL FLIGHT PATH RECONSTRUCTION FROM CRT DISPLAY

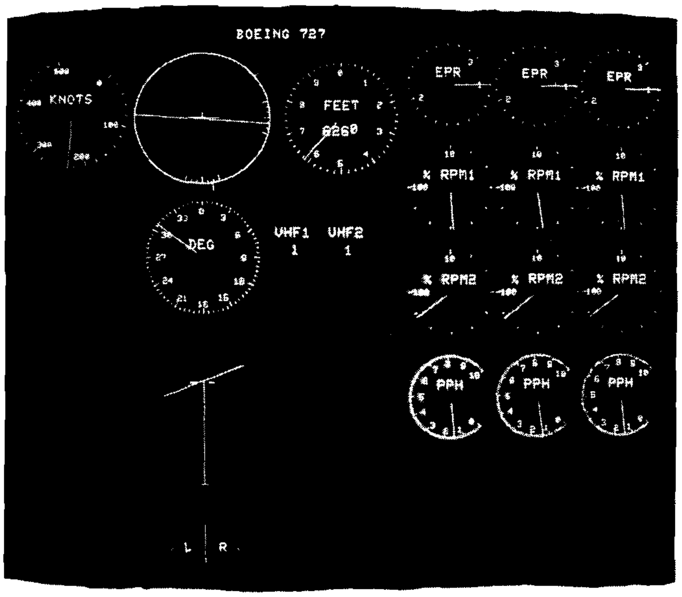


FIG. 12: REAL TIME FLIGHT INSTRUMENT DISPLAY WITH SYMBOLIC INDICATIONS OF PILOT'S CONTROL INPUTS

The Need to Go Beyond the Cause-Related Facts

Joseph R. Bailey M00821
President, Aerospace Management Services International, Inc.
4950 North O'Connor Road #265 Irving, TX 75062

In preparing for my appearance today, I found that I was having considerable difficulty in coming up with a precise and proper definition for many of the terms that we use in our daily activities. For example, a definition for words such as, "probable cause" and the meaning of the phrase, "cause-related facts". I felt a bit better when I read that in May, 1978 the United States Coast Guard asked for public comment on the proposed rule change that would exempt race boats from certain Boat Safety Act regulations. Almost a year later, on March 29, 1979, the proposed rule exemption was dropped by the United States Coast Guard because nobody could come up with the definition of "race boat". I thought if the United States Coast Guard and the U.S. public couldn't define "race boat" I had better get some help. I got a lot of definitions but one will suffice to give you an idea of the kind of assistance I received. "Fear is when you realize for the first time you can't do it a second time and panic is when you realize for the second time that you can't do it the first time". (This was given to me by a former naval aviator and in case any of you missed the point. . ."It" refers to night carrier landings.)

Well, I thanked those who were trying to help me and then solved my dilemma of having to come up with proper definitions by electing not to include any definitions, nor to engage in a battle of semantics, but rather, to tell you in my own words why a manufacturer must have detailed information concerning its product.

Most aircraft accident investigations are conducted to identify the facts, conditions, and circumstances relating to an accident in order to determine probable cause. An aviation manufacturer obviously needs those facts, conditions and circumstances relating to any accident where its product is involved. Perhaps less obvious are the benefits General Aviation receives when manufacturers are able to obtain *all* facts relating to their products, whether the facts are defined in a specific case as "cause-related" or not.

My position that manufacturers need more information than that normally provided by an investigation for probable cause raises the question of how much more information, for we all know that in the real world there are restrictions created by time, money, and results, on how far we may go in most investigations. In the majority of cases, the product itself, and the initial facts of the accident will dictate the extent of the investigation necessary.

I think we are all aware of the efforts that are extended in a major aircraft investigation. Teams composed of highly specialized persons devote that amount of time and money necessary to document, analyze, and report. Air transport aircraft accident investigations also have at their disposal the results of the flight recorder and cockpit voice recorder. It is well known that these devices provide additional facts which might never be uncovered through any amount of investigation. As a result of information obtained through the flight recorder and the CVR along with the skill of a team of highly trained specialists engaging in a sophisticated and scientific analysis of the wreckage on site, a very considerable amount of non-cause-related facts become available. Manufacturers utilize all these facts in evaluating their products with the view of improved safety.

It is certainly an understatement to say tht such investigations are not normally conducted in General Aviation accidents. Despite the great differences between the investigation of major aircraft accidents and those accidents involving general aviation, a manufacturer's reaction is the same. For example, an airframe manufacturer will respond differently to the case where the wreckage is distributed over a 3-4 mile area and the case where the wreckage is confined within a circle 60 feet in diameter. If, in the latter case, evidence at the accident site shows no pre-impact damage or airframe malfunction, the decision may well be to forego the complete reconstruction and extensive metallurgical examination that would take place in the case of an inflight breakup. But even if the decision is made not to reconstruct and perform laboratory testing, an opportunity for improved safety will be present if we keep in mind the need of manufacturers for facts beyond those labeled "cause-related".

We had such an opportunity, when, not too long ago, we participated in an investigation that resulted in a finding that the accident was probably caused by adverse weather conditions. Nothing could be found to indicate any other cause that might have contributed to the accident. During the investigation, it was found that the elevator cable had been rubbing against an internal fuselage ring to the extent that the cable had cut through approximately ¼-inch of the ring. The aircraft was new with a total time of approximately 50 hours. The necessary documentation of this condition was obtained and delivered to the airframe manufacturer. As a result of this information, procedures were changed to eliminate this type of event occurring again. That cable had nothing whatsoever to do with the accident. It was not a cause-related fact, but had the rubbing continued, it may well have developed into a probable cause-related fact.

Non-cause-related facts that benefit a manufacturer in many cases are easily and quickly obtained. We were involved in a case where a delightfully honest gentleman in his 50's readily admitted during a post-accident interview that he had been aware of a "Murphyism" on his aircraft for some time. On-scene investigation revealed that the gas filler cap on the top side of each wing of this popular 4 place general aviation aircraft was marked with an inscription which read "32 gallon capacity". This inscription was actually cast in the cap. This aircraft was known to have a 28 gallon capacity tank and the injured pilot stated he was aware of that and always figured 28 gallons, not 32, in his preflight planning. He further said that he had no idea where those caps came from, but they had been on the aircraft for quite a while. We felt the manufacturer would like to know about this and therefore made the information available to him along with photographs and other documentation. We do know that engineering steps were taken to eliminate the interchangeability between caps marked 32 gallons and those marked 28 gallons.

Not all information is as easily obtained. If we go back to the example of the possible inflight breakup, a considerable amount of work and analysis is involved, a great deal of which cannot be performed at the accident site. It may be, and is usually necessary, to transport all or selected portions of the material in question to suitable facilities where they can be properly analyzed. This latter situation, requiring special facilities and more detailed examination, is often the case when we deal with electrical and mechanical components of the aircraft; the avionics, the black boxes, the propeller, and certainly the powerplant.

In the case of the powerplant, if upon arriving at the accident site, the engine is observed to have a four inch hole with a connecting rod protruding out, all would agree that the engine should be disassembled and an analysis made as to whether the function of the powerplant in any way contributed to the accident. While we may have complete agreement on the need to completely disassemble the engine in that case, experience has shown that we do not have complete agreement when we arrive on an accident site and find no external or visible damage, disturbance or evidences of a malfunction. If we add to the facts I just stated; sufficient, provable facts that lead to an almost inescapable conclusion that the accident was a result of weather factors, opposition to removal and subsequent complete analysis and examination of the engine becomes more pronounced. I believe the need to proceed with the examination and investigation can be illustrated by looking at current developments within the aviation community.

Specifically, I refer to efforts that are presently underway which would result in a regulation enabling federal agencies, specifically the NTSB of the United States, to require pilots to submit to a medical examination at the discretion of the NTSB following an accident or incident in which they were a part. The reasoning behind the proposed regulation is very apparent. Until the medical examination is performed, there is no way of knowing whether there exists or does not exist physical conditions on the part of the pilot that may have contributed in some manner to the occurrence itself. The same is true with the powerplant. A teardown and examination is necessary to establish fact. The facts that are discovered during an engine teardown are always of value. The facts may be such as to rule out any involvement of the powerplant in this particular accident. Conversely, the facts may show that there was a malfunction which adds to our knowledge of the accident. In every case facts are obtained by the manufacturer which add to that manufacturer's body of knowledge concerning their engine, which enables it to make decisions for the improvement of the product resulting in greater overall aviation safety. The same reasoning behind a desire to examine the powerplant more completely is true of the other components; the avionic, electrical, hydraulic, and propeller. In short, whenever disassembly would add to information not otherwise available. The type of information derived from a continuing investigation of many of the component parts is the same type of information that is available to manufacturers following a major aircraft accident investigation where the results of this investigation are made available and utilized by manufacturers. The use of the information is the same, the rationale for the procedure is the same and no good reason exists why such information should not be made available to any manufacturer in the interest of aviation safety, be it a large air transport category aircraft or a small two seat aircraft. This small two seat aircraft may carry a maximum of two, however, it represents one of approximately 28,000 of the same make and model being operated by the general aviation community in the world today. It is a known fact that general aviation fatalities far exceed those fatalities in air transport category aircraft accidents every year.

In attempting to continue the investigation, I personally have been criticized by other investigators for wishing to continue after a determination of probable cause has been made. My purpose is not to criticize their determination of probable cause, but only to find additional facts both cause-related and non-cause-related. Neither I nor any other investigator standing on the side of the mountain can tell with certainty what may be found by a disassembly of that powerplant. I do know that what will be found upon disassembly combined with the documentation from the manufacturer's other sources of intelligence, including previous accident information, may give the manufacturer enough information to take action which could very well result in the improvement of the safety of that product. This, in the broadest sense, is an improvement in aviation safety and improving aviation safety is the name of the game. The cost of this powerplant teardown and follow-on component examination is always borne by the manufacturer (in the case of this taking place) subsequent to the determination of probable cause. The information obtained is made available to the NTSB or FAA as well as other manufacturers.

As I previously stated, I am in no way trying to criticize or point a finger at the federal agencies in their investigations. On the contrary, I will compliment their outstanding contribution to aviation safety and accident prevention as a result of their investigations. I did state that investigations may be restricted by factors of time, money, and results and I think you'll all agree that there must be a stopping point.

Recognizing and avoiding conditions which may lead to an accident is often much more difficult than in correcting a condition that is known to have caused an accident: a cause-related fact. I said at the outset that I was not going to get involved in definitions and I have attempted to avoid doing so. However, it does appear very clearly that a cause-related fact can only be a fact which in some way contributed to an accident. We don't want to wait for an accident in order to get facts that we can use. We want non-cause-related facts. I admit that what I'm advocating is not the easy way to do it. But I am advocating that the results from doing it the proper way are well worth the effort.

The Probable Cause: A Detriment to Air Safety?

Tom H. Davis, Esq. *M00588*
707 W. 34th Street
Austin, Texas 78705

Psychologically, people are fault oriented. Whenever an accident occurs, everyone asks, "who's at fault?"; "who caused it?" This same attitude encourages the determination of THE cause, as distinguished from the causes. While it is difficult to imagine a situation in which only one cause was involved, yet the whole course of aircraft accident investigation as legislatively mandated is to determine "the probable cause."

This is a misnomer and detracts from the accident investigator's role of finding all of the causes. While nearly everyone will agree that there is no such thing as THE probable cause, but only a number of concurrent or contributing causes, yet the search goes on for THE cause of the crash, without recognition of the fact that it is difficult if not impossible to attribute degrees of causation. While degrees of fault may be obtainable; for instance, a person going 40 mph in a 30 mile zone would not be guilty of the same degree of fault as a driver going 60 mph, degrees of fault cannot be correlated to degrees of causation, except on a pro-rata basis.

While the fallacy in searching for "the probable cause" might appear academic, its real harm results in the effect such search has on other causes not given adequate consideration but pushed aside or eliminated in establishing THE cause. Wouldn't it be better and more encouraging to the accident investigator if his task were only to list those causes contributing to the accident without having to apply some type of subjective approach in determining which of these was THE cause, or establishing the degrees of causation. THE cause concept also encourages overgeneralization as distinguished from specificity and encourages the approach that leads to "the probable cause" as "failure of the pilot to maintain suffient altitude above the ground." The search for "the probable cause" also results in determining what happened and not continuing the search as to why it happened.

The oft repeated phrase that the pilot exceeded the structural limitations of the aircraft hardly explains the causes contributing to such a catastrophic event. Very few pilots are going to overstress their airplane deliberately and yet, having determined that "the probable cause" was overstress, the investigator has accomplished his objectives and therefore stops and does not continue in an effort to find out the reasons why it was overstressed.

Even though the effect of longitudinal stability and stick force per "G" was presented at the Annual Seminar in Ottawa in 1975, few investigators have gone into this area to determine why an aircraft was overstressed. While certification may not require a stick force per "G" determination, there is no valid reason why accident investigation should not require this type of determination of an aircraft's characteristics.

Particularly is this true when it is an established fact that some aircraft have a much higher rate of in-flight breakup than others. Is this to be discarded as just a fact of life, or shouldn't accident investigation aimed toward accident prevention and safety address itself to why certain aircraft have a much higher incidence of in-flight breakup than others? Coincidence alone cannot establish these disproportionate numbers. There must be reasons, and if the inquiry were to determine all causes of a crash, it would at least encourage rather than discourage this type of investigation.

On the theory that examples are the best teachers, the following are presented:

The search for "the probable cause" of a series of in-flight wing failures of a popular light twin aircraft led to the conclusion that the pilot exceeded the structural limitations of the aircraft, overstressing the wings and causing the in-flight breakup. Since "the probable cause" had been determined, additional investigation was not considered necessary. Only after repeated failures was an investigation conducted by the manufacturer at the urging of the FAA. This investigation, lasting several years, resulted in the finding that this aircraft not only had low stick force per "G" characteristics, but actually, in various configurations, would have stick force reversal and negative stick force per "G" characteristics. As a result of these findings and litigation involving more detailed investigation along the same lines, an AD was finally issued over five years after this investigation started. Apparently this corrected a dangerous characteristic. At least the number of in-flight wing failures of this particular aircraft dramatically diminished. Whether this was the result of the AD or the fact that as the aircraft got older, fewer were left or were in use, is unknown. Had the accident investigator's task been to determine all of the causes of a particular crash, the investigation into the stick force per G characteristics might have occurred sooner, since a finding of the obvious that the pilot exceeded the load limitations of the aircraft would not have satisfied the directive of determining all of the causes of the crash. All causes require findings of why, not just what, happened.

On the first flight of a light single engine aircraft following an annual inspection, engine failure occurred resulting in deaths and serious injury during the attempt at an emergency landing. The probable cause of this crash was determined to be engine failure as the result of contamination in the carburetor. Since "the probable cause" had been found, the investigation stopped there. Even though it was known that this aircraft had not flown for a considerable period of time prior to the annual, and a portion of the substantial amount of contamination in the carburetor was actually preserved, no investigation was conducted to determine how this contamination developed or why it was overlooked during the annual inspection. Had this investigation continued, as it did as the result of litigation, a chemical analysis of the contamination would have been made. The results of this analysis could have been followed through to determine under what conditions this amount of contamination can develop inside the carburetor of an aircraft which is not regularly flown. Certainly this type of information could contribute to air safety, if it were made known to operators of inactive aircraft so that precautions could be taken to prevent a recurrence. Additional investigation would have disclosed that it was not customary or common practice to disassemble the carburetor bowl during an annual inspection. In fact, it was doubtful that the carburetor was even drained or flushed out as a regular procedure. This inadequacy could also have been corrected, either by education or regulation. Knowledge of the conditions under which substantial amounts of contamination could develop would have alerted those responsible for annual inspections that they should be on the alert for such conditions following a period of long inactivity.

In another accident of a single engine light aircraft resulting in two fatalities, the discovery of contamination in the carburetor led to "the probable cause" of the crash. The fact that this problem was currently under investigation by the FAA and the carburetor manufacturer and that an AD was in the process of being issued aided the determination of "the probable cause" in this case. However, the facts also disclosed that the aircraft hit in a near horizontal attitude as the result of a flat spin. Since "the probable cause" of the crash—the carburetor contamination—had already been determined, no effort was made to determine why the aircraft crashed in a flat spin, as distinguished from an attempt at an emergency engine-out landing. Later investigation as the result of litigation in other cases disclosed that this particular model aircraft, though used as a trainer, had very undesirable spin characteristics. In fact, they were undesirable to such an extent that a major modification was made by the manufacturer in order to eliminate this hazard.

While computerized accident investigative data have been able to pinpoint those aircraft which appear to have above average accident histories; for instance, certain models have a disproportionate share of stall/spin accidents, the search for "the probable cause" has not initiated any real effort to determine why. Had such an indepth investigation been conducted, it would have disclosed that characteristics of a certain light twin aircraft are such that it should have never been certified due to its failure to meet even the general requirements of C.A.R.3. This additional investigation would have disclosed that the single engine stall speeds do not appear in the operator's manual and that there are many combinations of conditions in which single engine stall speed can be higher than VME. Therefore, during many training situations, the novice pilot may encounter a single engine stall having violent and unexpected characterictics while attempting to demonstrate the single engine flight characteristics of the aircraft at or near V_{mc}. These stall characteristics can rapidly develop into a spin, the characteristics and recovery techniques of which are unknown even to the manufacturer, since there is no spin testing of light twin aircraft. In fact, at least one manufacturer has recognized that it is too dangerous to conduct spin testing.

Since "the probable cause" of another crash was determined to be that the pilot exceeded the structural limitations of the aircraft while flying in an area where thunderstorms existed, no effort was made to determine why a pilot on an IFR flight plan under radar control would fly into such a severe storm. As a result, no effort was made by the NTSB investigator to interview the air traffic controllers who had radar contact and communication with the pilot up until the crash. While FAA procedure manuals require that statements be taken of those in the best position to possess information concerning the cause of the crash, for some unexplained reason, this was not done in this case. Therefore, by the time investigation was initiated with the possibility of litigation in mind, the controllers involved could not be identified or located. Reconstruction through the use of weather radar photographs and technical information concerning the capabilities of the air traffic control radar established to the satisfaction of a federal judge that the controllers involved could see the weather into which the aircraft was flown, even though the tapes disclosed no warnings whatsoever or even the mention of the possibility of hazardous weather. The court found that the pilot and the controllers were equally responsible for the death of the passengers, thus recognizing at least two causes of the crash, as distinguished from the one probable cause. Even these two causes could and should be further expanded to include the various reasons why the pilot flew into a severe thunderstorm or why the controllers failed to provide any warning whatsoever.

There are an infinite number of examples which could be used. However, they only repetitively emphasize the fact that there is no "the probable cause," but only a multitude of probable causes, and that the attempt to isolate and emphasize one cause as THE cause materially detracts from consideration any additional investigation of other causes that were also responsible for the crash, the elimination of which could materially contribute to air safety through the prevention of similar crashes from the same cause or causes.

Conflicts of Interest in Accident Investigation

M. P. Papadakis, Esq. *M00871*
1928 One Houston Center
Houston, TX 77002

Nothing could be better illustrative of the topic matter of this talk than using the recent DC-10 tragedy at O'Hare as an example. Almost immediately it was evident that this air disaster would precipitate the most expensive and massive aircraft accident investigation of all time. In its course and scope nothing compares. While this endeavor rightly escalated from an on-scene investigation of a single crash to an investigation of a manufacturer and finally to an inspection of an entire industry, it is very illustrative of the fact that many participants in an accident investigation have vested interests.

Initially with almost 300 dead there is no doubt that the surviving family members' claims of damages from resultant lawsuits will be astronomical. Estimates of the damages run as high as one-half a billion dollars and realistically well over $100 million. Property damage in loss of the aircraft can be estimated between thirty and fifty million dollars.

Since a passenger may have a cause of action for wrongful death as a result of negligence or because of product failure, there may well be several defendants resulting from this accident. For instance, to list some possibilities that already have been discussed in the New York Times:

1. The airline for faulty procedures in maintenance
2. The airline for faulty inspections
3. The manufacturer for pylon design
4. The manufacturer for choice of metals
5. The manufacturer for leading edge devices
6. The supplier of failed bolt
7. The supplier of leading edge devices
8. The U.S. Government in failing to inspect
9. The U.S. Government in negligent certification

One can see immediately that certain participants in this investigation stand to suffer a pecuniary loss far greater than the simple changes required to preclude a happening from re-occurring.

In this case one could confuse the issue even further with some not so obvious interests such as:

1. The FAA had on a previous occasion with a DC-10 not performed as forcefully as it could have
2. A consumer group called the Airline Passengers Association going to court to seek grounding of the DC-10
3. Airlines losing millions of dollars in revenues while the aircraft is grounded.

Using a major air disaster as an example points out quite clearly that the many parties to the investigation represent interests whose pecuniary loss is substantial.

While an air disaster points out the fact that parties to the investigation may have vested interests in the outcome of the investigation, it is a poor example if one implies that results obtained by the investigator of a disaster are tainted.

At a major disaster there is such a massive contingent of talented investigators as provided by the government and legitimate parties to the team that no stone remains unturned. The spotlight of world attention forces an atmosphere of professionalism that transcends the borders of vested interests. Finally the public hearing is a forum to which evidence may be introduced by all parties, even those holding a minority viewpoint. Furthermore, funding for an investigation of this course and scope is usually adequate; the results meritorious. Luckily the air disaster happens infrequently as compared to the General Aviation accident.

This is the type accident where an abuse can happen more easily. Generally speaking there is only one NTSB investigator on hand. He is expected to be an expert in *all* facets of an investigation (in an Air Disaster the NTSB may furnish one or more of their own to head up many of the groups). Interested parties (those with vested interests) are just as present in the General Aviation accident, and the single NTSB investigator is responsible for the conduct of the investigation.

While an air disaster focuses the attention on a single event and the money interests are obvious, the pecuniary loss and exposure total is actually far greater in other than Air Carrier aviation. For instance: $100,000,000 in hull damages, and several thousand lives and billions of dollars in liability claims for injury and loss of life. (Just as in the air disaster, the claims are inflated as compared to what actually gets paid.)

However, it is altruistic to believe that the insurance companies' reason for existence is to alleviate the widow's pain. To the contrary, like any other company they are in the business of making profit. Certainly then, the criteria for success in that business is:

1. To sell as much as possible
2. To evaluate the risk of properly
3. To pay as little as possible

At the general aviation accident the NTSB investigator in charge is in an unenviable and very responsible position. He is not usually a master of all the disciplines required in a complicated investigation. Rather he is very similar to the Trusted Family Treating Physician who is calling the shots for a patient whose illness requires the advice of one or more medical specialists. This NTSB general practitioner is further restricted to some extent by time constraints and budgetary considerations. The time constraint is a result of the NTSB guideline that expects the in-field report be forwarded to Washington in a timely manner (usually 6 weeks to 60 days). With some regions investigating upwards of hundreds of accidents it is simply true that certain of the air safety investigators do not have adequate time to devote to a complete accident investigation. While government facilities and laboratories exist, their usage is on a priority basis and they at times are also overworked. However when an investigator at the scene allows evidence to be moved, dismantled, inspected, photographed and tested metallurgically there is the possibility of contamination.

Within our own federal court system the best legal minds have established a system where a federal judge is afforded a position of immense responsibility, respect and authority. To preclude the possibility of political pressures on the judge, his job is not subject to the electorate. His judgments need not be tempered by considerations of the political climate or of next year's election. His term is for life, thus job security is not a problem. His pay is designed to be adequate to free him from need and satiate his reasonable wants.

On a regular basis this federal judge makes determinations in civil cases where the outcome of the case may rest solely on the discretionary determinations by the judge of the probative value and trustworthiness of evidence offered by the parties. This federal judge then makes decisions of approval or disapproval over what the jury may or may not hear and see. The dollar amount in controversy of civil cases heard by the federal judge will always exceed $10,000 but seldem will they exceed the dollar amount in controversy in a single aviation case. The federal judge decides if proper predicates have been laid, if the evidence has probative value, if it is trustworthy, if it is too prejudicial and if it meets the requirements to allow it to be seen by the jury. A tough job.

But in truth the NTSB investigator in the field at a general aviation accident investigation is faced with problems and responsibility similar to that of a federal judge. While the plaintiff and defendants have not as yet become defined, the investigator is faced with working with potentially adverse fact gatherers. Furthermore, the investigator at the scene of the accident sorts through the wreckage and only reports facts he feels are relevant and material to show the ultimate causation. He alone determines the probative value of the evidence presented him. To include or exclude is a decision that is solely his and from which there is no appeal. Once the wreckage is moved, inspected and finally cleared for salvage those facts that went undiscovered will in most cases remain so.

What can be done to alleviate such problem?

1. Training — The NTSB investigator should get some indoctrinational training that will familiarize him and make him aware of the existent parties to the investigation who may have vested interests in the outcome of any such investigation. Foretrained is forewarned.

2. Continuing educational programs should be encouraged and promoted by the NTSB. Continuing education from within the NTSB, from universities such as USC and Arizona State and correspondence courses and related safety courses should all be promoted. Membership and attendance at ISASI should be credited. Cross-pollination with military schools should be encouraged. Continuing education simply provides the investigator with more of the tools necessary to better work with the diverse parties afield. Promotion and job preference should be dependent both on seniority and experience as well as education accomplished. Funding for education should be made readily available. Time for such education should be regularly provided.

3. At the General Aviation Level:
   a. More investigators should be hired
   b. More time should be spent per investigation when warranted
   c. More funding should be allotted for the investigation teams
   d. More funding should be allotted for laboratory and tear downs
   e. Expenses should be increased for the investigator in the field
   f. Investigators should be praised for continuing investigations instead of wrapping them up.

4. Excellence in investigative procedures should be recognized by awards, promotions and rewards.

I believe that Aviation Safety is advanced measurably every time an aircraft accident has been investigated properly. Since this job is so important, I believe that the NTSB investigator in the field should be the most professional person possible. To this end I suggest in a limited sense (limited to NTSB investigators) that bigger and better government is appropriate.

Fault-Tree Analysis: Accident Investigator's Role in Safe Aircraft Design

James Francois Leggett, Esq. *M00847*
Suite 2025, One Washington Plaza
1201 Pacific Avenue
Tacoma, WA 98402

The length of Mr. Leggett's paper precludes full reproduction. The major substantive arguments are presented. Readers desiring elaboration are invited to contact the author.

Introduction

A survey of recent court opinions and scholarly comments in the field of design liability reveals a single thread which ties this field of study together. Regardless of whether the theory upon which recovery is based is warranty, negligence, or strict liability, the common element which dictates the result is whether the item, as designed, is safe or not. Prone as the legal profession is to the negative, this requirement may be phrased as: unfit for its intended use; not living up to the buyer's reasonable expectations; negligent failure to foresee; unreasonably dangerous, or defective in design.

This may appear to be an oversimplification. However, its purpose, as is this article's, is to highlight the definition of the word "safe". The courts have long struggled indirectly with this term and attempted to define it by listing what it is not or by modifying it. Such efforts do little more than muddy the waters. The System Safety Engineering definition of "safe" is existence of risk at an acceptable level.

Many commentators have argued that the true basis, for judicial decisions holding manufacturers liable for injuries to consumers involving their products, is either that the manufacturer is in a better position to spread the cost of the injury or that the increase in the cost of the product to prevent the injury would be less than the cost of the injury to the consumer. True, the manufacturer/insurer theory has been mentioned in court opinions, but, in the same passages, the writers have disclaimed it, and instead, grounded the decisions upon some fault of the manufacturer. The discovery of this fault was facilitated by shifting the burden of proof to the manufacturer and by testing this proof against obtuse theories of warranty, misrepresentation, negligence, or strict liability all of which center upon the safety of the product design.

The difficulty with applying the balancing of costs test of the risk/utility theory to the modern basis for evaluating liability is that it too was born of fault grounded in basic negligence doctrine with all its defenses. The modern theories find fault in the lack of safety of the product design rather than in any overt negligent conduct of the manufacturer or unforeseen contributorily negligent conduct of the consumer.

All but the very conservative of courts and commentators have recognized a duty on the part of manufacturers to market a product which is safe for everyone upon which it may impact. The doctrine underlying the traditional negligence theory of product liability has very little place in the protectionist attitude toward consumers, and the realization of the unreasonable burden of proof upon the plaintiff in accident investigation has moved the overwhelming majority of courts to place the entire burden upon the manufacturer to prove that the product was safe. (The formalities of alleging proximate cause and integrity of the product after leaving the control of the manufacturer have no impact upon the safety of the design.)

Having established that this duty exists, it serves little purpose to attempt to limit its impact by discussing a cost/risk analysis of the adequacy of labeling. The American consumer has been led to understand that "someone" insures that all products are safe. The next step is to find a design tool that will enable the manufacturer to know in advance and the court to discover upon review that the product is safe as designed. Such a tool is Fault-tree Analysis. This process is an on-going technique of safety engineering and has been and is being successfully used by the National Astronautics and Space Administration and major aerospace corporations. Not until this decade have the applications of this process been fully explored.

With the implementation of the new federal rules of evidence in July, 1975, this process, which extensively relies on data collected by numerous secondary sources, has become a practical element of the case for the defense. The fact that a manufacturer utilizes a System Safety Engineering program is useful in a design liability suit in two ways. Where the court adopts traditional product liability theories, but as a result of recognizing the unacceptability of putting the burden of proof on the plaintiff, the factual documentation of a System Safety Engineering program acts to both rebut the presumption of an unsafe design and supplies the plaintiff with a comprehensive package of factual data on the safety of the product. This allows the basic issue, "safety", to be factually litigated and avoids distraction at trial with emotional side issues.

Where the court recognizes that the manufacturer has an absolute duty to insure that any product he places on the market meets a minimum safety standard, the existence of a System Safety Engineering program provides factual evidence that can be tested as to whether the product meets the standard. The existence of such a standard is consistent with the policy of fulfilling reasonable expectations of consumers which is familiar in the insurance field.

Unless manufacturers are provided with a tool which enables them to forecast exposure to future product liability with some reliability, the uncertainties now surrounding potential liability will guide the product liability field the way of automobile and malpractice insurance. The desired incentive for the manufacturer to design a safe product will be replaced by an incentive for consumers, who eventually pay the insurance premiums for the manufacturers, to encourage a statutory limitation on product liability recoveries.

Impact of Definition of Safety

The value of System Safety Engineering and Fault-tree Analysis to the field of product liability is found in the visibility of the definition of what is a safe design. The courts have attempted to define the acceptable standard of safety based upon the risk-utility theory, but their efforts have been increasingly hampered by balancing the risk to the mangled child against the utility of a cost increase. Faced with a situation, the outcome of a majority of courts is predictable, no matter upon which theory the action is brought. However, neither court nor commentator has felt free to hold simply that manufacturers are absolutely liable for any harm done by their products. Their technique to provide recovery and not impose absolute liability is to couch their theories in qualifying terms which translate into "safe". Because there is no strict rule, courts will often justify their decision by considering social policies that tip the balance in support of their position.

Armed with such an analytical tool, the defendant has the opportunity to cut through the tangle of fractionalized theories of liability and focus on fault. The test data, the adequacy of the qualitative diagram, and the computation of the ultimate probability of failure is open to cross-examination and attack by the plaintiff's experts. However, in so doing, the real issue in the product liability case is being presented to the jury — *Is this product safe?* Depending upon the position of the acting jurisdiction upon the continuum of product design liability theories, from traditional to strict, the impact of the resolution of this question upon the subsequent phases of the litigation will vary. Where the product is found to be unsafe, the case may be considered resolved and liability imposed without even proof that the product reached the consumer in the condition it left to the manufacturer. The burden of proof on this issue, as a condition precedent to application of strict liability doctrine, avoids potentially oppressive results. Of course, the plaintiff will still be required to prove proximate cause, but, having satisfied this requirement, the manufacturer of an "unsafe" product could be considered *per se* at fault.

A more troubling problem may confront the court where the product is found to be "safe". The particular jurisdiction involved may release the manufacturer from liability at this point, or which will most likely be the case, put to the plaintiff the task of proving some fault on the part of the manufacturer under traditional theories of product liability. In such a situation, the court would not be able to cloud their rationale in the conclusionary holding that the product was "unsafe". It would be forced to recognize the imposition of liability upon the manufacturer as a function of judicial economic redistribution, unless the plaintiff has proven the manufacturer was in some way at fault. The ultimate result of admitting the latter motivation in awarding recovery to the injured plaintiff would be a question for the legislature.

The basic requirement that the product design be safe exists in all current theories of product liability. The terms, used to describe what is a safe product, have been adapted to each field in order for the court to grant relief where the product was in fact unsafe. In many cases, the definition of a term such a merchantability or defective has to be expanded in order to prevent the manufacturer from escaping liability for putting an unsafe product into the stream of commerce. The difficulty with such an approach is that the responsible manufacturer is left without a reliable method to forecast the standard which his product will have to meet, and the reviewing court and the jury may be too confused by the nebulous theories available to support recovery and, in the end, find the decision turning on the fact of injury and possibility of a safer design rather than whether the existing design was safe. (The resultant effect on insurance and statutory response is examined later).

The requirement of a safe product easily fits into the various theories of product liability. The various modifications and exceptions attributable to each theory can be found to be unnecessary where a firm definition of safe can be found. The theories upon which product liability suits may be resolved are warranty, misrepresentation, negligence, strict liability, or Mr. Justice Traynor's application of strict liability. The terminology of these theories overlap, but they all attempt to define safety.

Conclusion

The judicial system should say to the manufacturer of consumer products: "Product liability should not be a subject from which to run or hide. On the contrary, it should be looked upon as a catalyst to motivate everyone to be honest and produce the very best product possible within the resources available. Product liability is perhaps the key factor to ensure that products manufactured in the future for public use will continue to improve in both quality and safety. Don't ignore it or it will ruin you. Recognize, understand, and use it, and it will help you to produce a better product and ensure a satisfied customer — which results in more business and profit."

Address by Dr. Assad Kotaite, President of the ICAO Council, to the Seminar of the International Society of Air Safety Investigators

I am very pleased to have this opportunity to address you — a group of professional investigators. There are several reasons for this.

The first reason is the international nature of your organization. I understand that the International Society of Air Safety Investigators comprises about 900 members from 30 countries, and that you expect members from additional countries in the future. I am also aware that your constitution states that your first objective is to promote international understanding of aviation accident investigation by providing professional education and I note that ISASI in that same constitution pledges its support to the role of the International Civil Aviation Organization in the field of aircraft accident investigation and reporting. Although the scope of the ICAO activities in this field is much broader than that of ISASI, I note at the same time that the concentration of ISASI on the professional and technical aspects complements the activities of ICAO in this field.

Another reason is the theme of this seminar: "The investigator's role in accident prevention". This emphasis on prevention parallels recent development in ICAO. Some of you have just attended an Accident Prevention and Investigation Meeting at ICAO. For those who did not attend that Meeting and who are not familiar with ICAO let me hasten to add that the title of that Meeting signified ICAO's intention to place increased emphasis on accident prevention, without losing sight of the important objective of thorough accident investigation and accurate reporting. It thus appears that both organizations are scrutinizing accident prevention more closely.

One of the main achievements of the 1979 Accident Prevention and Investigation Divisional Meeting (AIG/79) was a recommendation that a Manual on Accident Prevention should be produced by ICAO with a view to enhance aviation safety on a world-wide basis. For this purpose *Accident Prevention* was defined by the Meeting as:

> "The search for, detection and assessment of hazards and the development of appropriate methods, recommendations and actions to minimize or eliminate aircraft accidents and incidents,"

with the understanding that the basic intent of accident prevention is to *complement* existing administrative safety related methods (including accident/incident investigation) and organizational requirements. The basic philosophy upon which such an ambitious programme should be based was discussed at length by the Meeting and the Meeting agreed to a detailed outline for the future ICAO Accident Prevention Manual. Some of the main headings are:

Fundamentals
- — Causal factors in accidents (Man, Machine, Environment)
- — Roles and basic responsibilities in Accident Prevention
- — Trust and confidence between parties involved (no blame)
- — Risk concept and risk management

Methods
- — Information sources in the search for and detection of hazards and safety deficiencies
- — Methods and means for analysis and evaluation of deficiencies found and assessments of their impact on safety
- — Prevention action
- — Practical applications

Training for Personnel Involved in Accident Prevention

Appendices (typical programmes and solutions in use)

The Meeting also recommended several amendments to Annex 13 which is entitled AIRCRAFT ACCIDENT INVESTIGATION. These included:

a) an amendment of the definition of "Accident"; to include fatal or serious injuries caused by parts of the aircraft becoming detached, or by jet exhaust blast;

b) an amendment which emphasizes that the Investigation Authority shall have independence in the conduct of the investigation and unrestricted authority over its conduct;

c) the strengthening of a paragraph concerning the privileged status of certain investigation records or documents for purposes other than accident/incident investigation;

d) the addition of a new chapter on Accident Prevention dealing with the processing of urgent prevention action and safety recommendations resulting from accident/incident investigations.

Another achievement of the AIG/79 Meeting was the review of the ICAO Accident/Incident Data Reporting (ADREP) computer system with a view to improve the accuracy of the reporting and the services made available to States. To achieve these aims the Meeting made nine recommendations. These concerned a variety of subjects such as greater flexibility in the printouts which ICAO provides to States, many new codes added to the ADREP system to provide a better coded description of an accident and better statistical feedback.

I should perhaps mention that there are now some 7,000 accident reports stored in the ADREP computer with respect to twin engined and larger aircraft. This year, ICAO States have made some 130 requests for information to ICAO. The average response time to such a request is less than one hour.

Finally the Meeting made recommendations on improvements to Flight Data and Cockpit Voice Recorders, and on the need for automatic recording of radar data, with a view to facilitating accident/incident investigations.

These recommendations are only a few of those developed by the Meeting. In this context let me point out that these recommendations are not a *"fait accompli"*; they constitute a first step on the road to acceptance by all the 144 States of ICAO.

A Second Look at a Fatal Accident: Searching for an Elusive Cause

Raymond C. Lee M00561
Raymond C. Lee and Associates
3600 South Yosemite Street #400
Denver, CO 80237

Perhaps some of you were present at the 1975 Annual Seminar in Ottawa when Messr. Guilleve, in his elegant French, discussed the very difficult search for the cause of the Caravelle III crash off Nice, France, in 1968. Here was an accident with an element of mystery, insofar as cause could be determined. The difficult and almost miraculous retrieval of a critical part of the wreckage finally targeted the cause.

Closely related to that case, and in my view as an aircraft accident investigator, the two most intriguing cases on record still remain the BOAC Comet crashes off Elba in January, 1954 and Naples, in April, 1954. Like the Caravelle III, both were in the Mediterranian Sea, in difficult areas. The sea was very deep off Naples and the exact location uncertain. The Elba site was more promising—the water was about 600′ deep, but surrounded by a World War II mine field that was unswept, and, at that time, unsweepable. Four British ships and chartered Italian trawlers located and retrieved the major items of wreckage—engines, most of the fuselage and inboard sections of the wings. Unfortunately, the wreckage did not help much in pointing the way to a solution until it was combined with flight tests, stress tests and medical evidence. By applying sound logic and tireless pursuit of every available fact, the Royal Aircraft Establishment reconstructed the accident precisely, and proved that the pressurized cabin had failed at 35,000′ just after reaching the top of the climbout from Rome to Elba.

Now, in both of the cases related above, missing parts were crucial in determining sequence of events, and ultimate cause. Everyone here who has participated in aircraft accident investigation knows the frustration that results when parts of the puzzle are missing, and probably gone forever. Occasionally some of us here have had the satisfaction of finding that missing link, as Sir Arnold Hall did at Farnborough.

The case at hand certainly does not begin to approach the awesome cost in lives, treasure and hazard so clearly evident in the cases related above, but there are some parallels in what I shall call the "investigative track."

First, isolate the wreckage area and make absolutely certain that you have done everything possible to preserve the evidence. I cannot place too much emphasis on the requirement for a very cautious and deliberate approach to the examination, retrieval and storage of the aircraft wreckage. In addition, I would suggest that in cases involving fatalities, it should be firmly kept in mind that a profound difference exists between an investigation conducted solely for the enhancement of flying safety, and one conducted for both safety and potential litigation. By no means does the latter place less emphasis on safety. In fact, in my judgment, at least, it does a much better job of preserving the evidence for a more thorough investigation, if that becomes necessary in the future.

Second, look at the wreckage and try to deduce what happened. In some cases, for example, spins, we can easily tell the direction of the spin, and the approximate violence of the maneuver by the configuration of the wreckage. In cases involving fire, a variety of metallurgical and chemical tests can be very useful in determining intensity, rapidity of growth, etc.

Third, look at a similar aircraft and analyze its flight characteristics, fatigue patterns and engineering design.

All of the above assumes, of course, that you have been lucky enough to find the wreckage, or at least the critical areas. If you have been so fortunate, then a variety of disciplines can be called upon to assist in determining the sequence of events.

On August 30, 1978, a twin-engine chartered aircraft was scheduled to take nine passengers from Las Vegas North Airport, to Santa Ana, California. Ceiling and visibility were unlimited at Las Vegas, the flight plan was VFR. The weather was typical of Nevada for August: sky clear, visibility 50 miles, temperature 81 °F, wind 260° at 4 knots. Field elevation at Las Vegas North is 2207′ MSL, which, under the conditions related above, computed to a density altitude of 4100′, well within the take-off and climb capabilities of the aircraft.

Witnesses (who were pilots) stated the pilot started his take-off near the take-off end of the runway and became airborne at the intersection. The aircraft passed over the end of the runway at about 100′ above the ground, then began a sharp pitch-up to a climb angle of at least 50°. Two thousand feet beyond the runway at about 400′, the aircraft made a hard turn to the right (described as a wing-over by one witness), reversed direction and crashed in an open field 1150′ beyond the departure end of the runway and 650′ to the north. It struck the ground in an almost level pitch attitude, right wing slightly low, and with a mild left yaw. All witnesses stated the engines appeared to be running with a high power setting.

In the photograph of the wreckage (Figure 1), you can see that all the major components are confined to a relatively small area. Nothing is missing and quite obviously, we are not looking at an in-flight component separation problem. One can see by inspection that the "G" forces were probably between 60 and 70. The fuselage floor and lower skins are still separated. Note that the wings and the tail assembly are still quite intact.

We looked into his background sufficiently to be satisfied that he was a stable, family oriented adult, and dismissed the possibility that he would have permitted the aircraft to enter such a deadly attitude if he could have prevented it.

The Operational Climate

After examining the wreckage and questioning the witnesses, a potential control problem became suspect. Why would a fairly high-time, seasoned pilot enter such a hazardous flight regime?

It simply did not seem reasonable that he would do so deliberately. In fact, we rejected this hypothesis very quickly and began to examine control problems. A control problem could have been caused by:

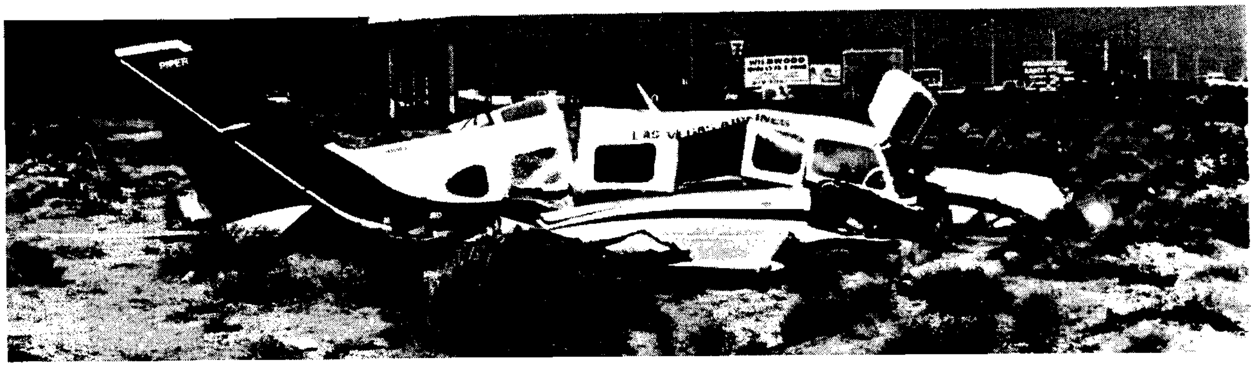


Figure 1

Now we get to the problem most of us have to face in the field. How did it happen? I use a fairly simplistic approach on accidents of this nature, and try to examine each possibility separately, e.g., the pilot technique, the operational climate, to include factors both inside and outside the aircraft, and the aircraft itself. Obviously some of these factors are not exclusive entities — they run together and it is often impossible to present them in exact chronological order. Let us examine each of these factors:

The Pilot

A 48 year-old, newly retired Air Force Colonel, with about 6400 hours. Became a rated pilot in the '50's. He had accumulated about 3500 hours in twin center-line thrust jets, none of them considered high performance aircraft in the Air Force, with the exception of the F-111, but all of them considerably higher in performance than the aircraft which crashed.

He had about 120 hours in the aircraft we are discussing — certainly enough to master the basics, but more importantly, he would have been, by nature of his Air Force training in jets, very cautious about entering high pitch-up situations. 1950 was the decade of the F-100 and adverse yaw associated with high pitch-up. Every pilot in training, or in the tactical force had this concept drilled in, and our pilot spent his early years in that era.

- Loss of power.
- Control system problems.
  - Cables and/or pulleys.
  - Trim problems.
  - Servo malfunctions.
  - Autopilot malfunctions.
  - Rigging problems.
- Weight and balance.

The operational climate within the aircraft was the subject of considerable research. Initial reports in the Las Vegas newspaper stated that the propeller on the #2 (right) engine was feathered, and not developing power.(Figure 2) Later investigation showed there were no blade hub markings to confirm this, and marks on the baffle plate indicated the control lever moved to feather position *after* impact. In the meantime, we wondered if the tourist in the right front (co-pilot's) seat might have inadvertently dropped a camera strap around the emergency fuel shut-off valve, which is located near the co-pilot's heel.

Could he have shut off the fuel when the camera was picked up? We tried to do this with a camera case and strap and found it was not possible. The force required to pull the fuel shut-off lever around the detent could not be generated from any angle, using a strap. It was unlikely that the pilot would have reached across the throttle quadrant, ducking below the windshield

Figure 2

and losing visual perspective, in the midst of an emergency maneuver. Furthermore, the aircraft could not have climbed to 400 feet altitude on one engine, so the fuel lever had to be on in the climb. All witnesses stated the engines were running at what sounded like full power. We concluded the lever probably moved as a result of high G-loads.

Some of you may have seen an Air Force film which was made years ago, in which an obsolete transport (Constellation) was deliberately crashed with a camera aboard to photograph control movements. The slow-motion film was very revealing. As impact was reached, the controls—throttle, mixture, propeller, etc., moved back and forth as if being manipulated by an invisible man.

The next candidate was the oxygen bottle, which had separated from its attachment point, which is just behind the rear cabin bulkhead. Could it have fallen down on the control cables, causing them to jam with resultant lack of elevator control? When the wreckage arrived in Denver, the bottle was missing. We located it and found that it had striations (imprints) of a small attaching cable (not a control cable), that had been made with such force that it looked almost like an engraving. Obviously, a cable had not sawed back and forth on the oxygen bottle. Furthermore, the condition of the material where it had been attached (which we finally located) clearly indicated the bottle had been ripped out with great force, undoubtedly on impact.

The last, but obviously very important item, was weight and balance. In discussing procedures with the fleet operator, we found that neither FAA nor company procedures required that passengers and baggage be weighed, and a weight/balance configuration calculated. By obtaining the various weights, it was found that the aircraft was approximately 236 pounds over the maximum take-off limit, but still .9 inch within the aft limit. Separate flight tests at this weight were not made until later, but type certification data indicated the aircraft would have met the FAA requirements for positive longitudinal static stability at 75% maximum continuous power.

The Aircraft

Six weeks after the accident (12 September 1978) our colleagues in the NTSB indicated a desire to reexamine the wreckage, which had been released by NTSB, retrieved by my company, and placed in our custody in Denver, Colorado. The engines were still in a shop in Los Angeles, after having been tested and found capable of producing power up to the point of impact. We recovered them some months later.

The NTSB team was particularly interested in a section of the flooring containing all aircraft control cables and turnbuckles, along with associated pulleys. In addition, they wanted a second look at all servos, the autopilot, oil pressure/temperature gauges and the fuel selector panel.

Their interest in the control cables was spurred by an incident at Martinsville,Virginia, on May 29, 1978, where a similar aircraft was damaged on take-off as the alleged result of an elevator turnbuckle becoming caught on the edge of a fuselage bulkhead lightening hole. (Cables pass from fore to aft through these holes.)

We were interested, too. Our fleet operator had experienced difficulty in maintaining sufficient cable tension to prevent a slack cable condition. Twenty-six pounds (using a tensionometer) was recommended, but some of the older aircraft had only sixteen pounds tension. A Service Bulletin had been issued on this subject after the accident, recommending that temperature be considered in adjusting cable tension, and also calling for the installation of cable guides in the lightening holes, as well as placement of a plastic sheath over the hydraulic return line.

For a short time, we thought this might be the problem in the accident we were investigating, but after removing floorboards on several aircraft and deliberately trying to catch the turnbuckle on the lightening holes, we found you could easily snap the turnbuckle past the obstruction, using only moderate pressures. We believed the pilot would have done so in this case.

In the meanwhile, all of the servos, trim motors and the autopilot components had been tested and given a clean bill of health.

By this time, one of my colleagues, Professor Norman Horton, and I, had had an opportunity to carefully examine the NTSB Group Chairman's Factual Reports. Simultaneously, we were taking a close look at the elevator, and particularly the variation in angle of the elevator that we had noticed in several fleet aircraft. When the aircraft is parked, the elevator is held in a down position by a spring which exerts 37 pounds of tension. Why were the angles different? We examined the spring in several aircraft, as well as the spring from the wreckage and found all of them to be free of defects. We also noted that the photographs of the accident aircraft, taken when it was lifted with a crane, showed the elevator to be in a streamlined position. (Figure 3.)

Figure 3

This examination lead us to a closer inspection of the elevator center hinge, (Figure 4.) which determines the limits of elevator movement around the horizontal axis. As you can see, the up and down movement of the elevator is controlled by two stop bolts, which are secured by single jam nuts. (Figure 5.) Could these stop bolts have moved, thereby reducing elevator movement? For the first time, a plausible cause became apparent. We discussed this with the maintenance director and learned that a similar aircraft had arrived from the factory with the elevator in the streamlined (almost horizontal) position with the elevator control in the full forward position. He had filed a Malfunction Defect Report with the FAA. The stop bolt had backed out approximately ¾", yet the inspection seal, which consisted of some putty-like substance, was still intact.

We found out later that, at the factory, it was not their practice to tighten the jam nuts to any exact torque specifications. In fact, a torque wrench was not used prior to this crash. That condition has since been corrected.

We went back to the NTSB technical review and found no mention of the center elevator hinge assembly. By this time, the secure area where we had stored the aircraft, was covered with three to four feet of snow—typical of Denver in December.

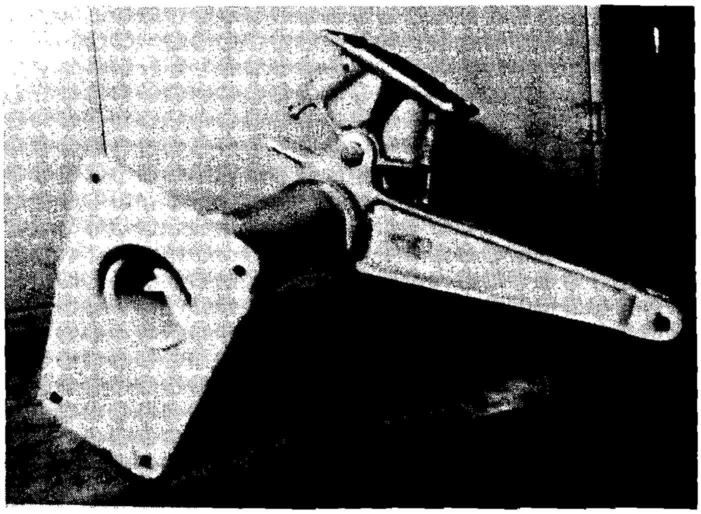


Figure 4

I called the storage area on a bleak and cold Friday and requested them to locate the center elevator hinge. On Monday, they called me to tell me that it had been located. I immediately drove to the storage area to have a look. Here is a photograph of what I found. (Figure 6.) As you can see, the marks where the bolt head struck the opposing hinge begin at a point where the bolt was initially screwed into the threaded hole, then appear to be spaced apart as the bolt backed out. The final mark is much deeper than the others.

Figure 5
Elevator Hinge Rotated against Down-Stop

I called the NTSB immediately and two investigators arrived to inspect the part. We agreed to leave it in the custody of the storage area until it could be examined by all interested parties.

Throughout the period we were conducting our investigations, Robert Burgin, of the Washington Headquarters, NTSB office, had been conducting flight tests which duplicated the accident aircraft's gross weight and c.g. conditions. He found that with gear down, 15° of flaps and maximum power, the elevator deflection require to prevent a pitch-up was 2.8° trailing edge down. The marks we found on the center elevator hinge indicated the pilot only had 1.5° of deflection. (The normal rigging is 16° up and 20° down ± 1°.)

In this respect, the accident investigation procedures resembled those in the BOAC Comet case—one party was working on structures and the other on flight characteristics. Burgin's work showed clearly that during take-off roll, with neutral elevator and neutral elevator trim, the aircraft would become airborne without elevator input. In fact, the test aircraft became airborne within 100′ of the lift-off point for the accident aircraft, then began a rapid pitch-up, which increased at the rate of 2° per second. The pitch angle reached 30° at an altitude of 320′, at a distance 5000′ from the take-off point. The test pilot left the gear down because the sudden pitch-up required his full attention. (Note: Gear had been retracted shortly after lift-off in the accident aircraft—this would have resulted in a more accelerated pitch-up.)

The elevator deflection required for take-off was 2.8° trailing edge down. As previously noted, our test indicated the pilot only had 1.5° of deflection. After examining the flight test data, and participating fully in the analysis of the elevator hinge assembly, the NTSB concluded that once the aircraft became airborne, the crash was inevitable.

The analysis of the elevator center hinge, conducted at the Denver Research Institute, an adjunct of the University of Denver, was attended by representatives of the manufacturer, the NTSB, the FAA, and my company. The results clearly indicated the following:

- The down elevator stop was backed out from its normal extended position.
- This had occurred over some period of time, as indicated by the seven strike marks on the torque tube arm. (Figure 6.)
- The threads on the bolt, which had been inside the aluminum hinge assembly block, contained smeared metal—smeared in the direction one would expect from a downward impact.

Summing up, I have tried to demonstrate that in our profession, which cuts across many disciplines, there is no substitute for patient and thorough investigation. Help should be sought from all qualified and unbiased sources. In this case, it was from both the public and private sectors. I commend the NTSB report on this accident to your study library. Not only is it a thorough and very professional document, it analyzes the approach to this accident very concisely. Most importantly, it contains some ideas and recommendations that will, if adapted, prevent similar accidents in the future.

Editor's Note:
Report No. NTSB-AAR-79-8:
Aircraft Accident Report
Las Vegas Airlines, Piper PA-31-350, N44LV,
Las Vegas, Nevada, August 30, 1978

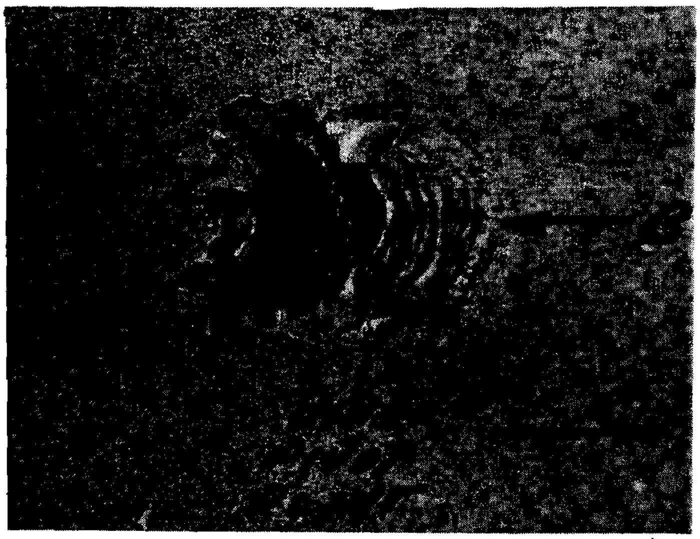


Figure 6

Mark on Hinge Frame Produced by Down-Stop Bolt (Approx 6X)

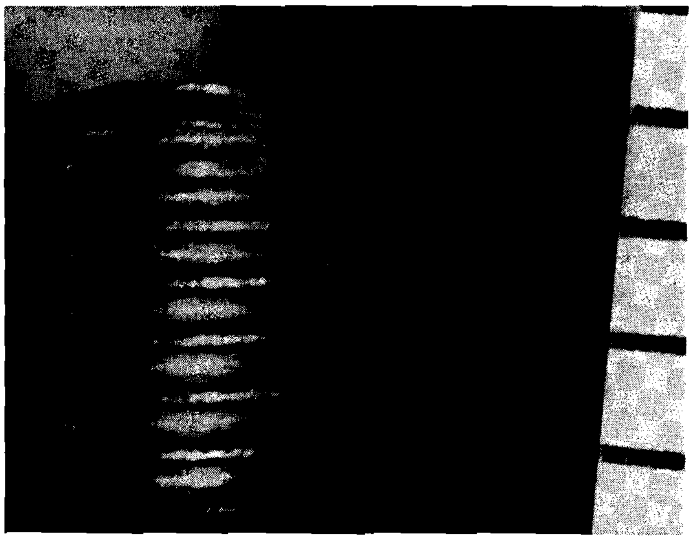


Figure 7

Lower Portion of Down-Stop Bolt showing Disrupted Coating

Ground Impact and Propeller Pitch Position

David S. Hall M00385
Crash Research Institute
Box 968
Tempe, Arizona 85281

This paper presents a generalized analysis of the effects of ground contact on the propeller system of typical general aviation turboprop and reciprocating engine aircraft, using single-acting, hydraulic control, constant speed propellers. A single-acting propeller of this type is one in which propeller control oil pressure is used to drive the propeller blade angle toward low pitch, while internal spring force (and sometimes compressed air) and counterweights provide the force to drive the blade angle toward high pitch. In some installations, the propeller is permitted to travel to full feather (high pitch) and reverse (low pitch) and in others the high and low pitch stops are more restricted, such as single engine installations where feathering and reversing are not used. Figure 1 is a drawing of typical constant speed, full feathering and reversing, single-acting propeller.

In addition to the above mechanical forces, aerodynamic force on the blade tends to drive it toward low pitch. A properly designed control system balances these forces, using appropriate propeller governor and control system design, to permit proper normal and

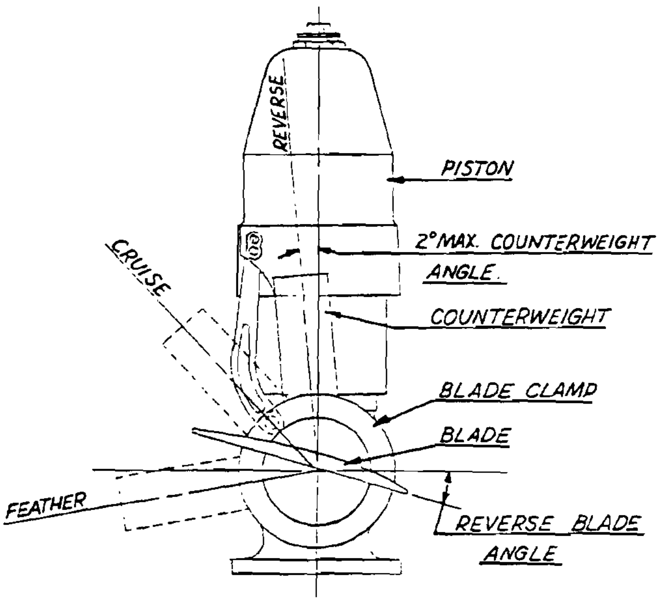
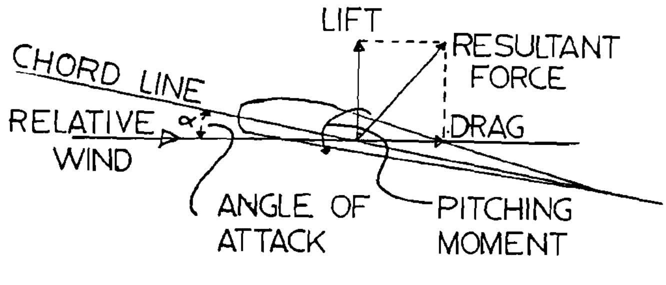


Figure 1

emergency operation over the full flight and ground envelope of the aircraft. It should be noted that since control system design is dependent in great part on the aircraft and engine performance, typically it is not possible to use the exact same propeller on different aircraft models, although the propellers may be physically interchangeable. A confirmation of correct model and part number of hub and blades is one of the first tasks of the investigator. It should also be noted that when oil pressure is not present these props will drive toward feather, or their high pitch stop, unless something like mechanical damage or a start lock system holds them at lower pitch. The investigator should not assume an engine problem just because the prop is feathered, even if it appears undamaged.

In addition, it is necessary that the propeller system provide the proper limit stops, feedback, and emergency feathering control. Discussion of these functions is outside the scope of this paper. A brief review of basic wing aerodynamics is necessary to our understanding of propeller aerodynamics, as was first recognized by the Wright brothers. Figure 2 is a typical wing section, with conventional aerodynamic force vectors and airflow indicated. See appendix A if these terms are not familiar. Note that lift and drag forces are respectively perpendicular and parallel to the relative wind, not the chord line of the airfoil. Aerodynamic pitching moment is assumed to act around the aerodynamic center of the section and acts in the nose down direction for positive values of α on subsonic airfoils. On a typical airfoil, maximum L/D occurs at a relatively low value (about 8 degrees) and high cruising speeds require very low values of α (1-2 degrees) to provide the necessary life because the lift is proportional to the square of the flight velocity.

When the airfoil section is part of a propeller blade, the relative wind is the resultant of blade rotation and forward velocity of the aircraft. This path is a helix and the propeller is sometimes referred to as an airscrew. Figure 3 shows the forces and angles of a blade element. The aerodynamic force can be resolved

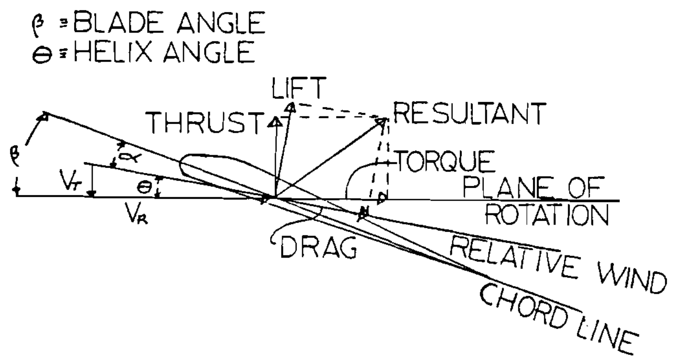


WING SECTION

Figure 2

into thrust and propeller torque, referred to the plane of rotation. Several significant relationships can be observed from this diagram.

1. As airflow velocity due to rotation (VR) increases at constant forward velocity, as would occur with a blade element farther out on the blade, the blade angle β will decrease for constant α. This means that a propeller blade should be twisted so that the section β at the tip is lower than the section β nearer the root.



PROPELLER BLADE SECTION

Figure 3

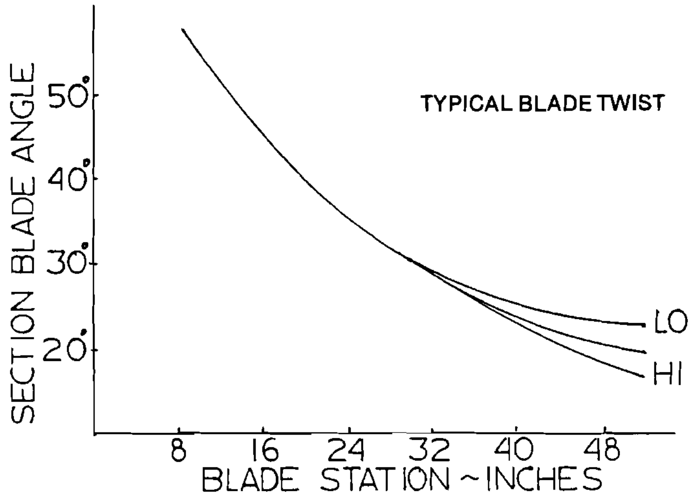


Figure 4

2. As flight velocity (VT) increases at constant rotational velocity, β must increase to hold a constant α.

3. As the table below shows, the helix angle of the relative wind is a function of blade radius and flight velocity, at a constant RPM.

HELIX ANGLE AT 30 AND 48 INCH STATION (2000 RPM)

TAS	30″	48″	DIFFERENCE
50K	9.16	5.76	3.4
100K	17.88	11.40	6.5
150K	25.82	16.82	9.0
300K	44.06	31.17	12.9

This infers that the twist built into the blade can only be optimum at one flight speed, and in fact the propeller manufacturer will optimize blade twist for the particular installation based on proposed aircraft and engine performance. The effect of RPM on this table is minimal. Typical values of blade twist are shown on Figure 4 for Hartzell blades.

4. As flight velocity increases and β increases the resultant aerodynamic force is tilted more toward the plane of rotation and thus the available thrust decreases while the power required to develop the thrust increases. Figure 5 shows the resultant force resolved into thrust and torque as well as lift and drag, at low and high β. Figure 6 is a typical performance curve for a turboprop installation.

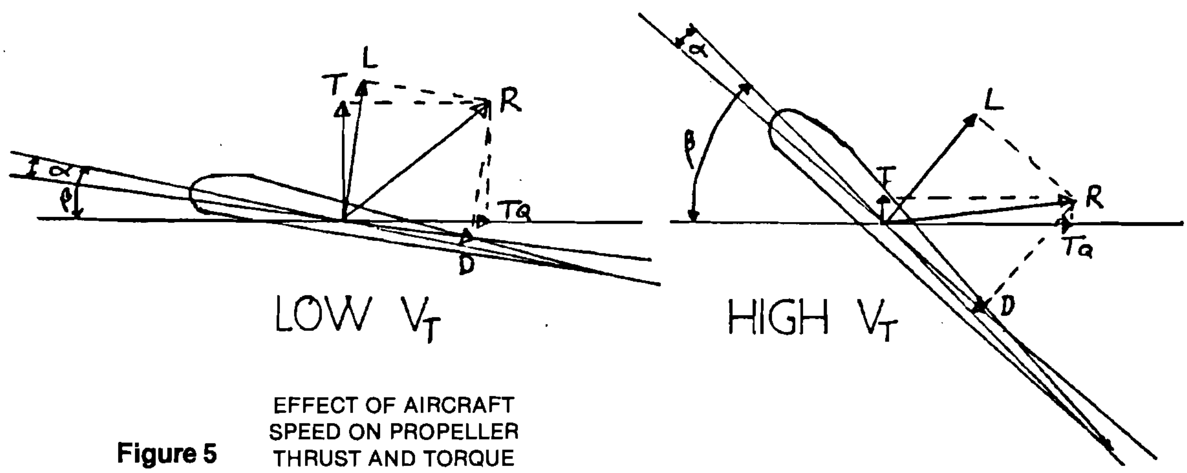
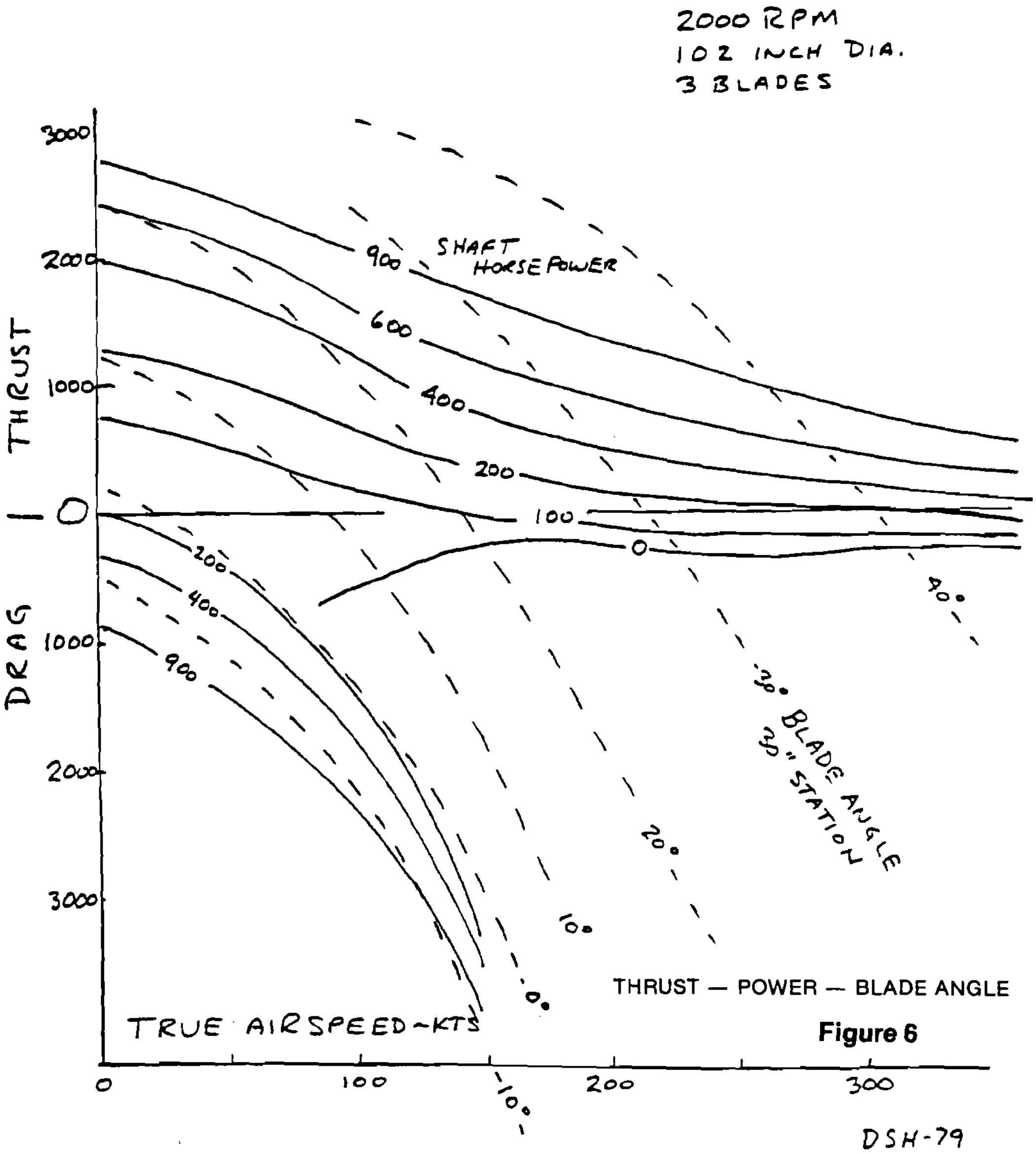


Figure 5 EFFECT OF AIRCRAFT SPEED ON PROPELLER THRUST AND TORQUE



THRUST — POWER — BLADE ANGLE

Figure 6

5. At high airspeeds very small changes in blade angle are required to change power required. Figure 7 is for the same prop as Figure 6.

6. A result of the above is that at low powers and moderate airspeeds, even props with low twist can have their tip operating at a negative α while producing positive total thrust.

7. Another result of this characteristic is that a windmilling propeller can produce enough power to drive itself to governing speed (assuming the engine load will permit it) as shown in Figure 8. Normal governing action will occur in this regard (if over speed occurs, β will be increased, thus L & D will decrease), but high negative thrust can be developed. Some engines provide a Negative Torque sensing mechanism to drive the prop toward feathering (high β) when this condition occurs.

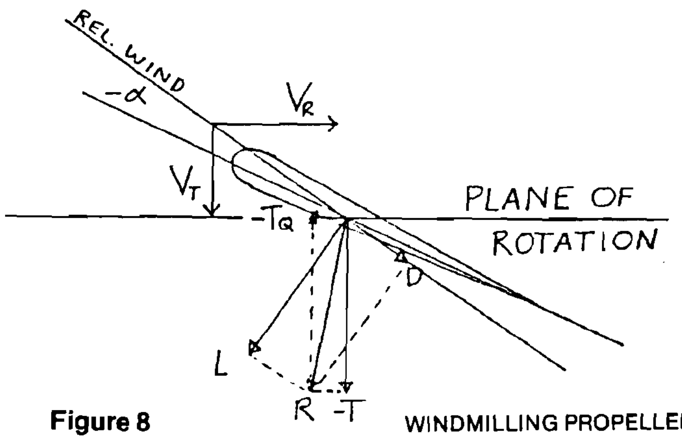
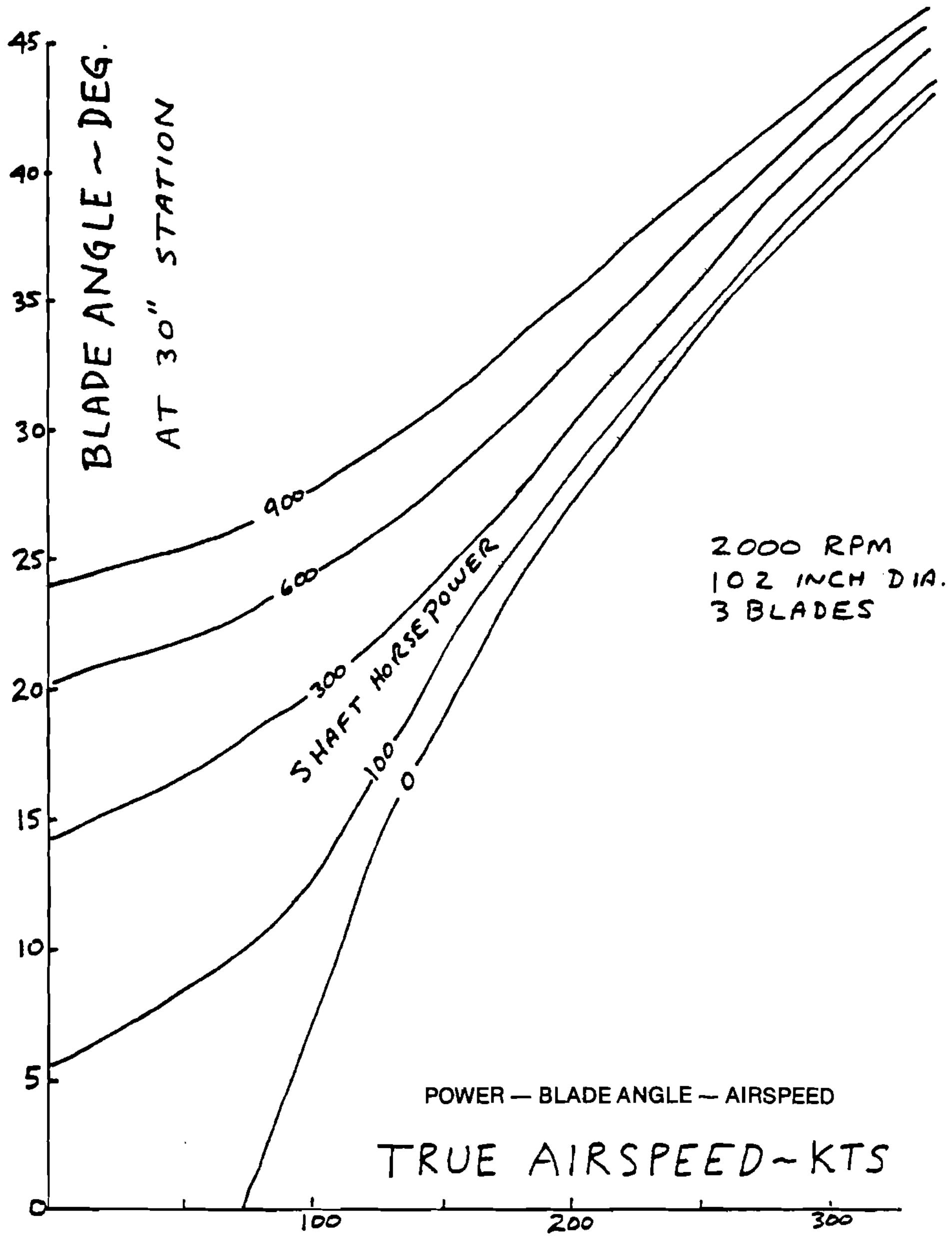


Figure 8 WINDMILLING PROPELLER



POWER — BLADE ANGLE — AIRSPEED

Figure 7 DSH-79

In summary, angle of attack (α) varies with flight velocity, propeller RPM, blade angle, blade radius and engine power for a given blade design. For a windmilling propeller, we can expect α to be negative for all blade elements, under all flight conditions, but for positive power, it is no necessarily true that the tip is always at a positive α for all flight conditions.

While the foregoing is not a complete study of propeller aerodynamics, it will permit an understanding of the resultant events when ground or water is substituted for air along the helix path.

The analysis which follows is based on this author's experience of investigating accidents involving these propellers for over 11 years. While rigorous mathematical proof is not provided (it may not be possible because of the many variables involved) the observed facts have been consistent with this theory in cases where the operating conditions at impact were known independent of the propeller evidence.

Let us now consider a typical light turbopropeller aircraft and its propeller system characteristics in accident situations. We will assume a 3 bladed propeller, turning at 2000 PRM, with forged aluminum blades and high twist (about 12 degrees from 30″ to 48″). All references to blade angle will be at the 30″ station unless otherwise stated. This prop might have the following settings at "Beta 30".

Reverse Stop	-6 degrees
Start	+2 degrees
Flight Idle	+12 degrees
Feather Stop	+88 degrees

When the aircraft is static and at low power, α and β are very small. At high cruise power, β is much larger than α (see Fig. 5). At the instant of ground contact, the ground will approach the blade along the helix angle and one might expect the tip to bend away i.e., forward for positive α and back for negative α.

For large positive values of α at the tip and low rates of descent into the ground, forward bending of the tip does occur. For large negative values of α at the tip and low descent rates, all blade tips will bend aft. These cases are typical of takeoff and landing accidents occurring at low flight speeds and low sink rates in a normal flight attitude. In other crash situations, and in all cases where the tip α is low positive or negative, most of the load of blade contact with the ground goes toward retarding the blade motion and trying to bend it along its stiffest axis. Although the blade is being forced radially outward by centrifugal forces, it is possible that the blade butt and hub might contact at a point in line with the location of the blade trailing edge. If matching contact marks can be found for this blade, the first to hit ground, β at impact can be established.

The predominant effect of this initial contact is to slow the rotation of the propeller and since it is unlikely that blade tip contact will appreciably reduce the aircraft velocity, the relative wind at the tip inevitably moves toward a higher helix angle and the tip goes increasingly negative (see Fig. 9).

EFFECT ON GROUND CONTACT ON α

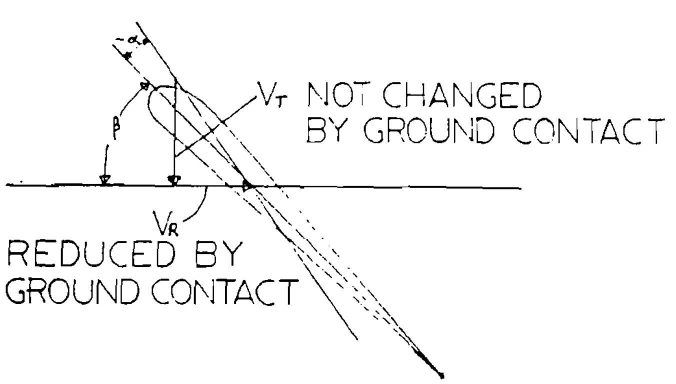


Figure 9

Under these conditions, and as contact with the ground continues, the tip now is forced to bend aft and, having begun to do so, becomes a lever around the blade axis of blade angle motion, providing a very large force in the direction of decreasing blade angle. The entire propeller mechanism is forced toward the low pitch stop, and the remaining blades, which have not yet hit the ground, are turned toward low or reverse pitch.

The high shaft torque developed will possibly shear the weakest point in the drive line on a turbo prop at this time, although this is dependent on the rotational inertia of the complete load. On a direct-drive reciprocating engine, the crank will probably slow with the prop. Neither of the above are absolute, as each case is a function of many impact related factors.

The second and third blades to hit, and any subsequent contact by all the blades, will be at very low pitch, often hard against the reverse or low pitch stop. Often the low pitch or reverse stop will be damaged and blades will be twisted beyond these stops in their clamps. This sequence is illustrated in Figure 10 with the impact marks on the blade butt typical of the Hartzell blade configuration. If initial blade contact is severe, the remaining blades will be inertially loaded toward the direction of rotation and may leave marks of this force or even depart the hub in this direction.

It is the author's experience that the above sequence of events is typical, although not absolute, in accidents involving this type of propeller system. Once the prop has slowed in rotation, the tip angle of attack will be negative. Once this has occurred and the blade starts to bend aft, full travel to the minimum stop is highly likely, and a full set of blades bent aft is the most likely accident finding. Contact damage to the low stop is also likely. Occasionally blades may have an S shape, with the tip forward and the midspan bent aft. In one case, both props were know to be fully feathered due to a severe lack of fuel in the vicinity of the engines, and both props twisted toward reverse after initial blade tip bending.

Detailed examination of the blade butt contact marks is necessary to determine which blade hit first, and then all other blade marks should be disregarded. Only when the first blade to hit can be correlated with hub marks can be impact blade angle be determined.

In summary, a finding of all blades bent aft and damage to the low pitch or reverse stop is not a positive indication of an engine and propeller system at no power or reverse blade angle at impact. This finding is possible even if relatively high power was being developed, depending on impact attitude, descent rates, and ground speeds. For accurate blade angle determination at impact, only the first blade to make firm contact with the ground or water will have meaningful data. All other blade contacts will occur after motion in the pitch change mechanisms.

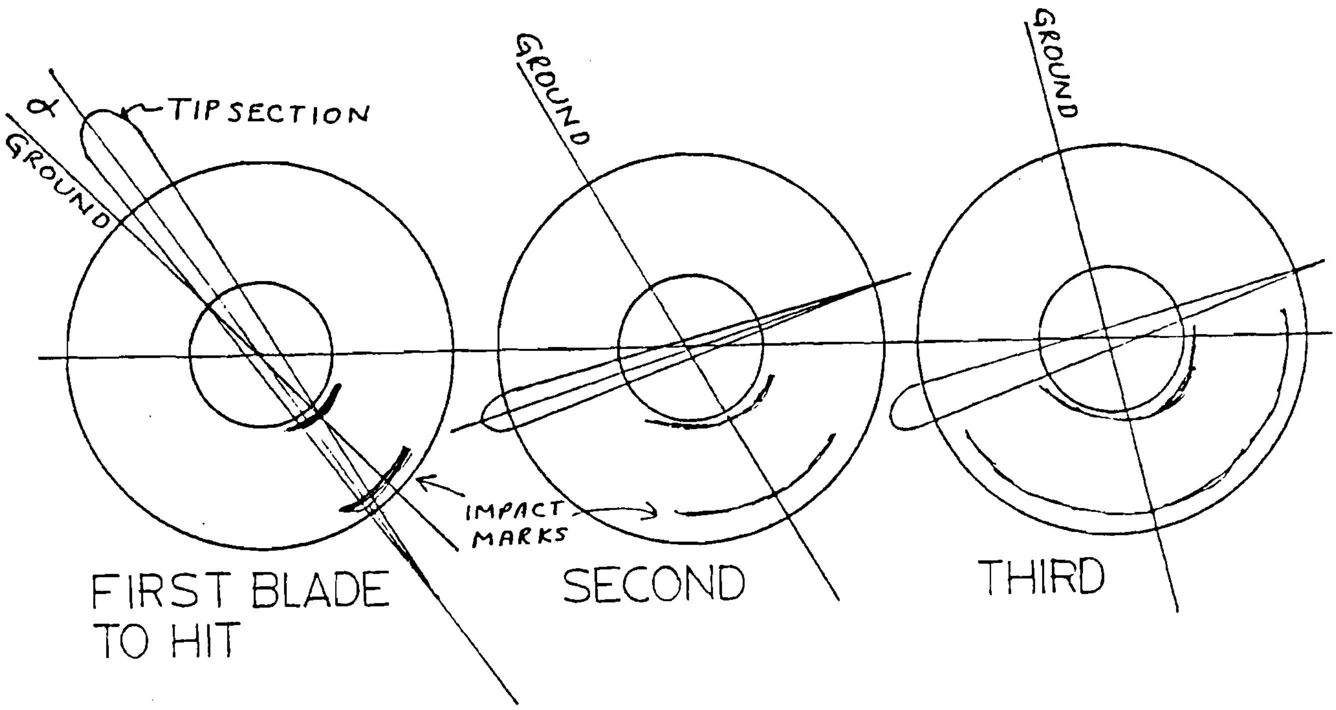


Figure 10 TYPICAL IMPACT MARKS ON BLADE BUTT FROM CONTACT WITH HUB

APPENDIX A

Important terms to understand, in moderately non-technical language. See Figures 2 and 3.

Resultant Force: The actual total force developed by aerodynamic effects on the wing or blade element, acts at some angle to the *relative wind* and at some point on the *chord*. This resultant force is mathematically resolved into perpendicular components and moments assumed to act at the *aerodynamic center* for purposes of analysis. These forces, if computed with reference to the relative wind, are *lift* and *drag*, and if computed with reference to the plane of rotation are *thrust* and *torque*. In general, aerodynamic forces are proportional to *angle of attack* for low values of , and proportional to the square of the airflow velocity.

Relative Wind: The direction of the air approaching the wing or blade.

Chord Line: A line drawn between the leading and trailing edge of the airfoil section.

Angle of Attack: The acute angle between the relative wind and the chord line, positive as shown. Represented by the letter Alpha

Lift: The force, perpendicular to the relative wind, developed by reaction of the wing section to the air flow around it, positive upward as shown.

Drag: The force, parallel to the relative wind, developed by reaction of the wing section to the airflow around it, positive aft as shown.

Aerodynamic Pitching Moment: The force, tending to rotate the wing section about the aerodynamic center, developed by reaction of wing section to the airflow around it, positive in the nose down direction as shown.

Aerodynamic Center: The point on the wing chord, approximately 25% from the leading edge for subsonic flows, where aerodynamic forces are assumed to act.

Blade Angle: The angle between the blade chord and the plane of rotation, usually stated at a specific radius for a given propeller blade, and sometimes called beta (β) angle.

Thrust: The force perpendicular to the blade plane of rotation, developed as a result of the reaction of the blade to the air flow around it, positive forward.

Torque: The force, in the plane of rotation, tending to retard rotation of the blade, due to reaction of the airflow on the blade, positive in the retarding direction.

INVESTIGATION CAN PREVENT AIRCRAFT ACCIDENTS

George B. Parker
Associate Professor of Safety
Institute of Safety and Systems Management
University of Southern California
Los Angeles, California 90007

Ironies of Ironies

On September 25th, it will be one year since George Saunders was killed in one of the most disastrous aircraft accidents in history. George was a member of the International Society of Air Safety Investigators (ISASI), one of the best investigating engineers and teachers in aviation safety. He was a contemporary of mine and a friend. It is truly ironic that he should have died the way he did, on his way to investigate another aircraft accident. Aviation would have been better served if George Saunders had been the investigator of the PSA 182 mid-air collision rather than the victim.

Another irony was the fact that thirteen days after the PSA mid-air collision, on October 8, 1978 and only about two miles from where the investigation was taking place, the Annual SAFE Symposium was being held. The proceedings included five papers presented on the subject of mid-air collision avoidance.(1)

It was also coincidental that the last time the author was in Montreal, just ten years ago (September 10, 1969), he bought a copy of *The Gazette* and featured on the front page was the account of the fatal mid-air collision of an Allegheny DC-9 and a Piper Cherokee.(2) This is another example of the repeat cause, or repeat of a known precedent. It is also evident that the previous investigation was not successful in preventing a repeat disaster—the PSA mid-air collision.

Accident Prevention

Last year the author was privileged to present a paper to the ISASI Annual Seminar entitled "Why Doesn't Aircraft Accident Investigation Prevent Aircraft Accidents?" The emphasis was on the problems in cause factor identity which, when lacking, result in a continuum of a cause or accident category.(3) In that this year the seminar theme is emphasizing accident prevention, this paper will strive to establish that investigation can, in fact, prevent aircraft accidents.

In the academic sense, there are two methods of preventing accidents:

1. Preventing occurrence, commonly known as "accident prevention" and encompassing before-the-fact management of the safety program.

2. Preventing recurrence, known by ISASI and others as "accident investigation" and comes into being when the first method fails, after-the-fact.

Both methods are, naturally, important. Hopefully, the first is the most important; it is also the most difficult to accomplish. The second method, the one most of us are involved with, is the least desirable for it requires that we sustain an accident in order to prevent one. It is an action taken almost as a last resort. And if it fails we are usually in serious trouble.

State of the Art

The crash of American Flight 191 DC-10 in Chicago, and its attendant publicity, has sullied the reputation of the accident prevention specialists in aviation. Coming so close on the heels of the PSA 182 mid-air collision, the press and other news media have come down heavy on the industry and those involved in the regulation of safety. While, in spite of the editorials and the cover story "How Safe?" in *Newsweek* magazine(4), the record of the United States air carriers has been improving from an already low accident experience. In 1978 the U.S. air carriers experienced the lowest accident rate in over ten years and a comparatively low number of fatal accidents and fatalities.(5) And barring further disasters like Chicago, the results of 1979 may not be excessive, statistically.

In U.S. general aviation the experience is not as good. The accident rate went up 5 percent, the fatal accidents increased 13 percent and the fatalities went up 11 percent in 1978.(5)

It appears then that the prevention specialists are doing well in the air carriers but still have not made much of an impact on general aviation.

The investigators have had a similar experience in general aviation — most of the causes are repeats. But even though it is too early to speculate on the history of the DC-10 engine pod failure, it is quite evident that the previous investigation of the Allegheny mid-air did not prevent the PSA accident.

Many investigators will argue that the responsibility for investigation is theirs but the responsibility for corrective action rests with other agencies and parties. And this is true, but only if the correct cause factors have been identified and proper recommendations have been made. In the parlance of computers, the adage "garbage in, garbage out" applies. The study of general aviation cause factors and mishap experience included in the author's paper presented at the 1978 ISASI Annual Seminar clearly indicated that many causes repeat and the reason is that they do not reflect root causes.(3) Petersen agrees when he states:

> Root causes are those which would effect permanent results when corrected. They are those weaknesses which not only affect the single accident being investigated, but also might affect many other future accidents and operational problems.(6)

C. O. Miller emphasized the fact that aircraft accidents have repeat causes. He said:

> Accident causal factors are seen repeated over and over again. Indeed, with the possible exception of rare hazards brought about by highly advanced technology, one hardly ever sees a truly new safety problem.(7)

If the system is to work the investigator must not only pursue the investigation and analysis with skill and integrity, but must have knowledge of how to identify the root causes so recommendations can be supported effectively and the repeats stopped.

Making the Investigation Process Succeed

The investigator must concentrate his analysis on the reason *why* the mishap occurred, relative to *how* it can be prevented. The *why* should obviously indicate, or be synonymous with, the necessary corrective action recommended. The *why* is not synonymous with excuse, blame, rationalizing, or factors that cannot be related to a management responsibility for correction.

Typical examples of ineffective causes, those that do not produce an answer to the *why* would be:

- *Pilot factor.* Indiscriminate use of pilot factor is a pretext that has been used in the past to indicate that "we haven't been able to find anything else wrong, therefore, the cause must be pilot error." The proclivity to use the word "error" instead of "factor" is a clue to the prejudice involved. The designation of any unproven factor is nothing but proof of a poor investigation and a lack of understanding of the investigative purpose.

- *Material factor.* Most often material "failure" is nothing more than ending the investigation process as soon as the *what* is answered. Material failure can be a handy excuse that may not hurt anybody. After all, "how can you penalize a piece of metal or a system? No one gets hurt this way." Unfortunately, no one assumes the responsibility to correct the problem either. Causes of this type fall into either the effect category or are a condition. Neither are root causes.

- *Act of God.* The ultimate in excuses. With this cause no one gets hurt at all — after all, "God is strong enough to handle it." This is a "cop out" that is used in disguised ways more often than recognized. The use of "weather," or "lightning strike," or "bird strike" are examples of things only God is responsible for. Again, we are dealing with conditions and excuses, most certainly not root causes.

With the proper evidence to support them and an analysis that answers the *why*, any of the above could be effective and proper cause factors. (The literate use of "Act of God" would be an obvious exception for most of us.) In later examples in this paper, root causes will be identified.

The Repeat Accident is not an Accident

An investigator can't have much experience if he is not aware of the fact that all cause factors today are one way or another a repeat of yesterday's causes. The term "accident" does not coincide with the repeat cause. The term, meaning "accidental," has many connotations which contradict the involvement of repeat causes. An event that is "accidental" would also have to be unexpected. There is nothing unexpected about a repeat cause factor that has been previously investigated, analyzed, and reported. Any factor thus designated is dealt with by recognition and action established to deter or eliminate. This is what investigation is for, what safety is all about.

McGlade tells us:

> The term *accident* is used in many contexts and with many nuances of meaning, thus creating considerable confusion about the meaning.(8)

Bird and O'Shell discuss the confusion about the term of *accident*, suggesting such alternatives as "event," "crash," and "contact."(9) However, none of them appear to satisfy the aviation situation.

Webster's Dictionary and Roget's Thesaurus provide us with literate alternatives such as "adversity" or "calamity." Degrees of misfortune are possible with increasing severity, ranging from "calamity," to "disaster," and "catastrophe," and, finally, to "cataclysm." But it would seem more practical to agree with Thygerson, who said:

> . . . In science if the cause of an event is known, that event is not an accident; most accident causes are known, but we still persist in calling them accidents. However, the word may be too deeply entrenched in the language to go out of use.(10)

All of which means that we are not going to be able to establish a better term for what we call an "accident." And it may not be important, in the literal sense. However, in the philosophical understanding and practice of the investigator it would seem imperative that he understand the misuse. And if he doesn't use a more literal term he must, at least, know that the adverse event he is investigating was in no way an unexpected or unforeseen caused situation. To establish effective recommendations for corrective action he must assign cause factors that concentrate on the repeat nature of the event. He must reconstruct the root causes by determining how often the cause has repeated — its history — and why the system allowed it to repeat.

Tradition and habit will force the investigator to continue to use the term "accident" but he must use it out of context and never consider the adverse event he is investigating to be accidental. If he does he will most certainly be a contributing cause factor to the next repeat of that adversity. The continuum of the cause will go on, and on, and on.

Multiple Causes

Any attempt on the part of the investigator to select a primary cause has been proven to materially detract from the prevention of recurrence. In the past, the unnecessary emphasis on pilot factor was due to the policy of determination of the primary cause or the most probable cause. The pilot was usually the last person who could have prevented or salvaged the situation. No matter how much he was the victim of other circumstances or events he was the last in the sequence of events and, therefore, deduced to be the primary cause. Unfortunately, no one kept track of the numerous times the pilot prevented an accident by his emergency procedure efforts.

Jerry Lederer in writing about the risks in the Apollo project stated:

> ... *The ingenuity of man can conserve an experiment when difficulties and malfunctions occur.* Men can accommodate and adjust equipment for unprogrammed events. A pilot might have been able to prevent the destruction of an $80 million Nimbus when its gyro control was set 90° off its designed axis.(11)

A few years ago the U.S. Air Force changed its regulations regarding the requirement for finding primary cause. The new rules for determination of cause state that:

> ... In most cases, mishaps will have several causes which acted in combination to produce damage and injury. Do not assign priorities to the causes with such terms as "primary," "contributing," "main," or "most important."(12)

Experience with student investigators in an instructional environment indicates that they often come up with differing cause factors for a given situation. This same difference would be expected if different investigators or investigation boards were to independently investigate the same accident. This is easily proven by the divergent opinions of cause offered in testimony of expert witnesses representing opposing sides in litigation.

The purpose of prevention is much better served by a chronoligical list of all causes involved in a mishap without any assignment of priorities. In this way prejudice will not influence the preventive effort needed to resolve each and every cause factor involved.

The History of the Cause

The National Transportation Safety Baord (NTSB) will often include data related to the history of a cause or problem in the narrative portion of the report. This history usually indicates evidence of the repetitive nature of the cause. Unfortunately, by the time the most probable cause is declared, the history is not included.

Every investigation is a search of the history of that event. Reconstructing the sequence of events and the sequence of failure is done by investigating and analyzing what happened in the past. Every accident is past history. The problem is that the investigation usually does not go back into the history of the cause in previous mishaps of the same nature. Why should an accident with a history of repetition be considered as a one-time event when in actuality it is part of a larger picture that is much more serious than any one-time accident?

At the Sixth SASI Seminar in October 1975, Hugh Youngblood presented a paper that clearly affirmed the importance of the history of a cause to the prevention of accidents. He had been investigating a fatal general aviation light twin accident with the author. We agreed that the investigation required the engineering expertise that Youngblood possessed. The accident was turned over to him with the conviction that one of the important aspects of the investigation should be a research of the history of the type of accident and the cause.

Youngblood did a masterful investigation, resolving the cause of the accident and by virtue of the history research was able to tie it into a continuum of repeat causes. In his paper, Youngblood recounted some of the history involved:

> ... In the National Transportation Safety Board's 1973-1974 listing of aircraft accidents involving inflight airframe failures, it is shown that some 200 accidents of this type occurred in two years. While some of these accidents were induced by material defects such as fatigue, it is shown by the NTSB that more than sixty accidents occurred because the pilot exceeded the design limits of the aircraft. Air safety investigators cannot continue to be satisfied with a probable cause factor of this type. Aircraft accidents will continue to occur as long as this is the only approach taken in the investigation of this type of accident....
>
> ... Aircraft... is a light general aviation twin engine aircraft which initially exhibits a dangerous low stick force gradient.... It should be noted that this type of aircraft has experienced twenty-two cases of inflight overload/overstress damage or failure of its wing/wings.(13)

Youngblood determined that the aircraft had a stick force gradient of only two pounds per "g" and with a most dangerous reversal at 2.3 "g's". His investigation resulted in an Airworthiness Directive that corrected a design problem, long incorrectly identified as pilot factor.

There is no doubt about the pertinence of the cause factor history to the prevention involved in this case. The original investigation of this accident did very little to resolve the problem. It was treated as a one-time event and allowed further accidents to occur. The Youngblood investigation facilitated the saving of many lives and aircraft. It also saved NTSB the cost and effort in the continuation of investigation of this repeating cause in that airplane. And it restored some lost honor to the pilot.

The Investigation Formula

The investigation process includes a formula for success. Not a mathematical formula but one of logic and reasoning. The formula involves the *investigation/analysis* which begets *cause factors* which begets *recommendations* which begets the *prevention* of accidents. Abbreviated, the formula reads:

I ⟶ C ⟶ R ⟶ Pfa

One may ask what is the "Pfa?" It is a very important emphasis in the process. Simply stated it means: "Pfa" = "Prevention of future accidents."

One may further ask, "Isn't that obvious?" And, of course, the answer is "no" because it is important to direct the emphasis to future accidents and not to the impression that we are dealing with a one-time event. There is nothing that can be done to prevent the accident being investigated. It is history. The clock cannot be turned back. Our only interest in the investigation is to learn as much as we can from this accident and use it to prevent repetition.

Of primary importance here is that the investigation use this emphasis in the determination of the cause factors. They must refer to the prevention of future mishaps and nothing else. This is not usually done.

Cause Factors and Recommendations

Each part of the investigation formula builds on the previous part. The prevention is dependent upon the recommendations; the recommendations are dependent upon the cause factors; and the cause factors are a summary of the investigation and analysis, therefore dependent upon them. A failure in the beginning will usually result in a failure in the end.

The Youngblood investigation is a prime example. Youngblood corrected the errors made in the investigations which had been previously conducted and which produced no prevention.

There is another, more subtle error made in the process which is quite common, even in the large disaster type investigations. This is the situation where every effort and talent is brought to bear in the investigation and analysis but the cause factors fall short of producing prevention. A good investigation but poor results.

The way to determine this problem is to compare the cause factors with the recommendations. If the recommendations differ in subject from the cause factors then something is wrong. The recommendations should be suggestions for corrective action based upon the cause factors. The error is usually that the recommendations are based upon the investigation evidence and the cause factors are not. The reason is probably due to the hypocrisy of not being candid in the assignment of cause — assigning causes that are vague and blameless, except maybe to pilots.

Fault and blame have no place in the investigation process. However, this is the fault and blame of individuals or groups of individuals. It does not mean that policies, procedures, techniques, technology, training, supervision, and management are to be protected. It is inconsistent if the recommendations are specific in the problem to be corrected and the action to be taken, yet the cause factors name none of these as why the accident occurred. A cause factor that states only the *how* and leaves out the *why* is incomplete.

It can be argued that if the recommendations include the proper action to be taken then it is not a great error to have vague cause factors. The reality of the situation is that often more attention is given to the cause factors rather than the recommendations. After all the recommendations are just that: recommendations. But the cause is a judgment, a verdict, it is the focal point of the entire investigation.

By dealing with a primary or most probable cause — focusing the emphasis on one cause — the cause factor will be even less productive. In the large air carrier type investigations there may be enough public pressure to produce the required prevention of future accidents, even with vague cause factors. But this is not always so, by virture of the many major air carrier accidents that have repeated. In the case of general aviation, where there is a lack of pressure and priority for action, the vague cause factor is very ineffective in the prevention of recurrence. The proof of this is in the high percentage of repeats in most categories of general aviation accidents.

Conclusion

This paper began with a reference to the PSA midair collision accident in San Diego. In summary, it would be pertinent to briefly review that accident and tie in the major emphasis of this paper: *making the investigation process succeed.*

1. *The Repeat Accident is not an Accident*

One of the most troublesome and persisting causes today is the mid-air collision. It is a cause that may involve significant cost and/or sacrifice to resolve. That the PSA accident was a repeat of this cause is certain. In the past fifteen years prior to the PSA accident there were 470 mid-air collisions resulting in 928 deaths. Eighteen of those collisions involved at least one air carrier aircraft and accounted for 45 percent of the fatalities involved.(14) No one can say with any sincerity that the PSA mid-air was unexpected or that it was accidental. Therefore, it was a repeat and not an accident.

2. *Multiple Causes*

The PSA report(15) listed fifteen findings, eight of which were causal to the accident. However, it listed only one probable and one contributing cause. It also listed four recommendations none of which reflected the probable (primary) cause identified by the report. In effect, no recommendations were made concerning the probable cause. If each of the findings that were causal were listed as such, the report would have greatly increased the emphasis on needed action for prevention. Further conflict of cause was evidenced by one Board member dissenting from the other members. He listed seven contributing cause factors in his dissenting opinion plus two probable cause factors, one of which was the same as the Board's opinion. The probable cause listed by both the Board and the dissenting member was pilot factor on the part of the crew. The reason why the Board did not list all the causes with recommendations for each is unknown. Unfortunately, this report is another example that makes pilot factor the scapegoat. There is nothing in the probable cause of pilot factor that tells us why this accident occurred or what we can do with the pilots to prevent recurrence. An all cause listing would have provided a great deal more emphasis on preventing repeats.

3. *The History of the Cause*

In spite of the long history of mid-air collision accidents, nothing was included in this report to indicate that it was anything more than a one-time event. The continuum of this cause has great significance in what has been and what has to be done to prevent recurrence. To ignore it is to ignore the root cause.

4. *The Investigation Formula*

The Board erred in leaving out the history of the cause in the investigation and analysis. It failed to carryover all the determined causes in the probable and contributing causes. And it failed to present recommendations to correct the probable cause listed. By following the investigation formula these problems would not have occurred in the report.

5. *Cause Factors and Recommendations*

The cause factors listed indicate a requirement for action that is not covered by the recommendations. And the recommendations include listings that do not relate to the probable cause. Two of the four recommendations relate only to the contributing cause listed, and two relate to neither of the causes listed. Effective prevention of recurrence cannot be expected unless the cause factors indicate the root causes and that the recommendations indicate the action needed to correct those root causes.

The PSA accident was not an accident, not caused by fate or luck. It was an assumption of risk taken by the aviation system with a predictable probability of occurrence. Simply stated, it was caused, allowed to happen. Hopefully, the effect of the blood priority attached to this disaster will bring the necessary pressure to bring about the necessary action to prevent further recurrence. If the PSA accident is repeated, the probable cause should read: "Failure of the safety system to determine and establish the root causes and corrective action of previous mid-air collisions." Prevention can be achieved by using the proper investigation procedures and being mindful of the lessons of history.

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The Use of Accident Scenarios in Accident Prevention

Gerard M. Bruggink M00492
2107 Centennial Drive
Dothan, AL 36301

The ability to perceive the first symptoms of potential trouble is one of the traits that distinguishes the true professional from the one who performs routine tasks in a perfunctory manner. The development of this trait varies with the individual's ability and willingness to learn from his own bad experiences and those of others.

Considering the intricacy of the modern air transport system, none of the professionals in design, production, maintenance, operations and traffic control can afford to rely on individual experimentation for the development of this early warning system. Aviation's trial-and-error period belongs to the past. We live now in an age where it is inexcusable not to be right the first time. Practically everything that could possibly go wrong has already claimed its victims. The more than 100,000 accidents that have been investigated and documented over the last 20 years constitute a collective pool of accident experience that covers every code in our cherished data banks. Unfortunately, much of this experience goes to waste because it is not assimilated by those who should use it to avoid repetition of past errors. The following examples show how little we, as air safety investigators, have accomplished in stimulating the protective imagination and skepticism of key individuals in the aviation system.

Unheeded Lessons of the Past

In January 1969, the first officer of a DC-8 flew the aircraft inadvertently into the water during an instrument approach to the Los Angeles airport, while the captain and flight engineer were attempting to diagnose and correct an unsafe landing gear indication. One would expect that the widely publicized cockpit distraction aspects of this accident would preclude repetition of that scenario. However, almost 4 years later a similar scene was reenacted when an L-1011 was allowed to fly inadvertently into the ground near Miami, Florida, while the crew was attempting to diagnose and correct an unsafe landing gear indication. With two such accident scripts already on record it is difficult to visualize a repeat performance. Yet, in December 1978, a DC-8 was forced down, due to fuel exhaustion, in the vicinity of the Portland, Oregon, airport, following the crew's preoccupation with a landing gear malfunction and preparation for a possible emergency landing.

Another area that demonstrated the sluggishness of our communication and learning processes was the one dealing with wind shear, a problem as old as aviation. A case in point: the two B-727 take-off accidents attributed to this phenomenon involved the same carrier. Actually, it took a rash of wind shear and thunderstorm-related mishaps to reestablish a modicum of respect for Mother Nature and to reaffirm two basic needs:

1. Real-time weather information in the cockpit, and
2. The ability to use the aircraft's optimum performance capability if the situation demands it.

An unwritten law that is regularly violated by the unimaginative and the unwary dictates that you shall not proceed on blind assumptions that carry on unacceptable risk. Typical in this regard are most of the controlled-flight-into-terrain accidents. (Mena, Arkansas, September 1973; Bali, Indonesia, April 1974; King Cove, Alaska, September 1974; Berryville, Virginia, December 1974; Kaysville, Utah, December 1977). Even aviation's worst mishap so far (Tenerife) was characterized by the uncritical acceptance of an easily verifiable assumption.

Practically every accident involves somebody's lack of understanding of a fundamental concept in accident avoidance; always go out of your way to make it easier for the other person — and yourself — not to make an error. We have seen repeatedly how just a touch of imagination and skepticism could have defused a critical combination of proven enabling factors in design, production, maintenance, operations and air traffic control. Instead of illustrating this point with examples — some of which are too recent for comfort — I will attempt to summarize the frustrations of conscientious air safety investigators with the following remark: it appears that the legal profession is better skilled in making profitable use of past accident and incident experience than we are.

Discussion and Conclusions

Aviation's past and present safety problems suggest that our traditional methods of communicating the lessons learned from accident investigations do not have the desired effect. Perhaps we rely too much on the limited distribution of formal accident reports and recommendation letters. In my association with flight crews, maintenance personnel, and traffic controllers I have found only a few who had — or used — the opportunity to spell out the latest accident reports. Most of them were aware only of the news media coverage of cause determination and selected highlights.

Perhaps the worst obstacle in the promotion of accident awareness, or accident sense, is the prevailing view that all the preventive aspects of a particular investigation find expression in recommendations dealing with regulatory, technological, and managerial fixes. As a result, we ignore the intrinsic educational value of a good accident report which lies in its analysis of the accident's origins and maturation process. Unless all peers of the role players in a particular mishap sequence understand thoroughly the conditions that tripped their colleagues, they cannot develop the ability to recognize the early symptoms of a potential threat. Just like a medical doctor becomes a health expert by understanding disease processes, the professionals in aviation can act with prudence and intelligence only when they understand accidents and their root causes.

How can we make more constructive use of our past failure experience? First, we have to create a climate conducive to the distillation of every ounce of preventive medicine in our investigations. This requires that we:

1. Curtail our vindictive preoccupation with cause assessment because such an attitude tends to favor after-the-fact prevention only.
2. Bring forcefully to the attention of all parties concerned the justifiable expectations about the level of performance that could have interrupted a mishap sequence.
3. Stress the fact that the missing of an opportunity to prevent an accident does not become blameworthy unless the persons involved and their peers fail to learn from it.

Once the international climate permits the frank disclosure of those aspects of an accident that promote the development of protective foresight, we should feel no compunction about the incorporation of existing accident scenarios into training and education systems. The first steps in that direction have already been taken. For example, the programming of wind shear and certain aircraft system malfunctions in flight simulators. However, some of these exercises are rather clinical since they do not confront the audience with the dynamics of the accident situations after which they are patterned. Furthermore, we are only addressing the pilot group and not the various other groups which play a safety role.

Without claiming to have the right answers, I suggest consideration of one or more of the following methods to keep the bad experience of the past before the eyes of those on whom we depend for the soundness of our brittle system:

1. Accident and incident reports that contain specific lessons for a particular group should be required reading for that group. An alternative is to discuss those reports during periodic meetings. No level of management is too exalted to be excused from this exposure.

2. Training curricula should be amplified with accident case histories pertinent to the training objectives involved. This is a very effective way to stress the importance of a particular task or profession.

3. Much wider use could be made of audio-visual techniques to reenact not only established accident scenarios but the flight and simulator tests conducted to verify the principal hypotheses in accident theories. These presentations should be adjusted to the intended audience so that the proper degree of realism can be used without ruffling professional pride in front of outsiders.

These suggestions were prompted by the obvious futility of continuing to preach to the same old choir. Unless we penetrate the barrier of indifference and self-deceit that shields too many from our well-intended sermons, the experience of the past is wasted. Somehow, we have to find a way to confront every member of the aviation community with what a particular accident has to tell him in his own language. As air safety investigators we have the obligation to show new initiatives in achieving this long-neglected goal.

Application of a Decision-Making Model to the Investigation of Human Error in Aircraft Accident

Ronald L. Schleede M00736
Air Safety Investigator
National Transportation Safety Board
Denver Field Office
10255 East 25th Avenue, Suite 14
Aurora, CO 80010

INTRODUCTION

The views expressed in this paper are solely those of the author and do not necessarily reflect the opinions of the National Transportation Safety Board.

It is becoming extremely trite to open a discussion about aircraft accident investigation by stating that human error is the major factor in the cause of accidents. It is also trite to state that a determined effort must be made to determine the "why" behind human error, so that prevention measures can be developed. Perhaps the triteness of the situation has lulled many of us into complacency and a general acceptance of a high percentage of human error in aircraft accidents. Or, our failure to solve this difficult problem may have given us a defeatist attitude, after many years of pursuing the "elusive underlying why."

That phrase, "the elusive underlying why," may in itself, indicate a trend in our thinking about human error problem solving. It almost appears that we have resorted to poetic "buzz-words" to impress our contemporaries in our quest, rather than using scientific methodology. For example, "root causes, the three 'Ws,' the five 'M' approach, elusive underlying why," are but a few of the terms and phrases bantered about to show that we all recognize that strange mysterious intangibles cause most aircraft accidents.

A few years ago, several pretigious gentlemen got together and researched this problem. They developed a scientific methodology, which they believed would lead toward solving the human error problem. The end product of their efforts was a document entitled, "A Method for Analyzing Human Error in Aircraft Operations." 1/ Unfortunately, that document appears to be the end rather than a means to a more important end. That is, the proposed methodology was designed to assist the air safety investigator in the investigation of human error aspects of accidents. The document was published in 1975; however, it apparently did not revolutionize the industry. I have failed to observe its use in actual cases. More importantly, I have not seen the proposed technique disputed or improved upon by the scientists, who developed it, or by air safety investigators, who were intended to use it.

1/ Billings, Charles et al, A Method for the Study of Human Factors in Aircraft Operations, TM X-62,472, National Aeronautics and Space Administration, September, 1975.

I submit that we may be more adept at lamenting about the problem than at solving it. We certainly have gotten considerable mileage out of discussing the human error problem. One has only to review the list of past symposia and documents regarding this subject to realize how we have massaged the human error aspect.

The purpose of this paper is two-fold. First, hypotheses are presented, which may account for our apparent defeatist attitude regarding this matter and which may explain our reluctance and failure to successfully apply techniques such as those proposed in TM X-62,472. Secondly, this paper briefly describes the proposed methodology and how this investigator has applied it in actual cases.

HYPOTHESES

The first hypothesis involves the supposition that one of our problems in this matter involves the very expertise of the persons involved in the quest, as well as the methods by which we employ our expertise in investigating aircraft accidents. The investigator of an aircraft accident or incident uses various mechanical tools, checklists, and methodologies in documenting relevant facts, conditions, and circumstances of an occurance. For example, we all have proven techniques, as well as equipment, to examine aircraft structures and engines. We are very good at documenting the hardware. Similarly, we are able to quite accurately substantuate the environment in which an accident or incident occurred. We have computerized retrieval methods to obtain aircraft performance, weather phenomena, etc. All of us have, in one form or other, quite excellent tools and methods for investigating the hardware and environmental aspects of a particular occurrance. Moreover, we are readily able to analyze accurately the findings of these areas of investigation and we generally are able to develop sound viable conclusions as a result of our analyses.

We have obviously not been as successful in investigating and analyzing certain human elements. Again, one of the reasons may be the fact that we attempt to apply the same expertise and methods, employed in hardware/environmental investigations, to the investigation of the human aspects. In general, we use persons trained in pathology and crash injury to investigate the "human factors" aspects. On occasion, operational investigators attempt to delve into crew performance. This technique will only work for certain human elements that we have tools and methods to measure. For instance, visual and audio acuity, human reaction time, physical incapacitation, crash injury data, and even workload limits can be measured or determined by repeatable methods. We have no apparent equipment to measure the "intangible" human factors, therefore, we cannot readily analyse or draw viable conclusions from our investigation of these aspects, if in fact an investigation was conducted. The investigation of human factors requires a well rounded multi-disciplinary background in aviation hardware and environmental aspects, as well as human factors. We should not expect technicians, trained only in pathology or crash injury (physiology), or strictly hardware/environmental specialists, to be able to solve the other human aspects. Without their familiar checklists and proven techniques, their expertise is useless and the problem is not solved.

What is our problem? Why haven't we been able to solve the "other" human elements as well as we have solved the other factors? This brings up the second hypothesis. The answer may simply involve the fact that the solution required a different reasoning process than that used to solve the aspects of hardware, environment, and measurable human factors. To support this hypothesis, the following discussion on reasoning is offered:

During the investigation of an accident, in which an aircraft was seen to lose control and crash immediately after takeoff, the investigator notes that all gust locks are still attached to the control surfaces. A thorough investigation is conducted and no other problems are found which could explain the loss of control. The investigator draws a conclusion by a simple reasoning process:

Premise A: All flight control surfaces were locked in place by the gust locks.
Premise B: Locked flight control surfaces will cause loss of control on takeoff.
Conclusion: Therefore, the loss of control was caused by the gust locks.

This is an example of a simple deductive argument. A deductive argument involves the claim that its premises provide conclusive evidence of the truth of its conclusion. That is, a deductive argument is valid when its premises, if true, provide conclusive evidence for its conclusion. There is not much doubt about the truth of the proceeding conclusion. Every deductive argument is either valid or invalid, and the task of deductive reasoning is to clarify the nature of the relationship between the premises and the conclusion. 2/ In the above example, there is obviously a definite relationship and the conclusion is therefore considered valid.

Now I offer a slightly different type of argument:

Premise A: To err is human.
Premise B: Pilots are human.
Conclusion: Therefore, pilots will err.

This is an example of an inductive argument. An inductive argument involves the claim, not that its premises give conclusive evidence for the truth of its conclusion, rather only that they provide some evidence for it. Inductive arguments can be evaluated as "better or worse," according to the degree of "likelihood or probability" which the premises confer upon their conclusions. 3/

We accident investigators essentially use deductive reasoning during our investigations. We feel secure using deductive methods because the validity of our conclusions is self-evident and cannot be challenged by our peers or superiors. Most of us use scientific laws and measurements in evaluating metallurgical findings, aircraft performance, electronic data, weather phenomenon, mechanical failures, even measurable human factors. However, when it comes to inductive reasoning, we become reluctant. When the validity of our arguments cannot be tested conclusively, and we have to deal with "probabilities," or "likelihoods," we become cautious

2/ Copi, Irving M., Introduction to Logic, MacMillan Company, New York, 1961, pp 8-9.
3/ ibid, pg. 9.

and withdrawn. Quite often we are accused of "second guessing" or drawing unfounded conclusions. A conclusion reached by means of inductive reasoning can always be challenged philosophically depending on the amount of probability the premises direct toward the conclusion. The premise "To err is human," quite obviously can be true or untrue, depending on the result of a philosophical argument.

The investigation of human error in aircraft accidents involves a great deal of inductive reasoning. Of course, the human performance criteria which we can measure can be investigated and analyzed deductively. However, the intangible aspects of the human involvement require inductive, "speculative" reasoning in order to draw viable conclusions.

One of the least measurable and intangible aspects of human error involves pilot information processing and decision-making. The lack of hard evidence regarding these aspects in a particular accident brings us back to our unpleasant task of inductive reasoning. Since this type of reasoning involves probabilities and likelihoods, if we are to be successful, we must organize our investigation and our analysis of these aspects to develop a "more probable" and "acceptable" conclusion.

Therefore, if we air safety investigators are going to attempt to solve the human error aspects, we must alter our thinking and use different techniques than those presently applied.

THE PROPOSED METHODOLOGY

The NASA document, TM X-62,472, describes "a method for the study of human factors in the aviation environment." The abstract of TM X-62,472 states, in part, that "It provides a conceptual framework within which the pilot or other human errors in aircraft operations may be studied with the intent of finding out how, and why, they occurred." It was the intention of the authors to "provide a structure and format within which systematic and comprehensive investigation of behavioral problems in aircraft operations can be undertaken." If the previously presented hypotheses are accepted as viable, then the intent of the authors of TM X-62,472 should be of more than passing interest to most air safety investigators.

TM X-62,472 contains three sections. The first section explains a conceptual framework for the proposed investigative method. It attempts to characterize human behavior in terms which can lead to an understanding of why a certain behavior may have occurred. The second section contains a proposed guide for interviewers who collect information from pilots or others who may have knowledge of an occurrence involving human errors. That section is an attempt to provide a systematic method to investigate the human aspects of an occurrence. The third section of the report outlines a classification system to provide eventual examination of large amounts of data collected by means of the proposed methodology. This paper deals generally with the first section of TM X-62,472, illustrating how this investigator has interpreted its content and how actual cases were evaluated using the proposed methodology. My interpretation may not totally parallel the intent of the authors; however, the use of the proposed methodology was considerably helpful in my analysis of certain accidents.

The authors of TM X-62,472 began their discussion by reverting to a common technique employed in accident/incident investigation. That is, the development of a chronology of events (history of flight, etc.) related to the occurrence. The proposed methodology involved the incorporation of a chronology "with particular emphasis on the behavioral events, relating them as closely as possible to all other events in the sequence." In what the authors titled a "Function Analysis," they stated, "In this process, we attempt to discover or infer what effect the behavioral events may have had upon the sequence, and also what external events may have motivated a particular behavior." The key word in this sentence is "infer."

This brings us back to our nemesis of inductive reasoning. Can you imagine an investigator being successful by "inferring," rather than proving, that a fatigue fracture occurred; or speculating rather than determining that an engine quit? In those examples we will generally accept nothing but conclusive evidence, by means of factual data and deductive reasoning.

The authors of TM X-62,472 proposed that the Function Analysis would help the investigator discover "first, what role human behavior may have played in the causal chain of events, and second, to discover why the people in the system behaved as they did." The Function Analysis, as explained by the authors, is included in total in Appendix A. It describes the functions considered necessary to conduct a flight in civil aviation. Essentially, the Function Analysis is a behavioral chronology, which the investigator must complete as part of his accident investigation. With our existing expertise and investigative techniques, we can readily accomplish this task. A complete chronology of relevant behavior events must be documented because of the interdependence of various events. The authors mention that a live cooperative flight crew is desirable, otherwise "the investigator must often resort to inference in place of facts." Of course, in an aircraft equipped with digital flight data and cockpit voice recorders, less inference is required.

The Function Analysis merely assists the investigator in organizing the "what happened" as it pertains to the human behavioral aspects of an accident/incident. TM X-62,472 next describes a method for evaluating "why" something happened. To accomplish this, the authors developed an information processing (decision-making) model of behavior (Appendix B).

The information processing model is a schematic method of reviewing the actions of a flight crew member and the decisions which led to such actions. This is exactly what we investigators need; a systematic means of organizing our investigation into the "intangible human aspects." We function best with methodologies and techniques to employ our expertise and hopefully our conclusions will be more acceptable.

The authors of TM X-62,472 offer the plausible proposition that "there is some reason for all human behavior." Therefore, a search for the reasons for each significant behavioral event listed in the Function Analysis can be accomplished. Since the Function Analysis demonstrates that each action by a pilot, or others in the system, represents an attempt by that person to implement a previous decision, an organized evaluation of the information processing by the involved person(s) would place us closer to our goal of understanding the "why" of the behavior and subsequently developing prevention measures.

TM X-62,472 describes the information processing model briefly as follows: "... *in order to accomplish any task, a pilot must first seek and acquire in-*

formation from whatever sources are available. He must then make some determination regarding the quantity, and the quality, of the information he has gathered. Previously gathered knowledge, contained in his memory, will influence the determination of whether he has enough information, of high enough quality, to allow him to proceed. Psychological or environmental stress can also influence his evaluation of the information.

Having determined that he has enough information, and that it is reasonably reliable, the pilot must then process these data in pre-determined ways (again based on memory) in order to reach a wise decision from a limited number of alternatives. Before he finally accepts the decision he has made, however, he will make some judgment as to the acceptability of the candidate decision in terms of its potential impact upon the likelihood of successful mission completion. If the decision is finally accepted, the pilot selects the ways in which he will implement it, and then takes appropriate actions.

A large part of this process involves the pilot's judgment of probabilities; he is attempting to make wise decisions, often in the face of uncertainty. In addition, he must consider cost and safety tradeoffs, and there is good evidence that all of these factors do influence decision-making in the aviation system."

Therefore, if we trace through the model the relevant actions by a person involved in a particular occurrence, we should get reasonably close to the underlying reasons for actions, which have been determined to be inappropriate (pilot error), "after the fact." To facilitate the use of the model, the authors suggested that a sequence of behavioral events takes place for each significant decision. The sequence of events involves information acquisition, evaluation of that information, processing of the information and finally decision selection from available alternative actions. Use of the model involves asking questions about each behavioral event as it applies to the particular case. The authors offered several questions to be asked by the investigator in order to better understand the reason for the behavior in question:

1. Was all necessary and pertinent information acquired by the pilot (or controller, or dispatcher, etc.)? Was the information he acquired correct? Was it in a format which he could assimilate in the time available to him?

2. Was the information properly evaluated:

a. With respect to quantity (was there enough information)?

b. With respect to quality (was it consistent and reliable)?

3. Was the information properly processed: did the pilot reach an appreciation of the true state of affairs?

4. Did the pilot select the safest and wisest decision (based on the information available to him) from among the available alternatives? If not, what other factors entered into his decision?

5. Was the decision effectively implemented once it was made?

It was proposed by the authors that, depending on the answers to the various questions, "the primary enabling factor(s)" in the accident/incident might be identified. In that manner, the action which was initially considered and identified as "pilot error" can be evaluated to identify the underlying factors which led the pilot to make an improper decision and select an incorrect alternative action.

This is obviously the type of methodology we investigators require if we are to be able to use our existing expertise in a "familiar environment." That is, the key words describing this method, "structured, format, systematic, and comprehensive," place us in a more acceptable arena of using a more scientific means of investigating the important human aspects. We still must use undesirable inductive reasoning (inferences); however, our conclusions will definitely be more plausible and acceptable.

A case history is illustrated in TM X62,472 to demonstrate the use of the proposed technique. Rather than cite a hypothetical example, two cases are presented in which the methodology was applied by this investigator. Both examples are de-identified to avoid possible misunderstandings and because the identification of the particular cases has no relevance to this discussion.

CASE HISTORY NO. 1

A scheduled air carrier aircraft crashed short of the runway during an ILS approach in a severe thunderstorm. Measurable human factors and hardware factors were eliminated as causal. The investigation revealed that the weather conditions in which the approach was attempted were extremely severe and such that aircraft control would have been marginal to non-existent with a normal approach configuration and airspeed. One of the key aspects of this case was the crew's decision to initiate and continue the approach into weather that was determined, after the fact, to be so hazardous. Additionally, several other air carrier aircraft were flown into the same conditions and two of them very nearly crashed. Therefore, the conditions and circumstances which caused these crews to make the decision (the "pilot error") to initiate and continue the approach and successfully negotiate the storm, were of prime consideration.

Following the proposed methodology of TM X-62,472, a complete chronology of relevant behavioral events was developed. It would be too lengthy to include in this paper; however, the means to develop that type of data should be self-evident to the investigator. The use of the cockpit voice recorder was essential in this case. The key aspect is the evaluation of the why of certain events in the chronology. In order to accomplish this, the information processing model from TM X-62,472 was modified to fit the circumstances of the accident. An example of the revised model is in figure 1.

Once the model was completed to fit the accident, the five areas of questions from TM X-62,472 were asked and answered for each phase of the model.

When the first question is asked in regard to the various information inputs, and in connection with the decision to initiate the approach, the answer was "yes" for all but three areas of input. (1) It was determined, from the chronology of events, that the known observed severity of the weather (a thunderstorm on final approach) was not passed from the weather service to the pilot in a timely manner. It is "very likely" that the pilot would have tempered his decision if he had had this important information. This condition is pre-

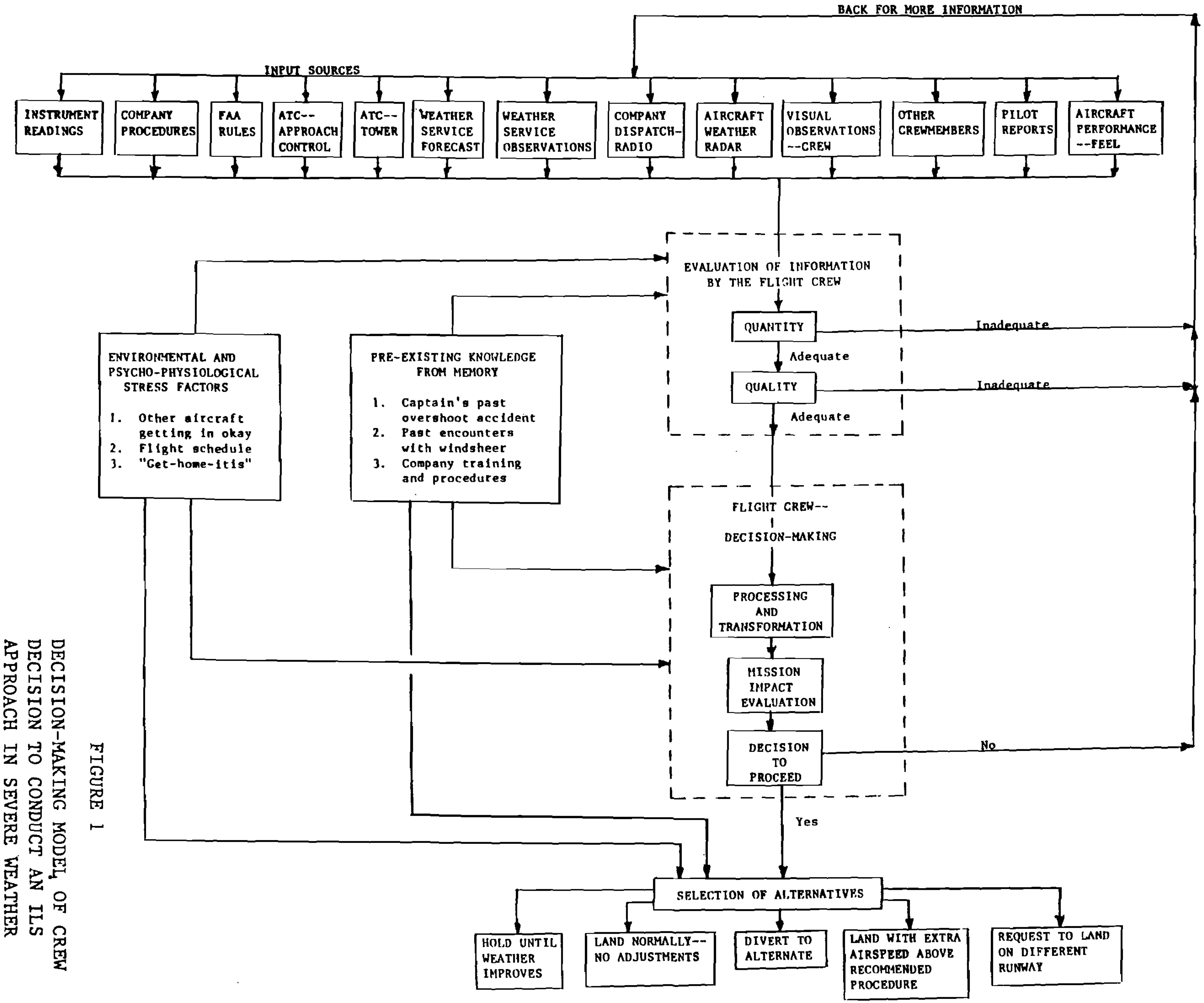


FIGURE 1

DECISION-MAKING MODEL OF CREW DECISION TO CONDUCT AN ILS APPROACH IN SEVERE WEATHER ventable and correctable and a very likely "why" in the pilot's decision and the ultimate cause. (2) The chronology of events revealed that the aircraft was dispatched with VFR fuel reserves based on a forecast for good weather with only scattered thunderstorms. Unfortunately, one of the "scattered" thunderstorms was on final when the aircraft arrived. The fuel state was discussed by the crew upon arrival in the terminal area. It probably was an important factor in the "why" behind the captain's decision to initiate the approach into severe weather rather than select other alternatives, such as diverting or requesting a different runway for landing. Corrective action for this aspect is possible. (3) An important pilot report about the severe weather was transmitted in a timely manner to the crew prior to the approach; however, the captain may not have heard all or part of it. The chronology of events revealed that a flight attendant was in the cockpit discussing personal business with the crew at the time the important pilot report was transmitted. It is very likely that the distraction prevented the captain from hearing or fully appreciating the significance of the report. The lack of that important information was probably a key factor in why he decided to initiate the approach. Again, this is a preventable aspect by restricting cabin personnel and other extraneous interference from the cockpit during the approach phase of flight. Some carriers have a procedure such as a "sterile cockpit" period for takeoff and approach and landing.

The answer to question No. 2 has to be "yes" based on the information available to the pilot. If the missing information illustrated by the answers to question No. 1 were available in sufficient quality and quantity, he most likely would have altered his decision.

Similarly, the answer to question No. 3 is "no" because the pilot didn't appreciate the true state of affairs, with the lack of the important information discussed previously.

Regarding question No. 4, the influencing factors of "environmental nad psycho-physiological stress factors" and "pre-existing knowledge from memory" (see figure 1) were found to be quite important in this case. The development of the Function Analysis revealed a "get-home-itis" aspect. This trip was the last leg of a three day sequence for the crew and the captain had a very important obligation at home that evening which would have been canceled if a diversion was made to another airport. Also, the other crewmembers had personal obligations shortly after the completion of the trip. The captain was aware of this fact and that a diversion or serious delay would adversely affect those plans also.

The "get-home-itis" aspect is a very difficult stress factor to document and analyze. More importantly, prevention of it from being a factor in the cause of an aircraft accident is equally difficult. It must be tempered by good strong management and supervision of pilots to ensure strict compliance to rules and procedures. So much judgment (decision-making) is delegated to air carrier pilots that strong enforcement and the instilling of professionalism into pilot's actions must be accomplished to overcome this strong influence in decision-making.

It must be also noted that the captain was aware, based on radio transmissions, that other aircraft were conducting the approach with apparent success. This is a subtle type of peer pressure affecting the captain's judgment. This stress factor, coupled with the known company flight schedule, would likely affect the captain's decision.

Regarding "pre-existing knowledge from memory" (training and experience), the Function Analysis revealed that the aircraft was flown into the severe weather at normal approach speed. The environmental investigation revealed that the lack of "extra" airspeed above normal approach speed precluded the crew from overcoming the effect of a severe windshear. It was further revealed that the crewmembers had not received substantive training in recognizing or appreciating the severity of windshear in the vicinity of thunderstorms. Two other flight crews had flown their approach through the same storm with extra airspeed and had sufficient performance capability to overcome the effect of the windshear. They had not been trained to do this, rather had "learned" from past encounters. Therefore, their decisions were fortuitously affected by pre-existing knowledge.

This phase of the analysis also revealed that the captain had "caused" an overshoot air carrier accident in the past when he landed "too fast for conditions" on a wet runway. That past experience may very well have influenced his decision to fly the approach at normal speed.

Regarding question No. 4, it is quite obvious that the captain did not select the "safest and wisest decision" from the available alternatives. However, when the phrase "based on information available to him", is included in the question, the answer is probably "yes." Using our method of "second-guessing" it is apparent he should have diverted to another airport, made the approach to a different runway, held until the storm passed or landed with extra airspeed to compensate for possible windshear. Therefore, based on the apparent impropriety of his decision, the last portion of question No. 4, "what factors entered into his decision?" is important. The answers to the first three questions provide this answer. The "why's" behind his improper decision and alternative selection are more apparent.

The answer to question No. 5 is not relevant in this case.

Admittedly, the preceeding is a condensed version of the effort expended in the analysis of this human error accident. However, it was intended to illustrate how some of the "real causes" of this accident evolved. Rather than stating, "the pilot initiated and continued an approach into severe weather which resulted in a loss of control and crash," we can more systematically describe the causal factors, and reasons for them, and hopefully develop viable prevention measures. This is not to say that the same conclusions could not have been, or were not, reached by conventional investigation techniques. However, without using the proposed methodology, or a similar method, the conclusions reached by "second guessing" are more open to challenge. One could always be asked, did you consider this or that factor? By using a systematic approach we can be "more convincing" and will reach a more meaningful conclusion by means of inductive reasoning.

CASE HISTORY NO. 2

A twin-engine general aviation aircraft crashed out of control, killing the four occupants, which included a well qualified commercial instrument-rated pilot and his three business associates. The hardware and environmental investigation revealed that the aircraft was flown into moderate to severe icing conditions while on an Instrument Flight Rules flight under positive control of Air Traffic Control. No hardware failures were found which could account for the loss of control and crash. Additionally, the measurable human factors, such as alcohol and pathological factors were eliminated as causal.

The investigation revealed that the pilot had received a weather briefing for the intended route of flight. He was briefed about nearly solid stratus cloud cover along the route with no forecast for icing at the flight level he proposed to fly. He was also advised about the possibility of scattered "imbedded" and building cumulonimbus (CB) along the route with forecast moderate to severe icing in the vicinity of the CBs. Just prior to takeoff, the pilot was given a pilot report of a moderate to severe icing encounter for five minutes by a general aviation aircraft adjacent to the proposed route. The pilot acknowledged the report and departed. A few minutes after level-off the pilot reported light rime ice and asked ATC if they were "painting any weather ahead?" The controller said "negative" and he repeated the pilot report of icing. Five minutes later the pilot declared "mayday" and the aircraft crashed.

Although a live crew was not available, excellent radio transcripts were available and the environmental factors could be well documented. It could readily be "deduced" that this pilot "initiated and continued flight into known icing conditions." But why? To us reportedly sane air safety investigators and pilots, the facts suggest very foolish or even suicidal actions. But the investigation of the pilot's background revealed the contrary. Therefore, to thoroughly investigate this case, the methodology of TM X-62,472 was applied.

After the chronology of behavioral events was developed, the questions from TM X-62,472 were asked using the information processing model to attempt to uncover the "why's." Again, the model was modified to fit this case. The revised model is included in figure 2.

The answer to question No. 1 is "yes" for all areas except one. All of the information inputs were apparently correct and relevant to assist the pilot in making the proper decision. However, one input requires further discussion. The pilot was obviously aware of the possibility of scattered CBs and associated icing. His question to the controller regarding whether he was "painting weather ahead" was an attempt by the pilot to obtain additional information, as illustrated in the decision-making model. But was the answer he received correct or in a format for him to properly assimilate? Not really, when the situation is examined further.

The controller's reply to the pilot's question was correct. He was not "painting any weather." However, the capability of the controller's radar in the configuration it was being operated would not indicate the type of weather to which the pilot was referring. The controller was not trained in interpretation of meteorological conditions. Moreover, at the time of the accident, there were no meteorological specialists assigned to the radar room to interpret and transmit real-time weather data. Therefore, the pilot received the correct answer to his inquiry, but not the information he was apparently seeking to make his decision to turn around, change course, or continue. This factor may be a true underlying why in this accident.

Regarding the answer to question No. 2, it is apparent that the information was not totally "enough or reliable," as revealed by the answer to question No. 1. Perhaps the pilot would have attempted to gain additional information had the inputs he received been accurate, or if he had understood the limited capability of the radar and the controller.

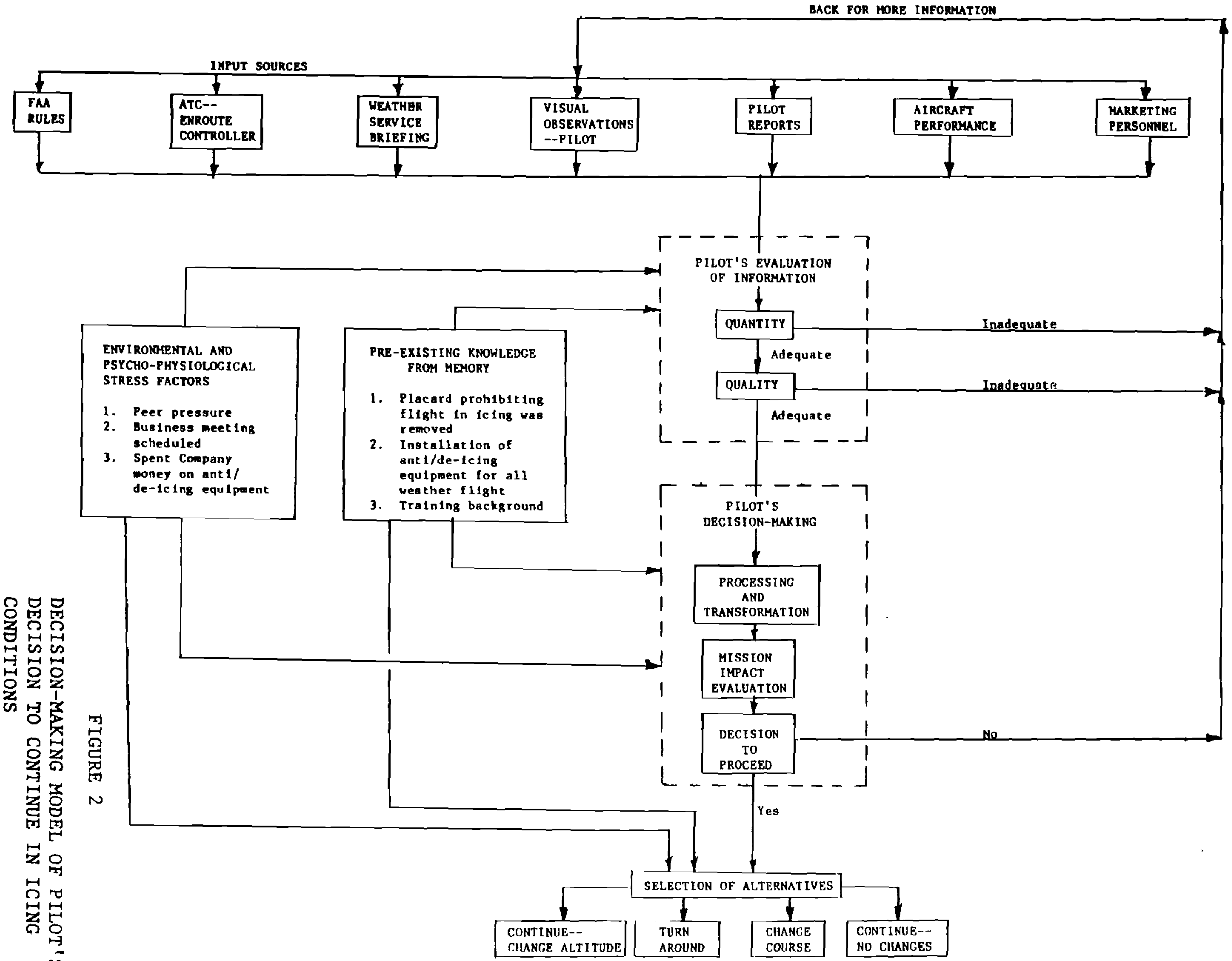


FIGURE 2

DECISION-MAKING MODEL OF PILOT'S DECISION TO CONTINUE IN ICING CONDITIONS

Similarly, the answer to question No. 3 is "no" based on the previous discussion because the pilot could not appreciate the true state of affairs. A "why" in this case involves the lack of knowledge on the part of the pilot regarding the radar capability.

Regarding question No. 4, it is obvious that the pilot did not select the "safest and wisest" alternative course of action. But why? He was given quite a bit of information about the weather which should have caused him to decide on a safe alternative action. What psycho-physiological stresses or knowledge from memory influenced the pilot's decision? Why did this well qualified and intelligent pilot continue into apparently poor weather conditions? One has to assume he intended to conduct the flight safely.

The investigation revealed that the aircraft was equipped with anti/de-icing equipment and it was functional for the flight. It was also revealed that several months before the accident, the aircraft was not so equipped and the pilot intended to buy a newer aircraft which was equipped and certified for flight in icing conditions. However, the cost of the new aircraft was quite prohibitive and the pilot was "convinced" to retrofit his aircraft with anti/de-icing equipment. The pilot's needs, including those of the company for which he worked, required all-weather operation and the new equipment "solved" his problem. The pilot was apparently convinced by the persons marketing the equipment that it would accommodate his needs for all weather operation.

An interesting aspect of this investigation involves the fact that for an aircraft to be certified by the Federal Aviation Administration (FAA) for flight into known icing conditions, it must be demonstrated by the manufacturer that the equipment will prevent or eliminate ice, and that the aircraft can safely be flown in icing conditions. However, many aircraft can be fitted with anti/de-icing equipment legally, but are not certified for flight into known icing. The FAA merely requires that the additional equipment not affect the aerodynamic qualities of the aircraft, when it is used. Therefore, it need not be demonstrated that the equipment will prevent or eliminate icing problems. In fact, the manufacturer of the aircraft need not demonstrate the aircraft's aerodynamic capability in icing conditions.

During the attempt to understand the rationale behind the FAA's reasoning in this aspect, a type of "Catch 22" was discovered. It was learned that the FAA is reluctant to require demonstrated icing capability for all aircraft with anti/de-icing equipment installed because the manufacturer's and ultimately the owner's cost would be prohibitive. It was learned, during the investigation, that it is the FAA's philosophy that the installation of anti/de-icing equipment on older aircraft, although not demonstrated or certificated as functionally adequate, is a safer condition than not having the equipment installed at all. Apparently the added cost of certificating the aircraft would preclude incidental installation of the equipment at a lower cost, such as in the case of the pilot in the subject case history. It was learned that the FAA believes that an additional level of safety would be available for the pilot who inadvertently encounters icing with "possibly functional" equipment than with no equipment at all.

The engineering drawing used to install the anti/de-icing equipment on the accident aircraft contained the following note: "A placard which reads, 'Not fully equipped for flight in icing conditions' must be installed," if certain anti/de-icing equipment is not installed. All of the required equipment was found installed on the aircraft and therefore, no placard was installed.

How does this all relate to the decision-making of the pilot of the case history? When question No. 4 is asked, and the influencing factors of "knowledge from pre-existing memory" are considered, we may be illustrating a "why." Did the pilot base his decision to continue on the knowledge that he had anti/de-icing equipment available? Did he have a false impression that his aircraft was capable of flight in icing? How about the fact that he had spent his, and his associates, money for the new equipment? How could he explain a diversion and subsequent delay to avoid the area of icing? As previously speculated, it is very likely that he assumed he could conduct the flight safely. However, neither he nor the aircraft manufacturer could predict the aircraft's capability in icing conditions. Perhaps only a small amount of ice would produce an uncontrollable aircraft, notwithstanding the anti/de-icing equipment. Therefore, a why in this case may, in fact, be traced to the marketing practices of selling anti/de-icing equipment and ultimately the aircraft certification and operational rules regarding flight in icing conditions.

Granted, the fact that we could not question the dead pilot about his actions and motivation always leaves doubt regarding the conclusions in this case. However, it must be recognized that the conclusions as a result of this analysis are more acceptable and reasonable than the description "pilot initiated and continued flight into adverse weather." We all need to know <u>what</u> happened. It is the more believable and provable <u>why</u> that is important for prevention measures.

<u>SUMMARY</u>

The authors of TM X-62,472 present a caveat in their document which cautions that their report be used by persons trained in the application of human factors principles of aviation problems. They warn that the application of the method "by untrained people may lead to erroneous or misleading conclusions". The authors do not illustrate what they consider to be adequate training background to use their methodology. The author of this paper is by no means a trained behavioral scientist; however, I am an air safety investigator charged with the investigation of aircraft accidents with the view toward determining the causal factors and developing timely prevention measures. Therefore, I will use any tool available to assist me in doing my job more adequately. We all should. I believe an air safety investigator, with a multi-disciplinary background, such as required of the "one-man team," can adapt and apply the proposed methodology. Of course, the rules of logic and reasoning must be followed, since our conclusions must meet the test of our contemporaries. We must abandon the purely factual deductive methods of hardware and environmental investigations and use our abilities to begin to solve the intangible human aspects.

I submit that the application of the proposed methodology, or any similar model and technique, by a well-rounded investigator, although not "trained thoroughly in human factors" is better than no investigation at all by the limited numbers to non-existant trained persons. We must begin to remove the "human factors" investigation from the pathologist's and crash injury specialist's realm and attack it as good air safety investigators. Incidently, we don't require that every air safety investigator have a degree in metallurgy or meteorology, yet we accept his conclusions in these areas, if logically presented.

Lastly, if no other result of this paper occurs than a scholastic argument and an increased interest in this subject with eventual improvement of our skills and techniques, the author's goals will be satisfied.

APPENDIX A

Excerpts From NASA Technical Memorandum TM X-62,472

The Function Analysis

As used here, the term "function" describes a set of tasks which shares a common subsystem goal and encompasses a common category of behaviors. Table 1 shows the functions considered necessary to fulfill mission objectives in civil aircraft operations.

Table 1: BEHAVIORAL FUNCTIONS IN AIRCRAFT OPERATIONS

FUNCTION	SUBSYSTEM GOAL	CATEGORY OF BEHAVIORS
	INTELLECTUAL FUNCTIONS:	
COGNITION or COGNITIVE BEHAVIOR	Acquisition of information regarding the position or status of the aircraft, the system and the environment.	Attention to external objects, perception of information, awareness of that information, & appreciation of the implications of the information.
DECISIONS; DECISION-MAKING BEHAVIOR	Selection of rules and of actions with which to implement the assigned mission.	Decision-making, concept formation, problem-solving, management skills.
	IMPLEMENTATION FUNCTIONS:	
FLIGHT or GROUND HANDLING	Control of the airplane's attitude and position in space and time.	Closed-loop manual tracking of airspeed, attitude, direction and altitude. Perceptual-motor skills.
SUBSYSTEM OPERATION	Operation of aircraft or ground-based subsystems in order to implement a decision.	Sequential discrete operation of switches and other controls; implementation of memorized or written procedures.
SUBSYSTEM MONITORING	Detection and identification of undesired subsystem states.	Monitoring behavior; scanning; vigilance.
COMMUNICATIONS BEHAVIOR	Transmission and reception of information.	Verbal and non-verbal communications skills.

Cognitive behavior is listed first in the table to indicate its priority among the functions. Cognition encompasses the behaviors by which a person becomes aware of, and obtains knowledge about, his relationship to his environment. In aviation, the flight crew and certain others (air traffic controllers, dispatchers) must all have knowledge of an airplane's location, status and intentions. Cognition is the process whereby each person acquires and appreciates this information.

Having become cognizant of the required information, each of the persons in the aviation system is in a position to do something about it. The process involved is called decision-making. A decision is the formulation of a course of action (from among a limited number of alternatives) with the intent of executing it. A decision may, of course, be to allow things to continue as they are: to do nothing. The process of decision-making is considered in more detail in the following section.

The execution, or implementation, of a decision involves one or more actions. The remaining functions in table 1 may be thought of as implementation functions: the actions one takes to implement a decision. In a sense, they all involve the same goal; they are separated, however, because they represent fundamentally different categories of behavior.

A simple example may help to illustrate the functions as they apply to aircraft operations. Approaching an airport in a terminal area, a pilot may become cognizant that the visibility is excellent and that there are few aircraft operating in the area. Based on his appreciation of the implications of this information for his on-time arrival, the pilot may decide to "cancel IFR" and to complete his flight by visual flight rules, an alternative mode of operation open to him.

Execution of this decision will require the use of some combination of the four implementation functions; it is important to note that the nature of the decision determines the appropriateness of the tasks which comprise the implementation functions. For example, certain subsystem operation tasks which were appropriate when operating under IFR are no longer appropriate when the decision to proceed under VFR has been made.

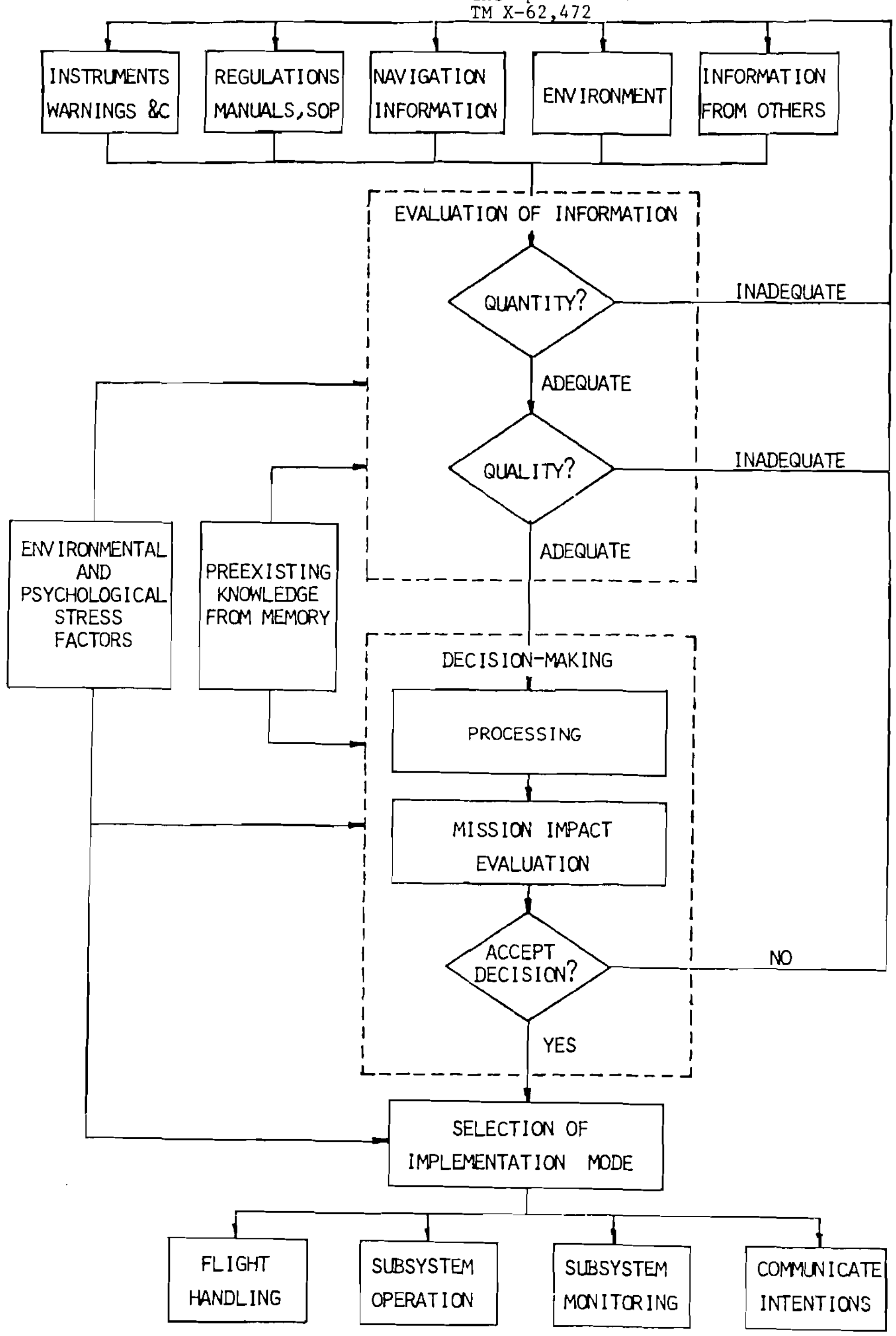
In implementing this decision, the pilot must communicate his intentions to his crew and to the air traffic controller handling his flight. He must select and communicate on the radio frequencies appropriate to VFR operations (subsystem operation). He must continue to monitor the status of his aircraft and must also monitor the environment for conflicting traffic. He may elect to control the airplane manually (flight handling) or he may perform this function through the autopilot (subsystem operation).

The human factors investigator must consider what decisions have been made in order to evaluate properly the "correctness" of the resultant behavior -- the performance of the implementation functions. Conversely, changes in the airplane's position or status caused by the performance of these implementation functions generate signals on instruments, etc., which are perceived, appreciated and become the basis for further decisions. This interdependence of the various functions is the principal reason why the function analysis, or behavioral chronology, must be as complete as possible. The development of a comprehensive behavioral chronology is aided immeasurably by the presence and cooperation of the flight crew, for in their absence the investigator must often resort to inferences in place of facts.

In summary, the function analysis is used to develop a chronology of the significant behavioral events in an incident or accident sequence, and to structure that chronology in such a way that behavioral events can be related to the occurrence of other significant events in the time line.

APPENDIX E

Excerpts From NASA Technical Memorandum TM X-62,472



A Review of the Unexpected in Aircraft Design

Captain Hal L. Sprogis *A00357*
117 Peaceable Hill Road
Ridgefield, CT 06877

Is the accident investigator serving in the role of accident preventer capable of detecting and eliminating more of the unforeseeable errors in new aircraft design, and how important is this capability? A review of some aviation history on this subject should prove thought provoking and possibly controversial.

To begin with I think the importance has always been there to a particular degree, but in the last decade or so this importance has increased. The main reason for this is of course the fact that a trend was begun toward wide body configurations and larger and larger passenger capacities in these designs. It has become morally and psychologically less acceptable to have the large *en masse* death tolls that are associated with catastrophic accidents in these aircraft. Therefore I feel there is an important need to improve this capability of detecting these incomplete design manifestations.

Now I'm talking about *unforeseeable* mistakes. The key word is *detected*! Naturally if a mistake is detected then the problem is not unforeseeable and it *can* be eliminated.

A basic and important accident prevention tool in our industry still is categorizing the "probable cause" in the interest of avoiding the same mistake twice. Does this concept serve well in the realm of the unexpected? No it does not. It serves well in the realm of existing knowledge. We rarely make the same mistake twice. We have access to thousands of safety reports, bulletins and even enormous safety knowledge from data banks such as that maintained in the United States by the National Transportation Safety Board (NTSB), and the United States Air Force (USAF). This information is of tremendous importance as an accident prevention tool within its limits. It shows us the way not to go, however it only does so after we once have gone there! But what about that first mistake, the situation where depth in design efficiency was not sufficient to foresee a probable safety hazard?

Because our industry is continually touched by tremendous technological advancements, such as new improvements in materials, aeronautical design, new concepts, etc., we have continued to accept a small degree of "unforeseeable" safety deficiencies. In the future I feel that the public will demand an improvement in its present level of risk.

Let's look at some examples of the history of the unexpected:

In the early 1930's a tri-motor commercial transport crashed in the United States. The aircraft was a high-wing monoplane constructed of a composite of materials. The wings were of an all-wood cantilever design with load-bearing plywood skin. Investigation revealed that moisture, accumulating in the interior of the wings, had caused deterioration of the glue, matereially decreasing the strength of the wing.

In the latter part of the 1940's a four engine commercial transport crashed at Bryce Canyon in the United States. Here investigation disclosed that a fuel tank overflow through the vent system occurred, and when the fuel streamed out it was sucked directly into the cabin heater air-intake scoop producing a serious in-flight fire.

In the mid 1950's the first commercial jet transport experienced several crashes. Break-up occurred at altitude. Exhaustive investigation revealed that after several thousand cycles, a point of weakness at a window corner allowed a crack to develop which spread unchecked. An explosive decompression followed.

In the 1960's a four engine turbo-prop crashed from over Tell City, Indiana in the United States. Exhaustive investigation here revealed that weakened engine mountings together with a heavy turbulence encounter created a situation termed as "whirl mode" which in a matter of seconds produced wing separation.

In the 1970's a four engine turbo-jet transport crashed near Paris, France. An uncontrollable fuselage fire developed in an aft lavatory and the resultant amount of smoke proved incapacitating.

Now, how can we improve on this situation and get a better handle on the unforeseeable? I am certain that among many of you in our industry a number of possible good ideas exist. And, it is within this very essence of cooperation and mutual desire to advance aviation safety, that I foresee *one* possible approach to fostering an improvement in the safety risks associated with the unforeseeable.

Amongst all of us, but not necessarily limited to those of us in the aviation industry, lie a potential source of important contributions. Those that could contribute are: the designers, engineers, chemists, physicists, aerodynamicists, scientists, pilots and test pilots, maintenance specialists and many other individuals; also then great contributions could flow from manufacturers, users such as airlines, military, business, private, and experimental operators. Other sources would be various government aviation agencies as in the United States, National Aeronautics and Space Administration (NASA), Federal Aviation Administration (FAA), Civil Aeronautics Board (CAB), NTSB, etc., and finally there are a myriad of special interest organizations such as: International Civil Aviation Organization (ICAO), airline transport associations, airline pilot and private pilot associations, engineering and experimental test societies, the Flight Safety Foundation (FSF), our own International Society of Air Safety Investigators (ISASI), and many others.

So, what kind of contributions could these sources give and how could they be managed and used?

First of all the contributions would be "data". Literally millions upon millions of bits of important aeronautical information, much of which would be completely unrelated, however collectively this data could become a useful *resource.*

Second, I envision that this resource would be stored in an adequate central computer facility. Access would be through several selected terminals which would be geographically appropriate. This information could be available to those who might find useful safety considerations that may not have been part of their original concepts.

Third, a cross-referenced program would be the heart of the system, whereby a search for the "unexpected" would be initiated. The computer's huge data bank could be queried in a variety of special ways, and be programmed in such a manner that the computer would trace out a specific line of reasoning and alert the interrogator of a possible compromise in safety.

Let's envision a theoretical example of this scrutiny that might follow this scenario:

In an experimental laboratory of physics in Stockholm, Sweden, a scientist using composite carbon plates notes that when the plates are fastened to aluminum 1012B, a small electrical current is generated. Further experimentation showed that the current was caused by the specific surface treatment to the aluminum together with a 90% humidity factor that was required in the experiment. The physicist used the same aluminum, but specified a different surface treatment and solved his problem. Noting also that the materials that he initially used were also being considered in current designs of aircraft structures, he forwarded a report to the "administrating agency for aviation design safety reporting". The information was put into the computer. Three years later a French design team was submitting its initial proposals for a new commercial transport. Material in the fuselage and portions of the wings included the same composite carbon plates and aluminum 1012B as initially used by the Swedish scientist. A safety design query was initiated of the computer and the initial information showed that the design features were satisfactory. However, after continuing with the integrated program query, when the computer received information that the transport was to be certified for day/night, and VFR/IFR flight, it immediately alerted the interrogators to a problem in the IFR operation. A print-out indicated that during IFR operation, weakening of the aluminum would occur as the probability of moisture being present was high, and during such times a form of electrolysis would occur. The team adjusted their design specifications and the potential unknown problem became known, and was not a safety factor of further concern.

This then is how I foresee the operation of such an investigative tool that would help us all dig into the "unknown".

It could be operated in a manner very similar to the NASA Aviation Safety Reporting System in the United States. It probably should be operated by a neutral organization such as FSF, ISASI, ICAO or by certain universities. Data submitted would be safety related as indicated and could be anonymous if desired. Also there should be no fear that new design secrets, or information of a classified nature either from a military or commercial source would be available in the computer. The individuals and organizations submitting the data would scrutinize and/or withhold any sensitive information as *they* might see fit. There is certainly enough extra and even discarded research accomplished in aviation, world wide, that even a small portion of safety data could build an important *preventive* tool that would benefit us all.

How Does the Investigator Develop Recommendations?

Richard H. Wood, P.E., CSP M00598
Institute of Safety and Systems Management
University of Southern California
Los Angeles, CA 90007

I believe this group would agree that the ultimate purpose of accident investigation is accident prevention. The investigation may also serve some other purposes, but if it does not contribute something to the prevention of the accident — if aviation is not somewhat safer as a result of the investigation — then we are wasting a great deal of time, money and effort in a procedure which is interesting, but has little value to society.

There is no mystery about the relationship of aircraft accident investigation to prevention. In order to know what to do to prevent the accident, we must first know what caused it. Thus the investigation is an essential first step in the chain that leads to preventive action. There is a problem in this process, one that is implied in the title of this paper, "How Does the Investigator Develop Recommendations?"

The answer, depending on your point of view, is either, "very carefully," or "not at all." I intend to develop some of the arguments on that problem, and my point of view should become apparent as we go along. The problem is perhaps best illustrated by an analogy.

Let's suppose that you are reading in your hotel room when your bedside lamp suddenly goes out. As an experienced investigator, you quickly determine that there is adequate electrical power at the wall socket and that the light bulb is perfectly good. Without too much trouble, you narrow the problem down to the light switch itself. With your pocket screwdriver, you dismantle the switch and discover that the spring holding the electrical contacts together has broken. Case solved. Cause determined. You call the hotel desk, report the problem and its cause, and ask that someone be sent up to replace the light switch.

You have just made a significant jump from determining the cause of something to recommending how it ought to be fixed. There is nothing wrong with your recommendation, and there is no doubt that it will solve the problem, but it is not necessarily the best solution.

As it turns out, yours is not the first bedside lamp failure. The hotel has 400 rooms with identical bedside lamps and the hotel manager has learned a lot about lamps and switches over the past few months. First, although replacing the switch may solve the problem temporarily, the replacement switch is no better than the original and it, too, will fail. It is better to replace the internal spring with a stronger spring. That seems to solve the problem permanently, but it takes longer and requires a reasonably skilled worker. Second, he doesn't have enough skilled workers to send them to the rooms to work on lamps. It is much easier to have a bellboy bring you a replacement lamp and deliver the broken one to the maintenance shop. Shortly a bellboy knocks on your door with a replacement lamp and order (not to say light) is restored. Everyone is satisfied.

Let's look at what happened here. In this simple situation, you made a resonable and sincere recommendation based on your analysis and your experience with lamps in general. The manager, with a slightly different viewpoint, based his action on questions of time, cost, parts and skill availability, and so on.

"Fine," you say. "I didn't really care how he fixed it. How am I supposed to know his trade-offs between cost and time?"

There. You've just put your finger on the nub of the problem. You're not. In the situation cited, your recommendation caused no great concern because the manager was under no obligation to follow it. Consider, though, what happens in air safety investigations.

We select aircraft accident investigators for their experience and skills as pilots, maintenance specialists, engineers, aerodynamicists, and so on. We train them in the skills of data collection and analysis, wreckage examination, witness interviewing, etc. We end up with a very talented and skilled group of people who are the best we have to offer to determine what happened. What caused this accident? Unfortunately, we did not teach them how to fix the problems they have found.

Take a simple structural failure. There are any number of ways, used singly or in combination, to fix a structural problem. Some of these are shown in Figure 1. Which is actually best in any particular case depends on some of the factors listed in Figure 2.

Suppose that we own a manufacturing business and we have a problem with one of our products. It did not result from an accident, but we are, nonetheless, going to convene a group to examine some of the alternatives suggested by Figures 1 and 2. Who do we put on the group? More to the point, would we staff that

HOW MANY WAYS CAN IT BE FIXED?

We Can . . .

Redesign the part and strengthen it
Use stronger material
Add additional material (doubler)
Reduce the applied load
Inspect if more frequently
Inspect it more thoroughly
Change it more often
Limit its operation
Reduce criticality of failure

FIGURE 1

WHAT FACTORS INFLUENCE THE DECISION?

Cost
Time
Parts Availability
Tool Availability
Aircraft Availability
Weight
Accessibility
Maintainability
Possible Side Effects

FIGURE 2

group with people with experience as accident investigators?

The answer, I think, is, "No." Now that we know what the problem is, the question of how to fix it demands a different group. As was suggested earlier in the paper, the problem of prevention is no less important than investigation and it demands the attention of a group with the best possible skills to deal with the problem — which is not the investigation group. If we are serious about preventing accidents, why don't we have a group of "recommenders" with equivalent background and training as our "investigators?" Like most controversial problems, the arguments on the other side of the question are not wholly without merit.

In aviation accident investigation, the total experience of the investigators cannot be ignored. This experience includes not only aviation, but this accident in particular and all accidents in general. They are capable of making responsible recommendations and they should be considered. Furthermore, preventive action has to start somewhere. We know from experience that if there are no recommendations, there may be no action. There is considerable truth in that. The investigator usually knows what must occur to prevent the accident. His problem is that he doesn't know exactly how that can best be achieved. Separating the "what" from the "how" may be where the difficulty lies.

On the question of preventive action starting somewhere, I agree. I believe, though, that having the investigators start the recommendations is a matter of cultural habit as much as anything else. As businessmen, we are intolerant of people who bring us problems without solutions. But in the aircraft accident prevention business, we train investigators specifically to "bring us the problems." What makes us think that they will also bring us the best solutions? We must really believe that they will, because in most of the major aircraft accident investigation systems in the world, the investigator is specifically charged with developing recommendations. According to the *ICAO Manual of Aircraft Accident Investigation:*

> "Invariably the investigator, having regard to the knowledge gained during the investigation, will form an opinion that improvements could be effected which would raise the level of air safety, and it is his responsibility to make recommendations concerning these matters."(1)

Actually, that's well put. The manual does not suggest that the investigator can make a recommendation that would prevent the accident, merely raise the level of air safety. Consider the instructions on accident recommendations published by the United States Air Force.

> "The recommendations are actions which should either prevent a similar accident or reduce its effect. The recommendations must be feasible and related to the causes of the accident."(2)

The key word there is "feasible." That goes directly back to the factors suggested in Figure 2 and it strongly implies that the investigator must go beyond that which will merely prevent the accident.

The United States National Transportation Safety Board has these words in the law describing their functions:

> "... recommending and advocating meaningful responses to reduce the likelihood of accidents ... and proposing corrective steps to make the transportation of persons as safe ... as possible."(3)

The key word there is "meaningful," and that could be broadly interpreted as requiring recognition of the factors shown in Figure 2.

The real problem here is not so much whether the investigataor should or should not make recommendations — of course, he should. We need all the ideas we can get. The problem is, "What level of credence are we going to assign to those recommendations?" If, on the one hand, we are going to accept those recommendations as being sincere and informed, but not necessarily practical or feasible, then we don't have a problem. On the other hand, as often appears to be the case, if we are going to treat those recommendations as being chiseled in stone and handed down from some higher authority, we have a serious problem. That problem exists in some countries today. In some investigation systems, the agency to whom the recommendation is addressed is under considerable pressure to implement it. This pressure comes from both the law and from public pressure. This latter pressure can be intense.

I am sure you all recall the situation immediately following the crash of the DC-10 at Chicago in the Spring of this year. Regardless of what you may think about how that investigation or subsequent grounding of the aircraft was handled, put yourself in the position of the FAA Administrator for a moment. He was forced into taking action based on recommendations developed largely in the news media before all of the facts bearing on the problem were available. At the time, he did not have enough information to know what the correct solution was — and he said as much in several interviews. When the recommendations of the NTSB on that accident are finally published, the FAA Administrator is going to be under pressure again — and he may have no choice but to implement the recommendations as written.

When the Administrator of the FAA finally receives the recommendations of the NTSB, this is what the law says he must do.

> "Whenever the Board submits a recommendation regarding transportation safety to the Secretary, he shall respond to each such recommendation formally and in writing not later than 90 days after receipt thereof. The response to the Board by the Secretary shall indicate his intention to:
>
> 1. initiate and conduct procedures for adopting such recommendation in full, pursuant to a proposed timetable, a copy of which shall be included,
>
> 2. initiate and conduct procedures for adopting such recommendation in part, pursuant to a proposed timetable, a copy of which shall be included. Such response shall set forth in detail the reasons for the refusal to proceed as to the remainder of such recommendations; or,
>
> 3. refuse to initiate or conduct procedures for adopting such recommendation. Such response shall set forth in detail the reasons for such refusal.
>
> "The Board shall cause notice of the issuance of each such recommendation and of each receipt of a response thereto to be published in the Federal Register, and shall make copies thereof available to the public at reasonable cost."(4)

Thus the Administrator has only three choices and, in a situation generating as much public pressure as the Chicago DC-10 accident, choice 2 or 3 may be unacceptable.

Under a system that works like that, it behooves us to make sure the recommendations are the best possible. Consider a simple logic diagram as illustrated in Figure 3.

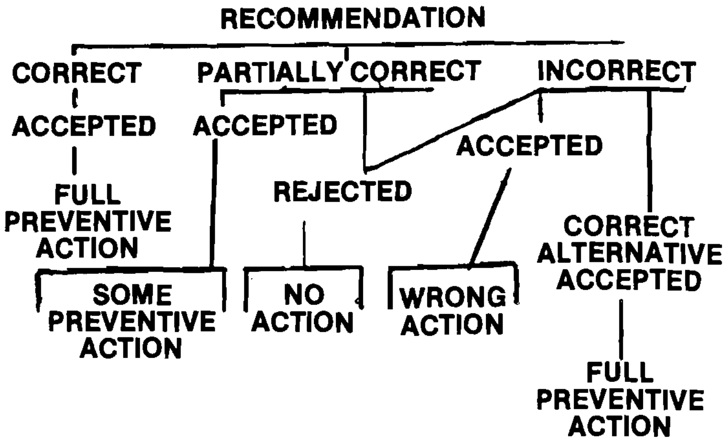


FIGURE 3

Let's assume (simplistically) that a recommendation can be either totally correct, partially correct, or incorrect. If a recommendation is totally correct, meaning that it considers all of the alternatives and problems listed in Figures 1 and 2, then we would expect it to be accepted and full preventive action to occur. If the recommendation is only partially correct, though, the best we can expect is partial corrective action. At worst, the recommendation may be rejected (because it is also partially incorrect) and there will be no action at all. I'm sure most of you can think of cases where this has happened. I'll mention one familiar to me. An aircraft accident investigation board examining a military aircraft accident recommended that certain fuel panel switches be guarded with red plastic covers to prevent inadvertent operation. The action agency rejected this stating that it would require a complete redesign of the fuel panel and the expense of that was unacceptable. Perhaps, but that didn't make the problem of inadvertent operation of the fuel switches go away, and there were other ways to prevent inadvertent operation. The recommendation was at least partially correct.

Consider the case where the recommendation is incorrect. It may be rejected (which leads to no action) or it may be accepted (which leads to the wrong action). This latter situation has also occurred and is usually the result of more pressure to fix something than the action agency can stand. I'll mention one such case involving a jet engine. For some reason, the engine had developed (or always had) a vibration mode in one particular section that investigators correctly diagnosed as being responsible for cracked fuel lines and other accessory fittings. The recommended fix was a steel cable that literally restrained the engine from vibrating. The action agency was not enthusiastic about this fix, but had no immediate arguments available for rejecting it. The steel cable was installed on all engines. The result was that the engine merely found a new harmonic frequency at which to vibrate and things started cracking at a different location; a situation that was both obvious from subsequent testing and intolerable. The steel cable was removed from all engines and the engineers started looking for ways to remove the rigidity from the accessory fittings and tolerate the vibration.

If the initial recommendation is incorrect, there is, of course, a third solution. It can be changed and the correct solution can be adopted. For this to occur, though, the atmosphere must exist where the initial recommendations are not chiseled in stone and there is general acceptance of the fact that people who investigate accidents do not necessarily have the economic background to determine what is really feasible. I'll cite one more example. A particular military jet engine had numerous problems which resulted in accidents. There wasn't much disagreement on the problems. There was likewise little disagreement on what it was going to take to fix them. Replacement of several internal parts with the latest state-of-the-art components was required. The problem was that this meant a complete overhaul of the engine and (based on availability of overhaul facilities and parts) there was a definite rate at which the engines could be overhauled. Optimistically, it would take more than two years to get the new parts installed on all engines and there was no feasible way to accelerate that process. Here was a situation based on time, cost, and parts/equipment availability that is beyond the expected knowledge of the accident investigator. Although the engines were eventually all modified, the military agency involved was astute enough to realize that the modification proposal was not a correct solution in terms of preventing near-term accidents. There had to be alternative solutions involving increased inspection and restricted engine operation.

As can be seen from Figure 3, there are only two acceptable situations. Either the recommendation is correct to begin with or the atmosphere exists where the correct recommendation will be developed and will replace the initial recommendation. All of the other alternatives are undesirable. Unless we believe that the investigating body will always develop the correct recommendation, we really only have one choice. That is to un-chisel them from stone, so to speak, and put them in their proper perspective. Considering all this, I have two solutions to propose. One is somewhat idealistic, but the other is meant to be immediately practical.

In the first solution, we accept the fact that we get our best causes from professional investigators and our best solutions from "professional recommenders." Figure 4 depicts a mythical country in which an organization or tribunal is responsible for aviation safety. There are two subordinate organizations; one for investigation and one for prevention. The prevention group is composed of representatives of the aircraft user, the regulatory agency, and the manufacturer. After an accident occurs, the investigation group submits its findings to the tribunal. If approved, the prevention group is then charged with determining what is to be done to prevent that type of accident. The tribunal passes judgment on both the findings of the investigation group and the adequacy of the actions of the prevention group. Since the prevention group is already formed, it's efforts proceed concurrently with those of the investigation group and there is little or no lost time. If the investigators have any suggestions, they pass them directly and informally to the prevention group. Good ideas are not lost. This solution puts the burden of developing the recommendations on the people that have the knowledge to do it and challenges them to convince the tribunal of their solutions. To add incentive and spur action, the tribunal may propose restriction or grounding of the aircraft if recommendations are not developed, initiated, or completed within certain time limits.

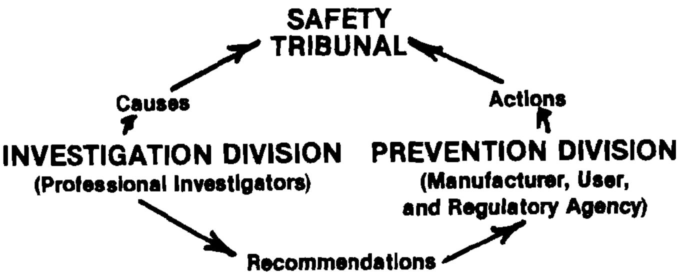


FIGURE 4

In many of our countries, that solution would represent a radical departure from our present system. In most cases, we do not have a single agency whose safety responsibilities include prevention as well as investigation. It is difficult to see how that type of idealized solution could work unless those two key elements of safety are organized under the same umbrella. To be practical, we are probably going to live with the situation where the investigator develops recommendations and these become the basis for initial preventive action. My second solution accepts this as a fact of life.

Recognizing the risks and pitfalls of this procedure, the question becomes, "What can we as countries or as individual investigators do to insure that we don't cause more problems than we solve?" First, I believe that each of our countries needs a system whereby the recommendations of its investigators are held in proper perspective. The agency responding to a recommendation should always have the option of suggesting (and justifying) an alternative solution that will provide an equal or greater degree of safety. There should be no pressure to adopt the profferred recommendation if a better solution exists. The preamble of the recommendations should make this clear to both the action agency and the news media. Along with this, I also suggest divorcing the recommendations from the report of investigation and handling them separately. The reason is that once the investigation report is officially adopted, it is held to represent the truth of the matter and is recorded for all posterity. The recommendations are always open to differences of opinion and they never quite achieve the same status as the official "causes." Nevertheless, if the recommendations are part of the investigation report, they, too, are chiseled into stone and recorded for all time along with it. Even the bad recommendations will stand forever.

Second, I believe that individual investigators can assist by putting more thought into the drafting of recommendations. A well thought-out recommendation should achieve two goals.

1. It should clearly focus attention on the problem, not on the suggested solution to it. This should

eliminate the possibility that the problem will be rejected along with the recommendation.

2. The recommendation should be flexible enough to permit the action agency some latitude in precisely how that objective can be achieved. This is particularly important if all the salient facts are not yet available and some additional examination and testing appears necessary. The Accident Investigation Manual of the United States Energy Research and Development Administration (ERDA) has some appropriate comments on this subject.

> "An investigation board may lack the time, information or competence to evaluate the financial, operational, and policy impacts of recommendations. If so, it is probably wise to suggest study and development of a plan to meet the needs. Then the reviewing authorities can judge the investment/benefit/value considerations and either direct that the recommendation be implemented or that a study be initiated."(5)

Anyone who has followed the National Transportation Safety Board's recommendations over the years would agree, I'm sure, that they recognize the difficulties inherent in an inflexible recommendation. Today's NTSB recommendations are well written. They do focus on the problem and they do permit considerable latitude in how the solution is to be achieved. In its annual report to Congress, the NTSB had this to say about recommendations:

> "The safety recommendation is the Board's end product. Nothing takes a higher priority; nothing is more carefully evaluated.
>
> "Under the Board's policy, its safety recommendations must meet four criteria: clarity, conciseness, technical feasibility, and adequate support. Each recommendation designates the person, or the party, expected to take action, describes the action the Board expects, and clearly states what is the safety need that is to be satisifed."(6)

Note the phrase, "technical feasibility." To me, this means that the Board has gone far enough to assure itself that the recommendation is at least possible, but they have stopped somewhat short of implying that it is economically the best among all alternatives.

All that is fine in principle, and there is no doubt in my mind that the NTSB puts its best efforts into its recommendations. In practice, though, the person or party expected to take the action is under considerable pressure to accept the recommendation as written. While the law (as quoted earlier) permits rejection, it does not encourage it. Neither does the manner in which the recommendations are issued. Under those circumstances, it seems to me that it would be prudent to at least consult with the person or party expected to take the action while the action is being drafted; particularly when technical matters are involved requiring consideration of the options suggested in Figures 1 and 2.

In summary, the process of developing recommendations is at least as important as the process of investigating the accident and determining its causes. Without it, the investigation is worthless. At the present time, there is a tendency to let the investigator develop the recommendations and ignore the real and practical considerations of time, cost, feasibility and so on. If there also exists an aura of omnipotency about the investigator's recommendations, then he has been accorded more power and more control over accident prevention than he reasonably can handle. There is a risk that he may be wrong, and that either the wrong action or no action at all will be taken.

We could change this, but it would mean a drastic overhaul of our present thinking about aviation safety organizations and the responsibility for aircraft accident prevention. It would, in short, involve elevating the recommendation process so that it receives the same level of attention as the investigation process. Failing that, we can relieve the situation by first creating an atmosphere where disagreement and alternatives to the investigator's recommendations are encouraged, and second by couching the recommendations themselves in terms that permit some latitude in the specific manner of implementation.

I'd like to close with a remembered quote from a senior manager in a fairly well-known manufacturing company. This occurred during a management seminar in meeting government specifications and had nothing to do with accidents, but it might be the same thing that a manufacturer or aircraft user might want to say to an investigator.

"Tell me what has to be done — but don't tell me how to do it."

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Pros and Cons of Punishment for Achieving Discipline in Aviation

Jerome F. Lederer LCH035
Electric Power Research Institute and
University of Southern California

These observations on the pros and cons of punishment concern only the acts of professional airmen, well trained and conscientious, with a history of disciplined performance. Unfortunately, judgments and actions are subject to the frailties of human nature and the force of circumstances. Air traffic controllers, mechanics, flight crews, in common with all mankind, occasionally experience a lapse in self-discipline. If an incident or an accident occurs, does punishment make them better airmen? Airmen are distinctive from most other professional groups in that their occupational misfortunes are more likely to become visible to the public. Punitive measures then become mandatory. Besides this the ego of management whose prestige has suffered because of an accident must also be satisfied by punishment. Both demand their pound of flesh regardless of its effect on the discipline of the offender. Unlike the physician, the other professional who deals with life and death, airmen cannot bury their mistakes.

Most of us were raised with the opinion that the most effective way to obtain discipline is by the *threat* of punishment itself. However, in the existing social, cultural and operative environment of aviation, in a democratic community, management is compelled to rethink the traditional concepts of punishment. (The military is not excluded.) John F. Kennedy suggested that "Too often we enjoy the comfort of opinion without the discomfort of thought."

The problem is, how can public safety be meshed most effectively with the accountability of a normally well-disciplined airman who has unexpectedly veered from some pundit's concept of perfection and has suffered an accident?

General Considerations

Discipline is essential in the conduct of high risk ventures. By one definition, curiously, it is a synonym for punishment as a way to spur self-control. In the context of this dialogue it means a systematic, willing, and purposeful attitude towards the performance of an assigned task. It is often achieved by a random system of communication involving subtle as well as direct pressures, and at times by negotiation rather than by command. Discipline is subject to distortion by life events (see Appendix), by understandable lapses in self-control, by miscalculation, by unforeseen circumstances which induce deviations from expected performance. Punishment for the consequences of undisciplined operation or for a failure in judgment is usually based on the expected conduct of a model airman who does not exist in real life.

Punishment and awards are important segments in the system of communications that leads to better discipline. Punishment, however, could be an uncertain variable. It may be argued that neither punishment nor awards are as effective in securing discipline, especially self-discipline, as the judgment of one's peers, or the latent mortification that follows misfortune, or the ordeal created by one's inner conscience. If this is so, what is to be gained by suspension, by fines, or other penalties? The professional has learned from his unfortunate experience. Nevertheless, punitive measures are applied through the regulatory agencies to appease an apprehensive public, or to satisfy the ego of a macho manager. Most important however, is the adverse effect on the discipline of the offender's organization if he is not punished. How can punishment be achieved without creating in the offending professional a feeling of resentment or impelling him to seek revenge among his peers, if they agree that under the same circumstances they would have acted in the same way? There is also the element of danger if the threat of punishment induces the concealment of mistakes that might otherwise be voluntarily admitted. This dilemma will be explored later. Constructive catharsis may better serve the public and the offender than the usual intent of punishment.

The threat of punishment must also be considered for its adverse effect on accident investigation. It is a dormant evil which inhibits full and free confession which a professional might make for the good of safety. Accident investigations by governments are assumed to be, and usually try to be, objective, non-accusative, non-adversary proceedings. They are expected to provide information to prevent the reoccurrence of an accident. However, the threat of punitive action, in addition to legal liability, cannot be disregarded; consciously or sub-consciously, by participants to the investigation. How much does this threat of punishment color the evidence submitted by the dedicated professional airman during the investigation? What is a dedicated professional?

The dedicated professional is represented to the highest degree by the following anecdotes:

Many years ago two accidents came to my attention which involved pilots with unblemished civilian records. Impelled by conscientious duty to themselves and to aviation, they freely confessed errors which led to their accidents. In one case the instructor pilot, who was also chief pilot of the airline as well as the pilot to the King of his country, widely recognized for his contributions to safety, allowed a trainee to land a DC-4 with the undercarriage up. No one was harmed. In the other case, a highly experienced scheduled airline Captain flying a DC-3, undershot an airport. A baby was killed. In each case their moral sensibility drove them to suicide.

If these two pilots had decided to live, would punishment for their accidents have made them any better pilots? Among professionals, which is more effective in stimulating discipline: their inherent desire to perform correctly, their reputation among their peers, families and friends, or their fear of punitive measures? Would they not have been better pilots for having been through the experience of an accident? Aren't we all better operators of dangerous equipment, such as automobiles, airplanes, motorcycles, for having nudged danger?

Punishment is commonly defined as the imposition of a penalty such as fines, suspension, pain, loss, or suffering for an offense. However, to the professional, it also implies a degraded reputation, humiliation, peer group censure, a feeling of incompetence or blameworthiness. This inner penance may be much more meaningful to the involved, conscientious airman than fines or suspension, but they may be very vague to the public or to management, or to the regulatory agencies which demand specific retaliation. Their pound of flesh. Of course, a willful or malicious act or lack of self-control, such as the use of drugs, demands prompt and tough punishment.

In addition, management is obliged to communicate promptly at least its apprehension and anxiety or strong disapproval of any complacency, lack of awareness, skill, disobedience, or poor judgment of the offender, if organizational and individual discipline is to be maintained. Steps taken by management will, of course, vary with circumstances.

Communication and Discipline

Punishment and rewards are forms of communication between management and employees. It is important to relate punishment to communication because communication in its broadest sense influences morale, motivation and therefore, discipline. Morale, defined as the mental and emotional attitude towards tasks and functions, the esprit de corps, can be powerfully affected by punishment and reward. Motivation, a close ally to morale, is defined here as need or desire that impels a person to act in the way that is best for his organization. It is very sensitive to punishment and rewards.

Morale and motivation which result from clearly expressed cmmunications combine to induce discipline, previously defined as a systematic, willing and purposeful attitude toward the performance of an assigned task. Discipline is essential for organizational control. A respected, exacting taskmaster is important, but discipline can be seriously influenced by inappropriate punishment which, among other consequences, may induce resentment and perversity.

Punishment as a form of communication in a high risk environment must be used adroitly in dealing with the well-trained, conscientious employee, whether he be in the highest or lowest echelon of the organization. Even the lowly cleaner who inadvertently leaves debris on the ramp or hangar floor can be the cause of damage, injury or even death. The word "inadvertent" should be stressed because willful departures from good practice, such as drinking on the job, are not considered in this discussion.

The inadvertent action may be caused by distraction, cockpit environment, design-induced error, inadequate training or supervision, fatigue, anxiety, illness, psychological pressures, even by the time of day.

Communication as a path to discipline need not be vocal, written or specific or itemized. It may be conducted by gestures, mannerisms, attitudes, facial expressions, symbolism, and by the poise of a supervisor to influence the employee's reaction. Silence is often an excellent form of communication. These types of communication may be more effective in strengthening discipline than a fine or suspension. A good manager knows how to use them as advantageously as he uses a smile or a pat on the back to reward good performance.

Management equates discipline as a respect for authority. In aviation, with its unique comraderie and social environment, coupled with a complex technology, this respect must be earned by management, not imposed by penalty except for unpardonable disobedience or deliberate departure from accepted practice. And it must be admitted that at times authority and therefore discipline results, not from command but from negotiation with peer groups (unions or trade associations).

Col. Richard Wood in his treatise* of December, 1978, "Can You Punish an Accident?", declares that "a particular unit or group perform in the way they do, not because they fear punishment, but because they have been trained that way and they are individually convinced of the wisdom of conformance as a means of achieving objectives." He considers adverse action taken against a pilot, for any reason, to be punishment, not discipline.

A corollary to this concept is the reinforcement of disciplined behavior by recognition for good performance. This may be more effective organizationally than the demeaning of professionals by public punishment for inadvertent departures from good practice. This, however, in no way should affect the great importance of calling attention of improper practices to the individuals concerned in person and to the organization in a generic sense. Monitoring of performance on a non-punitive basis to ensure compliance with accepted practice has already proven of enormous importance to safe aircraft operations.

*Prepared for the Institute of Safety and System Management of the University of Southern California.

The Military View

Punishment for deviations from discipline has been a strong military tradition. In today's operational and social climate, old military traditions, operable in the days of simple technology, are difficult to justify. Respect for authority, which is the basis of operational discipline, must be attained by means other than sixty lashes.

Respect for authority ideally stems from the decisiveness and good judgment of a firm management rather than from fear. In an emergency a clear touch of tyranny is also important for control.

General David C. Jones, Chief of Staff, USAF, had some pertinent observations on discipline in the May, 1978, issue of Air Force Magazine:

"Discipline

"'The more things change, the more they stay the same.' Some people claim to see a profound erosion in standards of discipline over the past few years. From my vantage point I see only a change in the way discipline is developed. The bottom line hasn't changed: confidence that orders will be carried out faithfully and promptly.

"When you stop to think about it, fear is probably the least effective tool for fostering the sort of discipline needed among a modern force of educated, technically oriented and trained people from a democratic society. It's one thing if a commander's only concern is narrow, uncomplicated instructions. But modern warfare has grown too complex for sole reliance on this essentially medieval foundation for military discipline.

"The shift I see is an evolution from a norm of arbitrarily imposed authoritarianism to greater a reliance on self-discipline. We have worked hard to substitute mutual respect and understanding of the mission for the other style 'do-it-because-I-say so' philosophy.

"Overall, we've made good progress both in the transition and in raising the standards of discipline of the Air Force, but still have a way to go on both counts.

"The sanctions are still there if needed, but our low rates of disciplinary action persuade me that they are being effectively employed by leadership as a backstop rather than as a club.

"In view of the increasing complexity and technical sophistication of the modern battlefield, I'm convinced we've chosen the right path in engaging people's minds, not just their bodies, in our concept of discipline. Our peacetime management and our combat capability will be strong, more flexible, and more imaginative because of it.

"A large measure of self-discipline is required to complete vital actions with neither error nor omission. Unfortunately, commanders can only encourage their subordinates to develop this special kind of discipline; it is almost impossible to enforce it. Therefore, if self-discipline is not an infallible solution to the problem—what is?"

Social Pressures

Respect for authority may be unevenly divided at times between management and peer groups. Authority or leadership is based largely on the competence of the person in command. He may be able to hoodwink his seniors, even his peers, but rarely his subordinates. A subordinate's faith in the competence of management is necessary for it to exert the authority of leadership.

However, in several organizations widely recognized for their operational efficiency and dedicated personnel, discipline results from the special characteristics of management/employee rapport supported by the mores of the people. Japanese industry is a good example. Several organizations in the U.S.A. also achieve outstanding results by encouraging self-discipline and group-discipline, some by participative management. Perhaps the principal reason for their success is a function of expectation: the employee becomes stimulated by what is expected from him by his peers and by his management, both operating in harmony. The pervasive threat of displeasure by fellow workers can be very effective.

Punish Management?

Management or regulatory bodies are rarely, if ever, punished for mistakes or errors in judgment which lead to accidents. But airmen are. For example, the pressure by management for on-time performance may persuade a mechanic to take shortcuts. The Los Angeles Times, August 15, 1979, reports that two airline mechanics reported a bolt installed upside down in the reverse thrust system. The plane was signed out nevertheless. The two mechanics were suspended but later exonerated by union intervention. If true, a grey area exists since management is rarely criticized, let alone penalized, for the pressure it exerts on employees. And who faults the aircraft manufacturer for approving a design that allows a critical bolt to be installed upside down!

Manufacturers are seldom subjected to punitive measures for design judgments that create operational problems, such as those which induce pilot error. This audience does not need examples to prove the point! But should judgment be subjected to penalty? Let him who is without sin cast the first stone.

These viewpoints attempt to crystallize a break with traditional punishment to secure operational discipline. Nevertheless, where public safety is concerned, complacency, carelessness or neglect should never be condoned. Morale and motivation on which discipline depends in our current societal environment rests on a system of understandable communication, on objectives accepted by management and employees. Several cases to support these observations follow:

Specifics

Some 25 years ago while visiting Europe, the President of an international airline faced a practical problem in discipline in its punitive sense. This airline's most experienced and respected Captain had landed a DC-6 at night in Cairo with the under-carriage up. Damage was minimal. Cairo landings presented awkward problems to flight crews at that time. Management pondered what punitive measures to apply. Suspension of the Captain from duty or his reduction to co-pilot status would have a very small corrective effect, if any, in comparison to the mortification and distress he had suffered from the mishap. Again quoting Col. Richard Wood, "Can you punish an accident?" On the other hand, organizational discipline called for management action. Other airmen might misunderstand management's tolerance of the Captain's misfortune, despite his stature.

The President happened to be a lawyer who had made a thorough study for a college thesis on man's compulsion to punish. He presented five reasons for the imposition of punishment and requested the Flight Safety Foundation to consider their application to his current predicament.

His five reasons for punishment were: 1. for revenge; 2. for protection of the transgressor; 3. for protection of society; 4. for instruction; 5. as a mark of authority.

Since this was an administrative problem, Professor Kenneth Andrews of the Harvard Graduate School of Business Administration was requested to prepare a study on the effectiveness of punitive measures in aviation for the FSF International Seminar of 1952. Under the title of "Crime and Punishment", its logic appealed to large organizations as well as other schools of business administration who requested copies. He concluded that none of the reasons for punishment applied in this case. His reasoning follows:

Punishment From Management's Point of View—Purposes for Discipline

Discipline for Revenge

"Most of us are familiar with the more common approaches to punishment taken by those who mete it out. One of the oldest and most primitive uses of punishment may have been simple revenge. An eye for an eye and a tooth for a tooth was an equitable retribution, evening a score, cancelling an offense. The offender paid in the currency in which he offended. Thus if a small boy breaks his sister's bow and arrow, and we as parents break *his* bow and arrow as punishment, we follow this obsolete approach to discipline. In certain very simple situations, this generally obsolete basis for punishment is still useful. But it is not practical to punish a pilot who has crashed an airplane through carelessness by asking him to ride in a plane which is crashed on purpose.

Discipline for Protection of the Transgressor

"A more subtle purpose of punishment is usually cited by management to be, rather than revenge, the protection of a man against himself. His transgression is punished to enable a man to keep his baser impulses under control in the future. This theory is false to present-day psychology which postulates that persons (at least those not suffering from schizophrenia) do not have personalities divided into bad and good halves. Our pilot, for instance, would probably not be punished to protect him from his *desire* to be careless.

Discipline for Protection of Society

"A closely related purpose is to protect society against offenders. We remove hardened criminals from society, not to protect them from themselves but *us* from *them*. This purpose hardly applies to organization discipline, and it is not relevant to organizations except where the law is violated. And in safety matters there cannot be laws against bad judgment.

Discipline as Instruction

"A more constructive purpose is said to be to teach offenders to comply. But our pilot, again, has learned his lesson from his accident. Most persons in aviation have more pressing reasons to abide by safety regulations. In violations where accidents do not occur this purpose might apply, but certain problems of communication keep most breaches of discipline which have no bad result from coming to the attention of management at all.

"The point of view most commonly taken toward the usefulness of punishment is that a penalty teaches others a lesson. Disciplining an offender thus deters others from the same offense. This purpose has much plausibility, but who wants to offend? Are the persons whose carelessness, bad judgment, and error cause accidents doing something which the fear of punishment would prevent them from doing? Without knowing more about the very complicated situations out of which each offense comes, it is not possible to say that proper punishment actually reduces the number of violations of good practice.

Discipline as a Mark of Authority

"Many persons in management who question the effectiveness of punishment as a method of administration cling to it for reasons of authority. Does not the administration of punishment underscore the power of management to manage? Does not the application of discipline go with authority? While the more common reasons for punishment prove more and more inapplicable to present-day situations, it is generally felt that punitive discipline cannot be abandoned without weakening the position of management and removing from it its prerogative of 'managing'. So whether punishment serves the purposes of better results or not, it is at least, from the point of view of management, a means of pointing out who's boss.

Punishment from the Offender's Point of View

"While it is true that managements in business organizations, and perhaps even parents in families, are a little unclear about what punishment is all about, its reason for being becomes even more confused when we examine it from the point of view of the persons being disciplined. What will our 'perfect' pilot make of being made an example for the trainee pilots of his organization? What is the reaction to his suspension of a flight engineer who fails to fasten a door properly and loses a passenger? When several people are killed because a mechanic does not change a fuel feed valve diaphram as required at engine overhaul, what is his reaction to being suspended? According to the logic of punishment fairly administered, these offenders should see the justice and importance of their being punished, learn a good deal from the experience, and go on to performance which is the better in the future because of the punishment suffered now.

"We know by now, however, that persons under the pressure of punishment do not look so logically at their predicament. They may resent being made an example. They may resent being punished for a violation of a rule which in their experience has never before been enforced. Since a whole range of information is available to them which is not easily available to management, they look upon their own offense quite differently. They may reason that because an accident occurred following their violation, bad luck is involved rather than a punishable misdemeanor. A stewing about a fancied injustice, the emotional disturbance of adjusting to important punishment like suspension or dismissal, not only creates negative rather than constructive effects in the offender, but may, through his expression of his feelings, have a bad effect upon the morale of others as well."

There often appears to be a considerable irrelevance between the theoretical purposes of punishment and the actual effects upon the offender and his associates. One of the commonest consequences of discipline rigorously adhered to is increased insecurity and fear, which is already an important factor in the performance of persons in crews and on the ground. Without doing more than ask you to think of instances from your own experience, I should like to raise the question, does not discipline serve the punisher better than anybody else? Does not the purpose of punishment as conceived by management often fail to be communicated to the organization and individuals supposed to be instructed?

Constructive Use of Punishment

Dr. Andrews advocated the use of "punishment" as a constructive force. This airline's action was in that spirit. It was constructive, while concurrently providing relief for the pilot's humiliation and need for penitence. Management ordered him to schedule a series of conferences with groups of pilots to explain what happened, why it happened and lessons learned.

An Adverse Effect

The threat of punishment may predispose an airman to conceal known errors. Charles E. Cornell of the McDonnell-Douglas Astronautics Company, summarized a formal investigation of this tendency in Space/Aeronautics for March, 1968.

A study was made of human errors for the purpose of minimizing them. One interesting "discovery" was that the tough boss's approach resulted in concealing errors.

"The 'crackdown' method of error reduction (historically, the military's favorite response to the failings of human nature), has an adverse effect, as shown by the typical distributions of human errors over the phases of an aerospace program. The total number of errors decreases only very slightly, but the operators threatened with the boss's displeasure or worse become adept at hiding their errors, so that more errors remain undisclosed until later program stages, when they cost more to correct."

Nevertheless, the working atmosphere should not be relaxed to the point where complacency sets in. Constant vigilance is necessary. Respect for management's intentions and know-how is important. The careful worker usually is well disciplined. Motivation programs are important. Recognition for good effort is vital.

The military services have formalized procedures to learn from accidents by encouraging free disclosures of personal error. Under USAF Regulation 127-4, accident reports will not be used as evidence for disciplinary action; as evidence in determining the misconduct or line-of-duty status of any personnel; as evidence before flying evaluation boards; as evidence to determine pecuniary liability. These confidential findings cannot be used for punitive purposes. But the military also conducts an independent collateral investigation, AFR 174-4, to obtain and preserve evidence for use in litigation or disciplinary action. The airmen's statements in the adversary investigation may differ from the confidential enquiry.

These examples indicate that punishment for accidents or inadvertent departures from accepted procedures may often be an unwise method to induce discipline among dedicated professionals operating in a high risk environment. Nevertheless, it would be difficult to disprove that discipline is not strengthened by apprehension in the mind of the airman that he will be called to account when he makes a mistake. The solution rests on the manner by which the offender is held accountable.

Strong punishment has been generally discarded as a way to correct relaxed discipline. A typical case: "B747 inertial navigation system indication incorrect. Crew had not followed the correct procedures for loading the INS. This was not picked up during the subsequent pre-flight checks. Chief pilot has discussed the incident with the crew concerned." On the other hand, gross departures from accepted good practice, as distinct from errors in judgment or inadvertent mistakes, are subject to severe punitive action; e.g., the firing of a crew for inadequate cockpit awareness and coordination resulting in a crash.

Peer group acceptance or criticism may be as effective, and in many instances more effective than organizational authority. An old War Department manual on leadership says, "Strong men, inculcated with a proper sense of duty, a conscious pride in their unit, and a feeling of mutual obligation to their comrades in the group, can dominate the demoralizing influence of battle far better than those inculcated only with fear of punishment or disgrace."

This paper had dealt mainly with the transgressions of the individual. The problems of dealing with management lapses are more complex. A few years ago the president of an airline was under criminal indictment for a fatal accident over which he had little if any control. An item in Aviation Week and Space Technology, September 3, 1979, says that legislation is being introduced in the U.S.A. to add *criminal* penalties to FAA violations. The pros and cons of this, if applied to management, should be of interest to all of us in the future. Such legislation would certainly exact a devastating affect on accident investigations.

Discipline is essential for operational safety. If these thoughts have stirred your interest in how discipline can be improved by methods other than the threat of common concepts of punishment, except for willful and deliberate misconduct, it will have served a useful purpose.

Appendix
CANDIDATES FOR ACCIDENTS

Studies indicate a pilot's emotional stability is related to flight safety

An Air Force general once told me how strongly he wishes for a device that would quickly indicate the emotional stability of a pilot just before takeoff. He kept careful tabs on the family life of his pilots, for example. Those who were soon to expect an addition to the family, for instance, were not permitted to fly very far from the base. He felt that a pilot was likely to take unusual risks to get back to his family if the baby arrived while he was some distance away.

Efforts have been made to develop a "Human Performance Measuring Device." One is described by that title in NASA Tech Brief 70-10619. Called the "Complex Coordinator," it tests perceptual and motor skills by posing a series of problems through means of a pattern of lights. The problems are solved by correct manipulation of the hands and feet. When the subject is in a good "psychomotor state." a base line is established for his response to problems. When he is distracted or under the influence of drugsj or alcohol, his performance will vary from the base line.

This can be applied to the early detection of psychophysiological body changes due to toxicity or stress. Other methods are under investigation, such as voice patterns electronically recorded or brain wave monitoring. The pressure with which a pen is squeezed and the pressure exerted on the paper while writing have also been validated as clues to varied emotional states (gripping the wheel).

Perhaps of more immediate usefulness, however, is a weighted list of life events that increase the probability of human error because of emotional instability. This concept was appraised in the September/October (1973) issue of "Lifeline," the excellent safety publication of the Naval Safety Center at Norfolk, Virginia.

In the article, Dr. Robert A. Alkov of the Center briefly described studies underlying the relationship between personal stress, disease or accident-precipitating behavior. Some people, he suggest, are more susceptible to emotional factors than others. He also suggests that "It is incumbent upon those in supervisory positions to monitor and observe how turmoil in the personal lives of these personnel affect their performance."

Dr. Alkov then presents a list of events with their scale of importance: It was developed by questioning hundreds of people.

TABLE ONE

Rank	Life Event	Mean Value
1	Death of spouse	100
2	Divorce	73
3	Marital separation	65
4	Jail term	63
5	Death of close family member	63
6	Personal injury or illness	53
7	Marriage	50
8	Fired at work	47
9	Marital reconciliation	45
10	Retirement	45
11	Changes in family member's health	44
12	Pregnancy	40
13	Sex difficulties	39
14	Gain of new family member	39
15	Business readjustment	39
16	Change in financial state	33
17	Death of close friend	37
18	Change to different line of work	36
19	Change in number of arguments with spouse	35
20	Mortgage over $10,000	31
21	Foreclosure of mortgage or loan	30
22	Change in work responsibilities	29
23	Son or daughter leaving home	29
24	Trouble with in-laws	29
25	Outstanding personal achievement	28
26	Wife begins or stops work	26
27	Begin or end school	26
28	Change in living conditions	25
29	Revision of personal habits	24
30	Trouble with boss	23
31	Change in work hours, conditions	20
32	Change in residence	20
33	Change in schools	20
34	Change in recreation	19
35	Change in church activities	19
36	Change in social activities	18
37	Mortgage or loan under $10,000	17
38	Change in sleeping habits	16
39	Change in number of family get-togethers	15
40	Change in eating habits	15
41	Vacation	13
42	Christmas	12

TABLE TWO

Rank	Life Style	Mean Value
1	Marital separation	65
2	Change in responsibilities at work	29
3	Change in living conditions	25
4	Revision of personal habits	24
5	Change in working hours or conditions	20
6	Change in residence	20
7	Change in recreation	19
8	Change in social activities	18
9	Change in sleeping habits	16
10	Change in eating habits	13

Life style as distinct from the life events in Table One also plays a part in a person's predisposition to error. An intolerable burden may develop when life events are coincident with changes in life style, as per Table Two.

Civil Aircraft Liability and the Investigator

James E. Satterfield M02071
J. E. Satterfield & Associates
10215 Quiet Valley Lane
Houston, TX 77075

The investigation of civil aircraft accidents poses problems not inherent in the investigations of the various military services. Furthermore, the general agreements between countries, are often not applicable within the boundaries of individual States. In military investigations an evaluation of the facts can be made without consideration of the ultimate dollar value of the accident, including life value of those injured or killed. The military agencies resolve such questions without involving the investigator. Similarly, liability losses are limited by international agreement in cases where a foreign civil aircraft or carrier is involved in an accident. However, within the boundaries of the several countries, and in some international cases, an investigation of cause can rarely be made without an evaluation of money liability inherent in civil accidents. How these facts apply to the theme of ISASI's 1979 seminar can best be judged at the end of this brief treatise. Let us first consider some of the problems.

The first question that comes to mind is "Why should I, the air safety specialist, consider the money factor when my job is investigation?" The answer is simple. You may be called upon to use your expertise by the owner, or his representative, usually an insurance carrier, to determine facts which will either require him to be legally liable for a great amount of money, or will determine that his client is not at fault. The amount of money he will spend in carrying out the investigation will be based on the expert's findings. A by-product of these findings is knowledge that will enable the carrier to foresee future problems and to take the necessary steps to see that his client corrects such problems as a condition of his assuming the risk. The investigator's efforts are a source of information that is of extreme value to the industry.

One important facet of legal liability which the investigator should understand is that the amount of money spent on investigation is usually, but not always, determined by the legal obligation to pay any liability claims that may arise as a result of the accident. This fact would indicate that a knowledge of the liability function as it applies to civil aviation should be a part of every investigator's kit of tools.

In considering the liability question we have had the opportunity to work with a number of expert investigators of civil accidents. We find that they are often frustrated by the seeming unwillingness of an insurance carrier to pursue a particular phase of an investigation. They assume that such carriers may be derelict in their failure to determine the exact cause of an accident. Often this is not necessary, particularly under the doctrine of Common Law known as Res Ipso Loquitor (The thing speaks for itself), or Recission. These actions merely limit money costs. To say the insurance carriers are derelict is not true. They are most anxious to reduce accident rates. The safer the risk, the less likely they will be faced with a catastrophic loss. If, under the above doctrines they can settle for a specific amount they will do so without further ado and pursue the investigation only if some precedent setting event (in a legal sense) has occurred which may upset their settlement at a later date. What they would prefer to do is nip the loss in the bud by requiring safe practices as a requisite to coverage. The expertise of the Air Safety Investigator can go a long way in assisting them in their search. An understanding of this can bring the investigator additional business as consultants, and, if called upon to investigate a civil accident, enable the investigator to evaluate the liability potential. Such action on his part would be appreciated and would, in the writer's opinion, enhance his reputation far more than a listing of credentials in trade papers. It is apparent that the providing of security for ourselves and our families is a paramount consideration for all of us involved in aircraft investigation, or in any other pursuit for that matter. We may be the best metallurgists, helicopter men, design specialists, chemists, or absolute diviners of government rules and regulations, but money is the one single denominator which will often guide the extent of an investigation. If we understand this we can name our own price and provide significant information that may prevent future accidents.

In discussing civil accidents, particularly those in the United States with which the writer is most familiar, it is imperative to understand the relationship of the several government agencies charged by law to investigate civil aircraft accidents, and those who represent the owners and their representatives. In the United States the National Transportation Safety Board has such responsibility. In a number of instances there have been problems. There are a number of differences in the approach the NTSB has in performing investigations and those which the owner, or his representative would require. The NTSB is charged to find "probable" cause of an accident. The owner (usually his insurance carrier) needs to determine "specific" cause. There are reams of computer statistics in Washington listing probable causes with few investigations (unless they are large and warrant public scrutiny) that ever reach the state where a specific cause is found. The probable cause of "pilot error" found in the death of a farmer piloting a Bonanza does not warrant the time and energy to seek for a rusted control cable when the facts are obvious that the man flew into an area of bad weather. We are the ones who will ultimately determine whether or not the control cable parted and place the responsibility where it truly lies.

Unfortunately, in the United States, the NTSB has taken the position, as a matter of policy, that its responsibility to investigate is total. It will sometimes permit the owner, or his representative, to be present on suffrance as an observer although they have a vested interest in the outcome of any investigation and a legal right to the property. It is not the purpose of this treatise to question the right of governmental authorities to assume responsibility for such investigations. Indeed, a non-partisan, objective evaluation of cause is to be welcomed. However, it is rare that all parties become involved in such investigations due to any number of factors, some political, others personal.

As an example let us consider the case of an engine failure. The NTSB will invariably call in the manufacturer's representative to assist in the evaluation of cause. In many instances we could hardly call this individual an unbiased investigator since finding his company at fault for a defective engine could hardly enhance his future job prospects.

A further problem is found when the NTSB representative orders destructive tests which can destroy evidence vital in determining cause. Seeking an injunction in the courts is a method that has been used in order to prevent he NTSB or the manufacturer from conducting such tests, or for refusing to permit the legal owner the rights to his property.

In a number of instances known to the writer the findings in a particular accident by the NTSB were entirely at odds with what was later developed by independent investigation. For example, in a case in which the writer was involved several years ago, the NTSB insisted upon shipping the engine of an aircraft to the manufacturer after the aircraft had crashed and burned on takeoff immediately after undergoing an annual inspection. The final determination was pilot error. However, we were able to retrieve the fuel injection system (spider) and with the help of a design engineer determine that the crash was caused by the introduction of a piece of foreign matter in the system which blocked fuel flow. Had we not been able to retrieve this particular unit, the accident would have gone down as pilot error and the person responsible would have gone scot free. The probable cause as determined by the NTSB and the specific cause as determined by an expert investigator on behalf of the owner emphasize the need for cooperation since "probable" cause, in this instance, would mean the loss of a considerable amount of money, not to mention the derogation of an innocent pilot. In most cases we find that we can develop an uneasy truce with government investigators. Sometimes this is based upon the fact that we have the money and resources to conduct technical investigations and to hire the necessary experts. Other times, such relationships are based upon friendship which permits a working relatinship. General policy of the NTSB, however, can exclude us entirely if the investigator on the scene believes it necessary or in what he considers it to be the government's best interest.

Our particular organization has been called upon to investigate accidents in Central and South America as well as the United States and Canada. In Central and South America few, if any, problems are involved in accident investigation. Physical retrieval to the United States is sometimes a problem but not in the field of investigation. In Canada we found the civil and military authorities to be most cooperative, recognizing the owner's right to be present and assisting in retrieval and preservation of evidence.

It is important that the investigator do everything possible to insure that evidence is not destroyed. Fortunately, for those of us who act as direct consultants for insurance carriers, we are often able to arrive upon the scene as quickly as the NTSB, to photograph the scene before it is disturbed, and to establish a rapport with those involved in the investigation. For those of you who are called in at a later date it would be well to understand the obstacles which may deter presenting you with sufficient information which your expertise can evaluate and upon which you can render a considered judgment of cause.

A knowledge of the limitations placed upon the investigation of civil accidents can do much to enhance the status of the expert investigator. It is one thing to be an expert in Air Traffic Control (as the writer is), or in any other field, if you merely sit back and wait to be called, say, as an expert witness. In many cases an organization such as the one the writer is associated with has already determined the cause and been paid handsomely for their work. In such a case we would call upon the so-called independent expert who reads our file, confirms our findings, and is paid a pittance. We do not suggest that people give up their independent status as investigators and lose their objectivity. What we do suggest is that in the investigation of civil accidents they learn the limits of liability and the legal problems that surround an accident that may detract from or enhance that investigation to their own benefit.

Each year Southern Methodist University, Dallas, Texas, conducts a seminar on Aviation Law. Experts from all over the world attend. It is well worth considering attendance at such a seminar. Of particular interest are the aspects which deal with the legal and insurance professions' roles in accident prevention. Further, the seminar will give an insight into the sources of money that are used in hiring we, so-called, experts and the limitations of such funds.

The theme this year is "The Investigator's Role in Accident Prevention". A knowledge of all facets of the investigative game, particularly the money end, can go a long way in determining ways to prevent future accidents. Let us share our findings with those who handle the risks and allow them to spend money before the fact in requiring certain standards before assuming the risk.

Helicopter Wreckage Analysis

Jerry T. Dennis M00608
Air Safety Investigator
National Transportation Safety Board
Anchorage Field Office
SRA Box 1452A
Anchorage, AK 99502

The views expressed by the author do not necessarily reflect positions taken by the National Transportation Safety Board

In any course on accident investigation we cover subjects such as aerodynamics, stability and control, fatigue, materials, structures, powerplants, maintenance, operations, human factors...the list seems endless and is very discouraging because it is impossible to know everything about all things. But this is our chosen profession and hopefully we at least will know where to look for the answer. Aircraft accident investigation is one of the few skills that is acquired by doing; by trial and error. The above mentioned courses help, but they are not the answer. Little things, like knowing how to determine the direction of rotation of a spin from the aircraft damage pattern, or just recognizing the difference between a spin and a spiral; recognition of impact versus pre-existing failures and resolving impact vectors to name a few. This is where the learned "art" comes to the fore and the skill of the individual is recognized.

The purpose of this document is to provide the experienced Accident Investigator (fixed wing) with information of those items and procedures peculiar to the helicopter. Common knowledge subjects such as powerplant investigation, structures, materials, etc., will not be addressed. The assumption is that the individual reading this paper is an investigator or in training to become an investigator. Therefore, basic subjects will not be covered except where necessary.

HELICOPTER CHARACTERISTICS

Autorotation

Let us first discuss what most people associate with the typical helicopter accident, the autorotation. Normally autorotations are associated with powerplant failures. While it is the emergency procedure for that problem, other malfunctions may call for an autorotation as the lifesaving maneuver; i.e., powershaft failure or some types of tailrotor failures. Other emergency procedures may call for the pilot to enter autorotation while completing other emergency responses — a good example of this is a governor failure (low or high side) on the Bell 205 series helicopter.

An unsuccessful autorotative landing normally results in a high vertical component, and may or may not have a horizontal component. The landing gear will be distorted and probably failed depending on impact velocity and surface composition. Current skid type landing gear is load limited and designed to deform at a set rate. However, on sod or wet ground the gear is not allowed to deform; the energy is transmitted to the airframe with little attenuation. Thus you might have a brittle fracture of rather ductile material. Passengers and crewmembers will probably have back injuries, normally the lower lumbar vertebrae due to dynamic overshoot and/or failure of the seat structure. The tailboom will have been severed by the main rotor blade as it flexes down or as the machine rocks forward. If a considerable amount of the tailboom is severed this may be indicative of one of two things; a high horizontal component with subsequent forward rocking, or an extremely high vertical impact with blade flexing. The combination of low rotor RPM and impact loading is another possibility. Extreme impact velocities may result in the failure of the tailboom through bending due to the long moment associated with the tailrotor assembly. The structural failure normally occurs near the tailboom attachment fittings.

During an autorotation the helicopter may achieve vertical velocities in excess of 3000 FPM. Rotor RPM and associated rates of descent are very much dependent upon many factors. First, if the blades have high inertia, they will lose RPM slowly with increased angles of attack, but they will gain it just as slowly after a reduction. Conversely, low inertia systems lose RPM rapidly but gain it back just as easily. Second, the higher the gross weight and/or density altitude the more the rotor wants to overspeed. Essentially this is due to a change in the size of the autorotative and propeller regions of the disc. Third, maneuvering tends to increase RPM due to increased rates of descent and resultant energy enhancement of the system. Autorotative descent capabilities are essentially a function of airspeed and rotor RPM. No matter what the conditions, a given indicated airspeed with a given rotor RPM will yield the same results; the lift-to-drag ratio does not change. To compensate for high gross weight and/or density altitude conditions, the pilot must increase collective pitch and thus the angle of attack to maintain operational RPM at a given airspeed. The difference is felt at the deceleration and touchdown. Here we have the classic tradeoff between potential and kinetic energy. With the higher gross weight and/or density altitude operations, almost all of the stored energy in the rotor system must be used to arrest the rate of descent. Under these conditions, there is a greater tendency to "fall through", which may result in a hard landing or a rollover. Technically the same procedures are used for a light machine and a heavy machine; however, they do not react in the same manner. This definitely has contributed to many accidents when taking the human element and habit patterns into consideration; i.e., practicing autorotations in light aircraft; mishap in heavy aircraft.

Perhaps this is the time to discuss the aerodynamic phenomenon known as "autorotation". In his book, *Dynamics of Helicopter Flight,* George Saunders discusses the autorotation in three phases; entry, steady state descent, flare and touchdown. The FAA Advisory Circular 61-13B, *Basic Helicopter Handbook,* lists two types of autorotations; the flare and "no-flare". The flare autorotation is when little or no ground run is desired. The "no-flare" autorotation requires a long hard smooth surface due to the resultant ground run. While this last technique is discussed in the FAA *Basic Helicopter Handbook,* it is seldom used. One can understand why by considering the terrain and normal helicopter operations. Given this we will just consider the flare autorotation.

First, with the loss of the driving force the machine will feel the effects of transmission friction and will yaw with the rotation of the rotor blades and the aircraft will roll as a result of the yaw and pitch down slightly. The pilot must counter this with anti-torque input while simultaneously lowering the collective to maintain a given RPM and controlling the attitude of the helicopter with cyclic input. It must be emphasized that these steps be almost automatic, especially at low altitudes. The reaction sequence becomes important when examining the engine failure at high speed. The collective must be lowered before there is cyclic input or the resultant flapping may cause mast bumping or contact with the tailboom. Again, it must be emphasized that a low inertia system will lose RPM very rapidly. A test conducted for me some years ago at the ASTA Facility at Edwards AFB yielded a decay rate of 40 RPM per second on an observation helicopter.

According to Saunders, after 5-8 seconds, the machine is in a steady state autorotation, which is "when there is zero torque maintained on the rotor, resulting in constant RPM, despite zero power being delivered from the engine." The Army's Field Manual 1-51 interprets this as being when the autorotative region's force (thrust) equals the anti-rotative force (drag). For our purposes it suffices to state that if the rotor slows, the autorotative region expands and tends to restore the equilibrium. If it overspeeds, the propeller region expands and thus tends to restore the RPM to its stable level. Autorotation equilibrium is stable only within a certain rotor RPM. If there is too much of a decrease in RPM then the rotor will become unstable which can result in a further decay in RPM.

Like the fixed wing, the helicopter in autorotation is dependent on the lift-to-drag ratio in achieving either the minimum rate of descent (max L/D) or maximum glide distance (tangent to L/D curve). However, extreme low and also high indicated airspeeds produce the same effect—high rates of descent, the worst case being the low airspeed condition with rates of descent exceeding 4500 FPM. Rotor RPM is a variable the fixed wing does not have; a reduction in the RPM (within limits) can increase the glide distance or the minimum rate of descent. As a result, there are many autorotation mishaps where there is the classic evidence of high vertical impact with a horizontal component and evidence of low RPM. Usually it is only a short distance to a safe landing area. One might equate this attempt at stretching the glide, and its results to a fixed wing attempting the same maneuver with the resultant stall.

At the termination of an autorotation, cushioning collective is applied in order to touchdown at a reasonable rate. In doing this, energy is used and the blades slow. This results in increased flexibility as the centrifugal force decreases, and a downward bending of the blade. During an impact sequence a permanent set may occur near the blade root on semi-rigid and rigid systems. On fully articulated systems the blades normally are easily deflected as they slow, which may result in one or more blades failing the flapping stops and folding over the rotorhead. Blades on articulated systems sustain more damage due to lighter construction. However, any rotor blade at operating RPM has considerable inertia and is very destructive, especially rigid and semi-rigid systems. This is understandable when you consider the fact that the tip speed of some rotor systems approaches the speed of sound.

A general observation in relation to rotor blades, both main and tail, is that if the blade is generally intact and only bent, the damage resulted from low RPM. If the spar of the blade is broken and the damage is in plane and aft, then the damage is as a result of high speed impact. Normally when power is present at the time of impact, on semi-rigid and rigid systems, the torque is resolved by an attempt to twist off the mast at the head. However, since the mast is usually extremely strong steel, the force is transmitted to the transmission and transmission mounts. The torque and inertia of the rotor system can literally pull the transmission out of the helicopter. Severe mast bumping is also usually evident in this type of impact. With articulated systems, after the blades flap up and fail the dynamic stops, the blades become meshed and assume the look of metallic spaghetti. While the tail rotor will exhibit evidence that is similar to the main rotor, it does rotate up to six times faster than the main rotor and is considerably more fragile. The tail rotor blades also have tip weights that come out very easily if the blade contacts anything of substance while at operational RPM. It follows then that the tail rotor blade is very susceptible to F.O.D. If one blade departs the machine at operational RPM, then the odds are quite high the other will depart along with the gearbox.

As the helicopter pilot applies collective to cushion the aircraft in an autorotation, the aircraft will turn the same direction as the rotor blades due to the increased friction in the transmission. At a 10,000 foot density altitude there is a 26% loss of thrust, thus there may not be sufficient tail rotor authority to control the machine, especially as the RPM decreases.

Height-Velocity Diagram

The Height-Velocity Diagram or, as it is more appropriately captioned, The Dead Man's Zone, is a combination of altitudes and airspeeds at which a successful autorotation is doubtful. The H-V Diagram on many machines is obtained by testing using manufacturers' test pilots that "simulate" the average pilot. While that is bad enough due to the limitations imposed, it is not as bad as the extrapolated H-V Diagram using data from a similar machine. While the H-V Diagram gives a pilot warning, it may not be adequate, and does give the pilot a false sense of security. With an autorotation from a substantial height at a minimum airspeed, I would expect to see tremendous vertical impact forces. If the autorotation is initiated at a low altitude and high speed, the aircraft would impact before the pilot could react.

Vortex Ring State

Settling with power can best be described as settling in your own downwash. Technically it is called the "Vortex Ring State", where the high rate of descent exceeds the normal downwash velocity on the inner blade sections and they stall. This then causes a secondary vortex which results in turbulent flow over much of the rotor disc. It has been demonstrated that the stall starts at the hub and migrates outward toward the tip as the rate of descent increases. Increased angles of attack (collective application) only increases the stalled area and resultant rate of descent. Descent rates exceeding 3500 FPM have been recorded. According to FAA Advisory Circular 61-13B, the pilot may get into this condition by "(l) Attempting an Out of Ground Effect (OGE) hover above the hovering ceiling of the helicopter; (2) Attempting to hover out of ground effect without maintaining precise altitude control; or (3) A steep power approach in which the airspeed is permitted to drop nearly to zero." Advisory Circular 61-13B further indicates that the following combination of conditions are likely to cause settling with power: (l) A vertical or near vertical descent of at least 300 feet per minute. Actual critical rate depends on the gross weight, RPM, density altitude, and other pertinent factors; (2) The rotor system must be using some of the available engine power (20%-100%); (3) The horizontal velocity must be no greater than approximately 10 MPH. That velocity is not necessarily the velocity across the ground, but the transverse flow through the rotor disc. As a result, a deceleration or approach can meet all the requirements, especially if downwind.

Recovery can be accomplished by increasing the forward speed and flying out or lowering the collective to reduce the stalled area. Entering a vertical autorotation and flying out is another possibility along with reducing the load. Since there is usually limited time, this last technique is primarily limited to external load operations; that is, unless you have a silver tongue and can convince the co-pilot and/or passengers to jump.

Rotor Head Controls

Inputs to the cyclic and collective pitch controls, either pilot or autopilot induced, are transmitted to the rotor system through a very complex system of levers, mixing units, input servos, stationary and rotating swashplates and pitch change arms. A cyclic input will result in the tilting of the stationary swashplate (star); this is in turn reflected to the blades by virtue of the fact that the rotating swashplate follows the stationary swashplate and the pitch change arms are attached in some form to the rotating swashplate. Due to gyroscopic precession, the application felt at the blades is 90° ahead of the desired response; however, the type of control system will determine where the swashplate is tilted. As an example, if the pitch change horn is 45° ahead of the blade, then the swashplate movement need be only 45° ahead of the blade. The swashplate is tilted by three servos or torque tubes; one each for left and right lateral input and one for the fore-and-aft input. Movement of the collective causes both the stationary and rotating swashplates and thus the blades to move simultaneously and equally. That then is the control system at the rotor head in its simplest form. I wish the systems themselve were that simple.

Rotor Blades

The main rotor blades of modern helicopters are extremely tough, durable engineering marvels. They have evolved from the wooden symmetrical airfoils of the past to composite asymmetrical blades designed for optimum performance in one area. Unfortunately, main rotor blades have been coming off helicopters since they have been flying. If there is an inflight failure of a blade, the helicopter will be destroyed with a high probability that all on board will receive fatal injuries. The remaining blade or blades will fail the mounting system and will sever the tailboom or come through the cockpit or both. The aircraft will literally disintegrate. There is a high probability that the same will occur if a section of the blade is lost, but this depends on the helicopter and the type rotor system. Semi-rigid systems cannot afford the loss of any, since rigid and semi-rigid systems flap through the bending of the blade and the action of the opposing blade; a mass imbalance is nearly always destructive. The articulated systems can sustain some loss and still fly, but I'm not going to speculate on how much or how long. If you have wreckage where there was an inflight impact with the tailboom or cockpit, the blade or blade retention system is suspect and all components must be located. However, every inflight failure that I have investigated has been over a forest or swamp and all components were not located in every instance. What can cause the loss of all or part of the main rotor blade? A failure in the blade retention system; fatigue fracture of the blade spar; impact with another object. While these are probably the most common, I'm sure that there are more. As a precaution some manufacturers have installed blade indicators on some helicopters to show blade integrity during pre-flight.

Next, let us discuss the wild blade. This results from the failure of a control component above the swashplate to the head. This allows a blade to be free about the feathering axis. On rigid and semi-rigid systems the blade will go one way or the other and the result will be inflight blade strike. If the failure is in the pitch change mechanism for a single blade on an articulated system, the blade may track within reason as long as no drastic control movements are introduced. As a point of interest, I know of no inflight blade strike where the aircraft was operating at normal RPM and there was no malfunction including pilot-induced oscillation. As long as the helicopter can swing freely in a pendular fashion, it will not become involved; again all things operating normally. However, all bets are off for inverted maneuvers. In the last paragraph, I mentioned an inflight blade strike at normal RPM. At reduced RPM the blade rigidity is reduced considerably in view of the fact that centrifugal force is directly proportional to RPM-squared. At low RPM, it is possible to have an inflight tailboom strike, especially when considering the blow-back effect that occurs at forward velocities.

Drive Train

The transmission of power in a helicopter is somewhat more complex than in a fixed wing. First, you have a driveshaft from the engine to the transmission, if the transmission is not attached to the nose case of the engine. In helicopters with reciprocating engines, the engine is normally mounted vertically in the airframe with the transmission immediately above. The turbine engine is normally mounted level and a power shaft runs from the nose case to the transmission. This powershaft is designed for flexibility since the transmission normally has more movement than the engine which is mounted rigidly to the airframe. This driveshaft requires lubrication and attention. It if fails the results are the same as an engine failure. Don't be misled at the scene; on some aircraft the driveshaft will pop out during the accident sequence, especially if the main rotor blade has contacted the ground. There will be evidence of the gears departing the splines with some force, rather than the overtemp and breaking that was probably a pre-impact malfunction.

The transmission, simply stated, transmits engine power to the main rotor, tail rotor and other accessories as desired, such as a generator, hydraulic pump, oil pump, etc. The transmission reduces the engine speed to an acceptable level to drive the various systems through reduction gears. A twenty-to-one (20-1) reduction ratio is not uncommon. In the transmission we also have the free-wheeling unit which gives the rotor system the ability to automatically disconnect from the engine and allow an autorotation. Without this the rotor RPM would decay as a result of engine drag. Some helicopters also have a clutch in or adjacent to the transmission to allow the engine to gradually overcome the starting inertia of the rather heavy rotor system. In the same gear train may be mounted a rotor-brake. It works in an opposite manner to the clutch and stops the rotor in a hurry.

The transmission might be called the heart of the helicopter. If it fails the results are disastrous. Fortunately, they have proved to be very reliable. Transmission monitoring systems and warning devices are an integral part of the construction, and impending failures are caught prior to failure. However, I have observed the failure of clutches, the discoloration of the case and gears due to fluid loss, and one failure of the over-riding clutch (free wheeling unit). Recently there have been some difficulties with rotor brakes which are hydraulically activated, with the pressure controlled by the pilot through a lever. I have observed helicopters rotate about the vertical axis and almost turn over due to a rapid application of the rotor brake. This normally will fail the shear pins.

The tail rotor driveshaft is also taken off the transmission because we want the tail rotor to keep turning if the engine fails. Normally the tail rotor driveshaft is a thin-walled tube supported by hanger bearings that do more than just support the driveshaft. Their placement along the driveshaft controls its shape. As the RPM increases the driveshaft progresses through a number of harmonic waves until the operating RPM is achieved. The amplitude and frequency are determined by a number of factors, but principally by the rigidity of the driveshaft, bearing placement and RPM. Some helicopters have critical RPM ranges where harmonic spikes can be manifested down the driveshaft. All become critical with overspeeds as the amplitude tends to increase, placing pressure on the bearing or touching the driveshaft housing. The driveshafting is so critical that shafts are individually balanced to achieve the minimum harmonic amplitude and avoid abnormal vibrations. If the driveshaft contacts any metal objects at operational RPM, it will soon fail. Unfortunately, the driveshaft tunnel has been the location of many lost tools; in fact, I found a rag in one. The failure of a hanger bearing also can create havoc, and will soon fail the driveshaft. Since the shafting is constructed as it is, it tends to leave evidence of torsional loading. By examining the failure you can determine if the tail rotor was being driven (tail rotor strike) or driving (main rotor strike).

The drivetrain in a helicopter has always been a critical item. As a result, all gearboxes on modern machines are monitored with magnetic chip detectors.

Flapping

Now let us examine a few of the rotor systems and their flapping modes. The semi-rigid uses a hinge that approximates the effect of a child's teeter-totter; as one blade goes up, the other comes down. The hinge at the mast is called, appropriately, a teetering hinge. As the blade flaps up, the angle of attack is decreased in direct relation to the induced velocity (vertical) of the blade. The maximum induced upward velocity occurs on the advancing blade at a point that is approximately perpendicular to the longitudinal axis of the aircraft. As the induced angle of attack is reduced, so is the resultant lift. The opposite occurs on the retreating blade where the resultant lift is increased due to the downward movement and resultant increase in the induced angle of attack. Obviously, this is a simplified explanation; the flapping action of a blade through a complete cycle is very complex. Another point; while the maximum downward placement of a blade is over the tailboom, it is not due completely to gyroscopic precession or flapping. It is due to both of these and a third effect called "blowback". You might say that blowback is the self-correcting tendency of a rotor; as a gust strikes the rotor disc, the flapping tendency is greater which increases the amplitude of the blade excursions both fore and aft. The thrust vector acts perpendicular to the disc so the lift vector is tilted aft, the nose pitches up and the machine slows.

On articulated systems, flapping is accomplished through a hinge that allows each blade to move independently. The flapping is controlled by centrifugal forces at operating RPM with static and dynamic stops to control the limits at reduced velocities or high amplitudes respectively. On the rigid rotor flapping occurs in the blade itself. While the blade may be rigidly attached to the mast, it is very flexible. Saunders has indicated that "90% of a typical rigid rotors' 'stiffness' comes from centrifugal forces." This being the case, low RPM conditions may be even more critical.

How does flapping come into play in an investigation? As RPM and blade rigidity decrease, or extremely high aerodynamic forces are encountered, the blade may contact the tailboom or result in mast bumping or contacting the dynamic stops. Damage in these areas can give clues to the forces involved. Flapping is associated with dissymmetry of lift and it does compensate for some of the unequal lift distribution that results from inflight dynamics. However, the principal compensating mechanism is cyclic feathering, which is the rotation of the blade about the blade longitudinal axis, the mechanism through which we change the angle of attack of the blade.

Dissymmetry of Lift

What causes dissymmetry of lift? With the helicopter in horizontal motion, the advancing blade is going faster than the retreating blade, the velocity difference being twice the velocity of the aircraft. Since the lift equation is based on V^2, there is a considerable difference in lift since all other factors are equal. As I indicated earlier, flapping does compensate for some of the dissymmetry of lift and through the blowback effect is a stability mechanism; it reacts to the change. However, the pilot can induce a change in the system through the feathering axis. This overcomes the lift changes due to velocity by decreasing the angle of attack on the advancing blade and increasing it on the retreating blade. Blade angle of attack can be changed by the controls, principally the cyclic control (stick). However, the application of the collective pitch results in a uniform change in the angle of attack over the entire rotor disc. Obviously the control system on a helicopter is complicated, which is the point I am attempting to make. If there is a failure within the system, it is difficult to determine what will occur due to the aerodynamic phenomena I have described and another factor that I have not; gyroscopic precession.

Gyroscopic Precession

Gyroscopic precession essentially means that the applied moment is felt 90° later in the plane of rotation. This can be observed in the forward tilt of the rotor disc as a result of the maximum or minimum blade angle of attack. As a result of this, the control input is 90° ahead in the plane of rotation so as to coincide with the cyclic movement. With this in mind, there is a reaction to pitch and roll inputs since the rotor disc does not operate in one plane. The forces applied to a spinning rotor disc by control input or by wind gusts will react in the following manner:

Force Causing Aircraft Movement	Aircraft Reaction
Noseup	Roll right
Nose down	Roll left
Roll right	Nose up
Roll left	Nose down

Loss of control continuity can and does create havoc when the aerodynamic and gyroscopic effects are compounded.

Coning and Coriolis Effect

Coning is the upward bending or movement of the blades are a result of the amount of lift generated. Obviously, the higher coning angles are a result of greater lift required due to a heavy load. Witnesses can sometimes give an idea of the coning angle and the investigator an impression of the load. Coriolis Effect is the tendency of a rotor blade to increase or decrease its velocity due to the movement of the blade C.G. When flapping takes place, the center of mass of the blade moves closer to the axis of rotation and the blade accelerates. When the blade goes back down the mass goes further away and the blade decelerates. The analogy is like a skater extending her arms to slow the rate of rotation in a spin while increasing the rate of rotation as the arms are brought into the body.

Blade Lead and Lag

The last axis about which a blade operates is the vertical, commonly called the drag axis, or lead and lag. In the articulated system there is a drag hinge that provides freedom for the blade in the plane of rotation. This relieves the bending movements induced by the flapping hinge as a result of the Coriolis Effect by allowing the blades to hunt or seek their own position in the rotor disc. However, if they were not restrained the blades could get out of phase. This results in a geometric unbalance vibration and, if severe enough, an inflight failure. It also can be the catalyst for ground resonance. Therefore, a damper of some type is used.

A semi-rigid system must be underslung with respect to the rotor hub to avoid having the same adverse results from the Coriolis Effect. Underslinging results in the rotor C.G. closely coinciding with the flapping axis of the rotor system; therefore, the change in distance from center of mass to axis rotation is small.

Horizontal Stabilizer

One additional area that deserves a comment is the horizontal stabilizer, or sync elevator. As the helicopter moves forward the flat plate drag of the fuselage tends to pitch the nose down. This is easy to see when you remember that the helicopter is suspended in pendulum fashion from the rotor head. The addition of a stabilizer or controllable elevator provides for a more level attitude at a cruise and extends the C.G. range of the aircraft. Normally, articulated systems use a fixed stabilizer, especially on smaller aircraft, and aircraft with semi-rigid systems have controllable devices necessary to overcome fuselage inertia and provide greater controllability. The loss of such a device at cruise, or its moving to an adverse angle of attack, can result in an inflight breakup.

Mast Bumping

A common phenomenon of semi-rigid systems is "mast bumping", which is the violent contact of the blade stops with the mast as a result of exceeding the tilt limits of the rotor hub in relation to the mast. Recall that the helicopter is suspended from the rotor hub, so a severe unusual attitude can result in mast bumping. Pilot induced low-G maneuvers can produce severe flapping while the helicopter is free of the pendular action whereby the helicopter will not follow the rotor disc, and mast bumping occurs. Engine failures, tail rotor failures or malfunctions, sync elevator disconnects or failures of the tailboom also result in mast bumping. Any maneuver or condition that results in excessive flapping can cause mast bumping.

Mast bumping and failure of the mast is a normal sequence of events in an inflight breakup. If the mast does not fail, the energy is directed to the transmission mounting and it may fail. On the articulated systems striking the dynamic stop is the equivalent of "mast bumping". While the results are not quite so catastrophic, the flapping taking place may result in an inflight contact with the tailboom. The consequences of that are obvious.

Ground Resonance

The next phenomenon we will discuss is "Ground Resonance". The effect is devastating with the aircraft literally disintegrating in a matter of seconds. Ground resonance is most common in three-bladed articulated systems having wheels and hydraulic shock absorbers. Basically, ground resonance is initiated when the landing gear transmits a shock or allows the fuselage to move in resonance with the rotor system. This dephases the rotor system and sets up an unbalanced condition, which amplifies very rapidly until the aircraft is destroyed. Low oleo struts and blade damper malfunctions contribute to this type of mishap.

THE ENVIRONMENT OF THE HELICOPTER

The psychological environment that affects the pilot is the subject of a presentation I made on the "Human Factor Aspects of Helicopter Accidents", at the 9th Annual ISASI Seminar in Seattle. For an insight into the total environment of the pilot, I suggest you read that paper. The environment I am addressing in this paper is the operating environment of the machine, normal pilot actions and situations that the pilot might be expected to evaluate.

Mountain Flying

Many papers and discussions have resulted from differences in opinion on mountain flying techniques, specifically pinnacle and ridgeline approaches. The U.S. Army at one time taught an approach into the wind that required the individual to "fly down the wire". The approach required a steeper than normal approach angle with a constant deceleration and collective application in order to arrive at the pinnacle with no forward velocity or vertical rate of descent. In theory, and for a proficient aviator, it is demanding but not too difficult. It does require a considerable amount of coordination and judgment on the part of the crew. If the pilot has not practiced these approaches recently, or practiced them with light loads he might have difficulty arresting the descent rate of a heavily loaded aircraft. Many times the pilot loses control at the termination and must make a go-around, or falls through and lands short of the objective. Unfortunately, this usually means that the aircraft rolls down the hill. While this technique is no longer taught, old habits are hard to break.

Current doctrine is to make a conventional approach until the aircraft is approximately 50 feet above the point of touchdown. Army training Circular No. 1-10 states: "At this point, the aircraft should begin losing translational lift. The aircraft should not be decelerated to the point of hovering out-of-ground-effect; however, prior to reaching the near edge of the landing area, the descent should be stopped and forward airspeed reduced to a brisk walk."

Another method is to make a rather flat approach so the rotor system is "loaded" well in advance of the touchdown point. The flight path is planned so as to approach the objective along the ridgeline, into or with a slight crosswind component. Direct approaches into the lee side of the ridge or mountain are to be avoided. However, if this cannot be avoided, a steeper descent angle should be used and the objective approached from an angle. This allows an emergency escape route in case of difficulty and may afford an advantageous wind component on the tail. This type of approach is by nature somewhat slower than the other and allows more time for decisions. It will also give a good indication of the aircraft controllability as the helicopter slows to an airspeed just above translational. High DA or gusty wind (especially downdrafts) make any ridgeline or pinnacle operation hazardous.

Departures from pinnacles are not difficult when the helicopter is light, but can be frightening with a heavy machine. Most pilots insure a proper margin by insuring that they have power at least to hover in ground effect prior to attempting a takeoff. However, I have observed and in one case (you don't do it twice) accomplished a departure by running the aircraft off a cliff and diving for airspeed — a very exhilarating experience. With pinnacle departures you are looking for airspeed; you already have the altitude, so one is traded for the other. In fact, it is commonly called an "airspeed over altitude" takeoff.

At high DA's there is a considerable loss of tail rotor authority. This can result in "unexplained" loss of control. Performance charts are available for helicopters, especially the newer ones, and torquemeters or manifold pressure gauges indicate power remaining. Use of the charts and the power measurement instrumentation should give the pilot and the investigator some knowledge of the power required and available. Unfortunately sometimes the latter is less than the former.

Visibility

Operations in mountains bring up another environmental condition; visibility. Operating in blowing snow or dust is very dangerous. The recirculation effect of the rotor system creates a localized "whiteout" or "brownout". In either case, visibility is reduced to a minimum and the pilot must take his visual cues from objects very close to the machine. This is an abnormal reference for helicopter pilots which may lead to spatial disorientation. With the movement of snow across a snow or ice field the pilot may have the sensation of moving when he is not. Where it is known blowing snow will be a factor, pilots plan the approach to the ground. Hopefully, the ground is even and capable of supporting the aircraft. The other alternative is an approach to an out-of-ground effect hover.

Associated with snow is cold. Operations in a cold weather environment require some precautions and common sense. The rapid application of the throttle while on ice results in a spinning helicopter. However, one point of interest is the fact that such low DA's may be created that some turbine helicopters may be temperature limited rather than torque limited. This, by the way, can be the result of a sick engine, and can occur in other than a cold environment.

Night Operations

The lack of depth perception cues at night is obvious, but you must remember that the helicopter pilot may be landing to an unimproved area, to unknown minimum lighting, or to an area illuminated only by his landing/searchlight. Normal depth perception cues used; Apparent Foreshortening, Linear Perspective, Vertical Positioning, Relative Motion, and Known Size of Objects are comprimised at night, especially if the pilot has not previously flown into the site. Fortunately, he does have the ability to make a slow approach and evaluate the situation. Most pilots find that it is difficult to judge rate of closure and height above terrain, which may result in a fast approach at a low altitude. When you couple night operations with rain, snow or dust in unimproved areas, there can be problems. However it is done routinely so don't be surprised if all of these elements are present in an accident; it is the normal environment for the helicopter pilot.

Instrument Flight

In the past few years, more and more helicopters have been certified for IFR operations. Initially the certification was on an operator basis with two pilots, based on experience. However, two pilot and, more recently, single pilot operations are becoming more common. In fact, some off-shore operations are nearly scheduled runs with helicopters capable of operating in *almost* all weather conditions. Due to the inherent instability of the helicopter, the FAA requires a stability augmentation system incorporated within the control system. For single pilot operation, a three-axis autopilot must also be incorporated. It is interesting that the stability requirement for helicopter IFR certification appears to be greater than that required for fixed wing aircraft. After the pioneering work done by off-shore operators, the FAA (with a push from HAA and NASA) is now investigating the unique capabilities offered by IFR helicopters.

I mentioned that the helicoper is not presently certified in all weather conditions. The greatest limiting factor is icing. Any modification of the airfoil compromises the autorotative characteristics of the aircraft and ice accumulation definitely modifies the airfoil. Some aircraft have a tendency to shed ice due to flexing, but accumulations usually remain on the inboard sections of the blade which are critical to autorotative capabilities.

Terrain

When I look at accident statistics, I get very upset because there is no terrain factor used in evaluating the mishap. A simple engine failure which would probably terminate in a successful autorotation had it occurred over the desert will probably result in a major accident with fatalities if it happened over mountainous, tree covered terrain. One might argue that the same is true for fixed wing aircraft, and I will agree. The important fact is that the helicopter operates over this adverse terrain routinely; it is the method of transportation in these areas. As a result, a high percentage of the time the helicopter is operating in a "high threat" environment where minor malfunctions can be catastrophic. I wonder how the accident rate would compare if this equating factor were computed.

External Load

External load capability is unique to helicopters except in Alaska, Canada and other "Bush" locations. (That last comment is as a result of seeing everything from building materials to boats strapped to the floats and skis of bush aircraft.) The dynamics of an external load are interesting and frightening considering that a load may have aerodynamic characteristics of its own and fly up into the helicopter. The high density load has the greatest stability; the light load is the least stable. The load introduces as many as six new degrees of freedom since it may act independently of the helicopter, yet it acts on the helicopter. This results in load oscillations, some great, some small, depending on the load, but more important depending on the technique of the pilot. Operations must be slow and deliberate. If the oscillation of the load becomes too great it must be released or it can result in the loss of the helicopter. The pilot, obviously, attempts to dampen these oscillations with cyclic input. However, if he catches the load in phase, resonance can occur which then amplifies the motion. A cable or choker that is too short may not allow the pilot sufficient time to dampen out the load.

A multiple point suspension system reduces some of the adverse effects of oscillation. It is presently incorporated on only one helicopter, the Sikorsky S-64; however, even on that machine the single point suspension is most commonly used. The long line is another world entirely. Essentially, the helicopter is operated out-of-ground-effect at all times with the pilot having to look vertically out the side of the machine. Pilots that fly sling loads consistently can become used to cable and load configurations that they have flown before. The difficulty comes (and accidents result) when something different is encountered. George Saunders in an article in *Rotor and Wing* magazine, noted the following changes that might be a factor in a mishap:

1. Flying with an "unusual" load (one of unfamiliar size or shape, or significantly different weight-to-size ratio);
2. Flying at airspeeds only slightly above what was previously thought to be safe (the onset of dynamic instability may occur over a relatively small airspeed band);
3. Flying with a different cable geometry (length or number of segments, number and location of attach points);
4. Flying in turbulence of greater severity or of different nature than usually experienced; and

5. Maneuvering more abruptly, or not flying in a coordinated and smooth manner.

Sling operations are probably one of the least tested areas as far as the aircraft performance and stability is concerned. It amounts to the pilot becoming a "test pilot" every time he picks up a load with unknown characteristics.

Center-of-Gravity

With external loads, there is a definite modification to the pendular action and (possibly) a constantly changing CG. In investigating the helicopter accident it must be remembered that there are three CG computations that can be critical to the operation of the aircraft. The standard fore-and-aft will be considered first. With the CG forward, the pilot may run out of aft cyclic in attempting to hover or takeoff and strike objects in the path of the machine, or tumble, or possibly both. An aft CG would have similar consequences, with the added disadvantage of not knowing just what you were going to hit. With the positioning of the cargo compartment forward of the mast in most current production models, the empty CG is very close to the aft CG limit. In fact, some manufacturers require a minimum weight in the front of the aircraft if the aircraft is very light. I know of one case where this aft CG condition was a salvation when the aircraft lost its tail rotor gearbox, the aircraft ptiched forward, but not over.

Lateral CG is critical when landing on a slope. If it is downslope and the pilot technique is a little off, the helicopter just might keep rolling. Since the helicopter is suspended in a pendular manner, there is a tendency for the CG to swing under the mast. As a result, the helicopter may fly with one side down. This not only results in adverse yaw and roll characteristics (fun in an autorotation) but over a long term can cause considerable damage to the bearings in the head of a semirigid system. The last computation that must be made is the vertical CG, which again is important in slope operations. The last two may contribute to a lateral rollover tendency known as Dynamic Rollover.

Dynamic Rollover

All helicopters have a critical rollover angle which is dependent on the type rotor system, gear width, height. If the critical rollover angle is exceeded, the helicopter will roll over, even uphill. Cyclic corrections will not be effective beyond his point. In fact, if the angular momentum is sufficient to carry the helicopter beyond the critical rollover angle, cyclic inputs made prior to teaching the critical rollover angle will not be effective. There is no thrust vector created by the rotor system that can stop the momentum of the machine, only gravity can do that and, as we know, gravity works about the CG. However, tail rotor thrust (translating tendency), crosswind conditions and even soil composition can contribute to the rollover tendencies of the helicopter.

For Dynamic Rollover to start, one ski or wheel must be on the ground. That then becomes the pivotal point of the rollover, usually because the pilot pins it there due to improper control coordination. It also may be trapped or snagged, but the rollover is still induced by the pilot through control input. Normally, upslope Dynamic Rollover occurs during departures from a slope, again, principally because of the requirement to hold the landing gear into the slope while coming level. Incorrect coordination, or rapid collective application will lead to grief. As a rule, downslope rollovers occur during landing. In this case the slope may be too steep for the operating parameters of that helicopter, or the rapid reduction of the collective may result in momentum being generated that will cause the helicopter to continue rolling. I have investigated an upslope dynamic rollover that occurred during a practice touchdown autorotation. In that mishap, the instructor knew that the touchdown was going to be on a slope and warned the student about it. However, on touchdown the student overcompensated and the helicopter rolled over in a fit of destruction.

The prevention: take it slowly on these maneuvers. Insure that the skids are free (they will freeze to the ground in the winter) and the slope is within the capabilities of the helicopter. Some have gotten away during a downslope rollover by pulling collective rapidly and becoming airborne. While this has worked for some, others have lost control *after* becoming airborne due to the tendency of the aircraft to swing back under the head.

Retreating Blade Stall

The feathering and flapping which, as previously mentioned, is an attempt to compensate for Dissymmetry of Lift, results in a constant change in the blade angle of attack as it moves around the disc. The retreating blade is at the greatest angle of attack because of the velocity difference created by the forward airspeed of the helicopter. At some point, dependent on airspeed, "G" loading, airfoil, rotor RPM, gross weight, density altitude, the retreating blade stalls. This results in severe vibration, a rolling tendency toward the stalled side and a pitchup of the nose. If the stall is extreme, the controllability and structural limits of the helicopter may be exceeded. Retreating blade stall usually does not usually result in a mishap; the gyrations usually result in slowing the machine and provide a very visible warning to the pilot.

IMPACT DYNAMICS

USAABAR Study

In 1971, USAABAR (Army Safety Agency) conducted a crashworthiness study of 71 utility helicopter accidents. The criteria for inclusion in the study were; (1) same helicopter model, (2) at least one survivor, and (3) at least one individual received a major injury either from fire or impact. The timeframe for the study was October 1968 through January 1970. As a result of the study criteria, the sample is confined principally to those accidents involving moderate to severe impact forces. While data gathered may not be representative of the typical mishap, it is representative of the type damage for severe mishaps:

1. Inverted impact — The helicopter made initial contact in an inverted attitude.
   Frequency of occurrence — 3

2. Severe longitudinal "soil plowing" — The tendency of the aircraft to scoop earth and push it ahead of the aircraft during the initial high vertical deceleration combined with a high forward velocity.
   Frequency of occurrence — 5
3. Helicopter rolled forward "end over" — The helicopter rotated at least 90 degrees about its pitch (y) axis during the crash sequence.
   Frequency of occurrence — 6
4. Cockpit penetration by main rotor — Intrusion of the rotor blade into the cockpit sufficiently to constitute a hazard to the crew.
   Frequency of occurrence — 9
5. Excessive vertical G — Vertical deceleration forces were exerted on at least one occupant in excess of human tolerance.
   Frequency of occurrence — 11
6. Transmission penetrated troop space — Displacement of the transmission or mast into the troop space sufficiently to constitute a hazard to occupants.
   Frequency of occurrence — 15
   Note: The helicopter involved in the study has a 8G tiedown strength; FAA requirements were only 4G. New designs such as the S-76 have a 20G capability.
7. Post crash fire occurred — Fire broke out upon impact.
   Frequency of occurrence — 18
   Note: Installation of crashworthy fuel systems has reduced the incidence of post crash fire considerably, and thermal fatalities virtually to zero. In the study, 41% of the fatalities were due to fire while 49% of the remaining fatalities were listed as impact fatalities in an aircraft that had post crash fire involvement.
8. Occupants thrown out at impact — At least one occupant was ejected from the helicopter during the crash sequence.
   Frequency of occurrence — 24
   Note: Of the 59 occupants ejected, 46 were not wearing a lap felt.
9. Personnel crushed or trapped — One or more occupants received injuries or were trapped by inward movement of the fuselage shell or the transmission.
   Frequency of occurrence — 28
10. Aircraft rolled on side or landed on side — Aircraft either landed directly on its side or rolled on its side at least once during the crash sequence.
    Frequency of occurrence — 43

Given the last parameter you might think that finding the helicopter on its side is a common occurrence. It is, and considering the narrow skid type gear on most helicopters and the high CG, I would expect this to be the norm.

Characteristics of Typical Mishaps

Let us go over a few of the more "common" mishaps with this thought in mind: the overall pattern of evidence is the goal of the investigator; wreckage analysis of individual components is only a part of the picture. The investigator must fit the damage pattern into the impact sequence of the mishap. In the following situations, I will attempt to show you the probable impact dynamics and, in some cases, the pilot actions that resulted in the helicopter impacting in that particular manner. What happened and, more important, why, are for you to determine.

Situation — For some reason, yet to be determined, the helicopter is in a power-off autorotation.

Characteristics

A. Hard landing
   1. Helicopter landing gear will exhibit evidence of overload failure either vertically or aft.
   2. Fuselage belly will exhibit evidence of ground impact.
   3. The tailboom and/or tailrotor driveshaft assembly will have been contacted by the main rotor blade. Pieces of the boom or the tailboom itself will be located adjacent to the aircraft. If the tailboom is a consideraable distance from the wreckage, it is good evidence that there was a substantial amount of energy involved.
   4. If the impact was extreme, the tailboom may fail through bending before the rotor blades have an opportunity to contact the tailboom. There will be good evidence of tailrotor driveshaft rotation in this type mishap.
   5. The helicopter will probably be on its side after rotating in the same direction of rotation as the blades. This is due to the transmission friction and the loss of tailrotor thrust with reduced RPM, or loss of the tailboom.
   6. In extreme conditions, the occupants will have back injuries similiar to those received in an ejection seat mishap. There will be evidence of dynamic overshoot in the seat pans and failures of seat support structure.

B. Overrotation at Touchdown (Flare)
   1. The aircraft will probably be on its side, having rotated in the direction of rotation of the blades.
   2. There will probably be a greater amount of impact damage to the lower nose section of the helicopter due to ground contact.
   3. Since the overrotation is probably an attempt to dissipate forward velocity, it follows that there could still be a considerable forward component at impact. This would result in tumbling or rolling over several times.
   4. Look for evidence of a ground strike with the tailrotor or the tailrotor guard. The tailrotor itself will exhibit definite evidence of a stroke: the guard will be bent up toward or into the tailrotor.
   5. Tailboom strike is quite common in this type mishap. However, there usually is more energy involved which scatters the parts considerably more.
   6. Look for evidence of compression buckling on *top* of the tailboom assembly and evidence of driveshaft rotation at that point.

The bending will normally take place forward of the point where the tailboom is struck by the rotor.

C. Forward Speed at Touchdown
   1. On a smooth dry surface, where most pilots practice autorotations, this is not a problem. On rough, uneven terrain it may result in the aircraft rocking and catching a skid. If it catches a skid, it probably will tumble or roll over. If the rocking motion is too great, the tailboom will make contact with the rotor. In this type mishap, the helicopter usually remains upright.

D. Trees
   1. Terrain will be the first clue. However, the technique for autorotating into trees is to perform the autorotation to the tree tops, letting the aircraft settle while pulling off RPM until the main rotor contacts the trees.
   2. The aircraft will exhibit evidence of high vertical loading with little or no evidence of rotation by the main rotor or tailrotor at impact. Occupants will probably be injured because the only restraint on the helicopter is the tree foliage.
   3. Main rotor blades will exhibit low speed damage with considerable tearing, gouging and bending. Bending will be upward.
   4. Another method is to autorotate to the tops of the trees, but not bleed off rotor system RPM. There will be relative high speed damage and deformation of blades, along with low speed damage as blades are slowed by contact with the trees.
      Note: I have investigated both types several times, and have found no consistency. It appears to be the luck of the draw in determining how the aircraft is slowed and strikes the ground. I remember two occasions when the helicopter never got to the ground.

Situation — Anti-torque failure

Characteristics

A. Fixed Pitch
   1. Depending on the position of the tailrotor, the pilot may attempt either a run-on landing or an autorotation. In most cases, the helicopter is flyable and the pilot has time to evaluate the situation.
   2. If the situation dictates an autorotation, the mishap will probably have the look of the autorotation with forward speed at touchdown. In fact, if there is damage to the tail rotor assembly, the impact damage may mask the condition that resulted in the fixed pitch.
   3. The unsuccessful run-on landing will probably result in the helicopter tumbling. However, there will be evidence of power at impact and the approach angle will be very shallow with a "fixed wing" type touchdown. The pilot will have picked out the largest and smoothest area available, preferably a runway.
   4. If the pilot has let the airspeed get too low on the approach, there is the distinct possibility that the helicopter will begin to rotate as dictated by the anti-torque malfunction. If the pilot feels that he is losing control, the normal reaction would be to enter autorotation. The impact then would exhibit characteristics of rotation at impact and probably a hard landing with forward velocity. The helicopter would probably roll over and/or tumble. The tailboom would be severed.

B. Loss of Tailrotor Blades or Thrust (Driveshaft Failure)
   1. Depending on where the loss occurs the pilot may have to enter autorotation immediately or elect to continue flight due to the streamlining effects of the aft aerodynamic surfaces.
   2. On takeoff or landing, the evidence is usually quite clear. First, the blades are missing. Second, due to the sudden nature of the occurrence, the pilot has had to take what he has been given, which is probably not the best landing area. Third, the helicopter will probably be rotating on touchdown.
   3. If the loss occurred at cruise and the pilot was able to fly the machine to a forced landing area, he may try either an autorotation with some forward speed or a run on landing. Both those situations have been covered earlier. The difference is that you will definitely have a turning moment at touchdown and the blades will be missing.
      Note: Find the blades if you can; some come in matched pairs and have the serial numbers in the tip. Without both it is difficult to come up with any definitive conclusion.

C. Loss of Tailrotor Gearbox
   1. Due to the long arm associated with the tailrotor gearbox and its weight, the loss of this component along with the attached tailrotor blades normally will result in a violent pitchdown moment. This can result in an inflight tailboom strike and breakup of the aircraft. However, if the CG of the helicopter is near the aft limit, and the pilot is living right, the helicopter may streamline and be guided to a run on landing or an autorotation.
   2. The obvious is that the gearbox and associated components will be missing.
      Note: I know of only one instance where the helicopter lost the gearbox inflight and the machine was successfully landed with little additional damage. There may be more.

Situation — Main Rotor Control Malfunction or Component Failure

Characteristics

A. At a Hover
   1. If the aircraft is equipped with boosted controls there is a possibility of having the controls go to their maximum position as a result of a failure in the system. This can result in a "hardover" where the lateral servo is activated and the helicopter flops

over on its side (if the pilot is not fast enough to catch it). Depending on the type system, the pilot may not receive any feedback as a warning. The hardover can also occur in the collective servo, but there should be no difficulty unless the helicopter is not at operational RPM. If this is the case, then the machine will go up like a corkscrew if the pilot has allowed the collective to get away from him. This mishap would be characterized by rotation at impact with power to the blades. The aircraft would probably impact in a nose low attitude.

2. If there is a failure of a control torque tube the helicopter will act in an unpredictable manner which is dependent upon which control is severed and where. The machine will impact in an unusual manner, probably in a turn with the blades striking the earth before the fuselage. The helicopter will roll over or tumble; in fact, it may attempt these maneuvers prior to impact.

B. In flight
   1. An inflight hydraulic failure is a rather simple emergency; all helicopters that have boosted controls either must have capability for manual control (smaller helicopters) or redundant systems. With a hydraulic malfunction, the helicopter is usually flown to a run-on landing. The results of an unsuccessful run-on landing have been discussed. However, on helicopters with two systems, one pump maybe on the engine while the other is on the transmission. The consequences of having the one go out on the transmission and then having an engine failure are rather ominous.
   2. An inflight control failure results in an inflight breakup or uncontrolled impact with the ground, depending on the altitude.

Situation—Inflight Breakup

Characteristics

A. Wreckage
   1. The wreckage will be scattered over a large area and will be subjected to secondary ground impact damage. Those objects striking the ground with the most energy dissipation should be subjected to close examination as they probably have the most reliable evidence of the initial phases of the breakup.
   2. In the initial sequence, there is high probability that the tailboom will be severed by the main rotor blades. After that, the head or the transmission and blades will separate and the blades will strike the fuselage in numerous locations.

B. Causal Factors
   1. Pilot induced unusual attitudes (zero G maneuvers in some machines).
   2. Situation resulting in excessive blade flapping: low rotor RPM along with excessive airspeed and/or a rapid control application.
   3. Failure of a blade damper, which can result in out of phase excursions of the blade especially when coupled with high airspeed or a rapid control input.
   4. Control failure
   5. Sudden forward CG shift
   6. Loss of aerodynamic component providing download on tail (sync elevator, stabilator, etc.)

Situation—Disorientation

Wreckage
1. The helicopter will be on its side after one or more rollovers. There will be evidence of power on the rotor blades and massive destruction to the blades and the aft fuselage.
2. The probability is high that the rotor blades will have struck the ground before the fuselage and there will be lateral movement across the ground. For some unknown reason, most disorientation mishaps at a hover result in the helicopter traversing the ground laterally or to the rear, but very seldom to the front.
3. Inflight disorientation will probably result in the helicopter striking in an unusual attitude, or an inflight breakup.

Environment
1. If the mishap occurred at a hover (most do) it is probable that there was a dusty environment, loose snow, darkness with no reference lighting, or a combination of the above.
   Inflight disorientations are motivated by the same situations as in fixed wing with the added problems created by vibrations.

Situation—Wire Strike

Characteristics
1. Wire strikes are normally associated with takeoff or landing situations. The wires either snag the landing gear and pitch the helicopter over or become entwined in the controls resulting in an uncontrolled impact. There are a high percentage of fatalities due to the fact that the helicopter impacts in an unusual attitude.
2. In an extreme situation, the cable may come into the cockpit and incapacitate the crew. If the impact occurs above 60 KIAS the resultant mishap is almost always fatal.
3. In every strike that I have investigated the evidence has been clear: either the wire/cable is stil wrapped around the aircraft or the cable marks are so prominent that they could not be missed. Usually the helicopter strikes the ground in close proximity to the wire/cable support structure.
4. Current aircraft have a wire strike tolerance such that they can survive an encounter with a ¼-in. taut copper or aluminum wire.

Situation—Blade Strike

Characteristics
1. The typical main rotor blade strike also oc-

curs most frequently on takeoff or landing, especially when working from confined areas or in mountainous terrain.
2. The blade strike can result in the loss of a section of the blade and thus the loss of control of the helicopter. At the low speeds at which the machine is operating at take-off and landing there is little wreckage scattering due to inertia. However, multiple impacts with object in the area can create confusion as to which is the initial strike.
3. The strike tolerance of the heavier machines today is a 3-4 in. tree. Larger trees will result in structural damage to the blade.
4. The tail rotor is the most strike sensitive device on the helicopter. Any strike will result in the loss of the blade if that strike occurs at operating RPM.
5. The normal tail rotor mishap occurs at a hover when the pilot puts the tail rotor into some brush or trees. The tail rotor fails and a hovering autorotation must be performed.
6. Besides the obvious fact that the tail rotor has sustained other than ground impact damage, the helicopter will exhibit evidence of rotation at impact and may be on its side.

Situation—Dynamic Rollover

Characteristics

1. The helicopter appears to have just simply rolled over, either uphill or downhill.
2. The inboard landing gear will exhibit evidence of constant ground contact.
3. Check the degree of the slope and the CG parameters of the helicopter. Remember crosswind and translating tendencies.

WRECKAGE DOCUMENTATION

Accurate documentation of wreckage is one of the most important aspects of an investigation. Not only will it provide evidence and clues to the nature of the impact, but it might indicate why the impact occurred in the manner that it did. Documentation of wreckage also provides statistical data that can be used by researchers to improve the product. Therefore, it is necessary that *complete* documentation of all systems be accomplished and the investigation not stopped when the "cause" is found. There have been a few times when the "cause" was not the "cause" at all, and there was inadequate documentation of the mishap to assist in determining the real cause of the mishap. Some call this a negative investigation and because of that are opposed to it. I call it a thorough investigation, necessary to insure the credibility of our profession.

General Appraisal

The wreckage distribution of a helicopter differs from that of a fixed wing due to the obvious: the helicopter is trying to self-destruct during normal operation. When the impact of the accident interacts with the normal rotational forces, the machine literally beats itself to death. However, even in this chaos there are indications of the difficulty that led to the mishap, be it mechanical or human. If there are none, then that is an indication that you must look elsewhere.

The first and most important factor in any investigation is the application of common sense and logic. You as the investigator are trying to determine what happened and why; with that in mind we must always keep in mind that an accident is a sequence of events. Your function is to ascertain the facts that define that sequence of events. Normally this starts at the site of the accident with the wreckage. Thorough documentation of the mishap is necessary as a minimum. Obtain a general overview of the wreckage. An aerial view can provide greater insight into the overall pattern of destruction without becoming involved with individual damage patterns or failures. In helicopter mishaps, pay particular attention to pieces that are at the greatest distance from the accident scene. Account for *all* aerodynamic surfaces. The blades have weights in the tips; look for them.

Note the attitude at impact and the direction that the helicopter rolled, if it did. Note the terrain and obstacles that might have interfered with the operation of the helicopter. Note the slope of the ground and its composition. Note any strikes on the ground and/or on any object in the vicinity. On the aerial survey, look for any good forced landing areas in the immediate vicinity of the point of impact.

The techniques of fire investigation are dealt with in a basic investigation course and do not differ with helicopters. There have been few inflight fires involving helicopters. However, due to the fact that helicopter accidents normally involve high G forces and a rollover tendency, there is high probability of post crash fire. Helicopter structure is extremely lightweight and easily destroyed by fire, thus obscuring some of the more obvious clues that may have been in the fire zone.

Before going into a detailed examination of the helicopter, take photographs of the general scene; it may not be that way again. I like to take four photographs on the cardinal headings (this also assists in orienting the aerial photos), then quartering photographs of the helicopter and the initial point of impact. You probably will not be able to recreate the impact scene or the helicopter as you found it, and you may be the *only* person ever to visit the scene, so document it well with your camera.

Attempt to ascertain the initial impact damage and resolve the resultant damage patterns in the airframe. Older machines are generally of lightweight construction with tube truss type fuselage and tailboom. More modern machines have conventional construction with monocoque or semi-monocoque fuselage and tailboom assemblies. This type construction makes load paths and failure modes more readily identifiable. Attempt to trace back the bends and failures in the airframe and resolve the force vectors involved. Keep in mind at all times that the helicopter has many rotating components and that damage patterns result from reactions to these components striking an object; e.g., damage to transmission mounts as a result of main rotor blade ground strike. A vector diagram is very helpful in resolving the impact forces and essential when documenting the forces acting on the occupants. I have found that in many instances the human body retains a considerable amount of evidence that is useful in resolving the forces that acted upon it. Normally this evidence is in direct proportion to the initial impact forces felt by the aircraft. Unfortunately, investigators usually arrive at the scene after the victims have been removed. Having a knowledge of the nature and extent of injuries of the occupants can be very valuable in determining the impact vectors.

The most complicated feature associated with the helicopter mishap is the control system. It also has the distinction of being number one on the FAA Malfunction and Defect reporting system for helicopter categories. This indicates that the control system may have more of a contributory factor than has been documented in past accidents. Impact damage would have a tendency to mask the evidence of a preexisting failure in the main rotor control system. This is another reason for complete documentation in every accident. A diagram of the control system should be taken to the accident scene and the system traced, piece by piece, with all fractures or failures recorded on the diagram. The importance of this tool will become readily apparent after you use it. This is especially important when you consider the number and types of control systems in use today. With the propensity for the machine to self destruct and the direct linkage of the control system to the blades, damage to the control system must be considered the norm, not the exception. Accurate identification and recording of *all* (I repeat ALL) control fractures and bends cannot be overemphasized. Look at the torque tubes, rod ends, hinges and bearings for evidence of corrosion or fatigue. If a fracture, failure or bend cannot be resolved, document it as accurately as you can and, if possible, remove it for further evaluation. One of the difficulties encountered investigating a helicopter mishap is that it normally occurs in a remote location, generally eliminating all but the most elementary reconstruction. In this respect it is fortunate that the helicopter is of lightweight construction; recovery usually results in considerable additional damage to the machine.

Documenting the Wreckage

A. Wreckage Distribution
   1. Plot and record the location of all parts
      a. Determine orientation of scatter path — use as reference line
      b. Determine impact heading
      c. Record heading of aircraft at rest
      d. Photograph all parts as they are found
   2. Determine impact attitude
      a. Pitch, roll and yaw.
      b. Did helicopter strike object prior to ground strike?
   3. Impact velocity
   4. Terrain
      a. Composition
         (1) Grass, dirt, sand, etc.
         (2) Frozen, wet, loose, mud, etc.
      b. Slope
      c. General features
         (1) Mountain
         (2) Desert
         (3) Forest
   5. Obstacles
      a. Type, size and proximity to impact point
      b. Evidence of blade strike or other impact
   6. Ground scars
      a. Dimensions including depth
      b. Orientation to aircraft at rest or initial impact
      c. Ascertain source of strike — Main rotor, tail rotor, landing gear or fuselage.
   7. Environment
      a. Light conditions — day, night, dawn or dusk
      b. Light angle in relation to pilot — looking into sun?
      c. Weather conditions at time of mishap
      d. Restrictions to visibility (includes dust or blowing snow)
      e. Visual landing aids (any light, VASI, etc.)
      f. Actual wind conditions at site including gusts

B. Structures
   1. Impact deformation
      a. Make accurate recording of location, depth, size and type of fuselage indentation or penetration. If the penetrating object can be identified, record it (including ground contact).
      b. Record evidence of compression buckling and bending of the airframe, and resolve vectors that caused the deformation.
      c. Look for evidence of creep damage in fire zone, do not confuse this damage with preimpact damage. Look for abnormal damage in the fire zone.
      d. Inspect fuselage and support structure for evidence of corrosion.
      e. Account for all fuselage components and accessories. Note type of damage and location of component.
      f. Inspect cabin area for infringement by any object — record location and object that penetrated the cabin. Do same for cockpit area.
      g. Inspect seats for evidence for loading and/or failure.
      h. Note type landing gear and mode of failure.
      i. Note and resolve all fuselage blade strikes, both main and tail rotor strikes.
   2. Failures
      a. Look for evidence of fatigue in all failed components
      b. Check tailboom attachment for security
      c. Check mounting structures for transmission and engine for possible failure.
      d. Inspect aircraft for evidence of an inflight blade strike

C. Flight Controls
   1. Continuity
      a. Account for all fractures or separations and insure that all controls were connected at impact.
      b. Check freedom of rod ends to see if they

have been staked.
c. Check hydraulic actuators for condition, position and operation
d. Check hydraulic lines for condition
e. Check bellcranks and other isolation links on flight controls
f. Check for evidence of chafing or rubbing on the torque tubes
g. Check cables, torque tubes, chains and pulleys to the tail rotor
h. Insure that interconnect systems are properly connected and adjusted.
i. Check for integrity and authority of stability augmentation systems or autopilots
j. Check freedom of force trim system if installed
k. Check operation of yaw damper if installed.

D. Rotor Systems
1. Main rotor
a. Check for evidence of high RPM damage to outboard sections or inboard downward bending of the blades as a result of low RPM
b. Ascertain the integrity of the blade to include tip caps and weights
c. Check main spar for evidence of failure or cracking that did not result from impact
d. Examine blade area aft of spar for evidence of strike damage. Strikes at low speed with a high angle-of-attack will tear into the blade aft the spar.
2. Tail rotor
a. Examine the blades for evidence of rotation at impact. High speed damage will tear the tips up and generally separate the blade from the head. Low speed will rsult in bending deformation to the blades.
b. Insure the integrity of the blade and account for all components, or at least know why they are missing
c. Check the pitch change mechanism
d. Check the bearing integrity
e. Look for evidence of lubrication or overtemp
f. Check pylon area for evidence of strike
g. Handle tail rotor blades carefully. They usually have grease and exhaust soot on them which can retain imprints of strikes of light objects. In one investigation there was a fabric imprint on the blade from a cushion that had blown out of the cabin and struck the blade.
h. If installed, check dampers for integrity and operation.
3. Rotorhead and mast
a. Check blade grip retainer bearing
b. Check trunnion bearings and trunnion (semi-rigid system)
c. Check the integrity of the Tension-Torsion Straps (T-T Strap)
d. Check horizontal and vertical hinge pins (articulated)
e. Check dampers for integrity and operation
f. Insure integrity of stabilization devices (bar, paddles, gyro)
g. Check for evidence of excessive flapping (mast bumping on semi-rigid or impacting the flapping stop on articulated)

E. Drive Train
1. Engine
a. As on fixed wing, ascertain the operation of the engine at impact.
b. On turbine helicopters the engine bleed air is used for many functions (E.C.U., heating, anti-ice etc.). Determine position of bleed air port and bleed band. This is very critical on high D.A. operations.
c. Note positioning of VIGV if so equipped
d. Note coloration of exhaust and swirl pattern of exhaust from turbine engine.
e. Pull mag sump plug and check for particles
f. Note integrity of engine mounting. In vertically mounted reciprocating installations, the engine is an integral part of the transmission/rotor system and is restricted at the base. Turbine engine misalignment can result in failure of the power shaft.
g. Verify position and operational capabilities of the engine relight system if installed
h. Engine controls
(1) Establish continuity and operation of collective correlation system. This provided for an increase in power as the collective is increased without having to twist the throttle.
(2) Check droop mechanism. This device is in the collective/throttle linkage and allows the power to lead the pitch application (at a non-linear rate) so that the engine RPM will not decay. (Engine decay will result in rotor decay will result in engine decay, etc.)
(3) On turbine engines, measure the length of the linear actuator
(4) Check fuel control and governor settings
(5) Check positions and function of throttle, mixture and carb heat if possible
(6) Check position of throttle twist grip and friction on all controls
2. Powershaft
a. If free turbine and the engine is free, see if the shaft will rotate opposite to the driving direction. This will check the freewheeling unit. On fixed shaft turbine applications, there will be a clutch to engage the engine to the transmission; the freewheeling unit can be checked between the transmission and that clutch.
b. Look for evidence of overtemp or long-term slinging of grease
c. Look for fractures of mating surfaces that do not correspond to impact forces
d. Usually when the shaft separates at impact and the system is under power, the flexing of the rotor/transmission allows the powershaft to pull free. This results in a deformation of the last contact surfaces as the transmission spline is slowing and the driveshaft is still under torque. After the driveshaft separates under these conditions, it will do a considerable amount of

damage to the surrounding baffling and adjacent components. Along with this there will be evidence of rotational scoring on the powershaft. Failures prior to impact are generally due to lack of lubrication, which will be evident on the mating surfaces.

3. Transmission
   a. Check for presence of fluid and take a sample. Check for proper oil pump operation.
   b. Look for discoloration of paint or other evidence of overtemp.
   c. Remove and inspect magnetic plug for evidence of large particulate matter. Fuzz is not uncommon and helicopter pilots do not like to fly with a transmission chip detector light illuminated. The helicopter may have been making a precautionary landing when the mishap occurred.
   d. Index and check for evidence of rotation (generators, hydraulic pumps, tachometers, etc.).
   e. Check clutch (if installed) for proper operation and evidence of overtemp
   f. Check rotor brake (if installed) for evidence of overtemp or stress. Rotor Brakes are usually equipped with shear pins to prevent damage.
   g. Check action of freewheeling unit
4. Tailrotor Driveshaft
   a. Look for evidence of overtemp or slinging of grease from the hanger bearings (newer ones not lubricated).
   b. Check for scoring on the driveshaft and tunnel (possible evidence of overspeed). Look for balance weights and marks on driveshaft.
5. Gearboxes
   a. Determine if gearbox has oil or grease and take a sample
   b. Look for evidence of overtemp
   c. Check magnetic chip detectors

F. Systems
1. Hydraulic
   a. Note quantity and take a sample of fluid
   b. Check filters to see if the filter is in bypass
   c. Check actuators for integrity and proper operation
   d. On machines with hydraulic boost, there are normally two hydraulic systems. One pump may be driven by the engine while the other is driven by the transmission. Check for proper operation.
   e. Check accumulator charge if installed. *Caution — This item can be very dangerous, especially if in or adjacent to the fire zone.*
2. Fuel
   a. Note quantity and take a sample (contamination is a very common cause of engine failures in helicopters). Remember, jet fuel is hygroscopic and can have a considerable amount of water in suspension. The turbine engine will flame out if just a small amount gets into the fuel control.
   b. Check filters for bypass and contamination. In some turbine fuel controls there is a final filter that may not have a bypass feature.
   c. Check operation of boost pumps and engine driven fuel pump.
   d. Note position of fuel selector and tank selection.
   e. If possible, note position of fuel valve. Most are electric and will normally remain in position during the impact.
   f. Note source of refueling and filtration system used. If some fuel is in the system, take a sample. *Note — Many helicopters are operated from field sites where they are refueled from 55 gal. drums. While there are many good filtration systems available for drum pumps, many still believe that a good chamois will filter out the water. In Avgas it will, but it will not in jet fuel; all it does is add fiber to the fuel.*
3. Electric
   a. The electric system investigation is the same as fixed wing.
   b. There are warning lights for almost every critical function on a helicopter, from filter bypass to engine failure. Check all indicator bulbs for filament elongation.
   c. In modern helicopters there is an engine out/RPM warning system and in some a relight system. Check these for proper operation and/or activation.

This will give you a good start in documenting the helicopter wreckage; it is by no means complete. The normal procedures utilized in the documentation and evaluation of fixed wing mishaps is utilized for inspection, testing or teardown of components. Other areas of documentation such as the cockpit are essentially the same. Be alert to the fact that there are controls on the cyclic and collective.

One additional area of consideration that I like to document, and wish that others would with a little more confidence, is crashworthiness. In evaluating the potential for survival of the occupants I would suggest the following as a minimum:

1. Document the percent reduction of the occupiable volume of both the cabin and cockpit areas.
2. Document the environmental hazards and their involvement with the occupants; e.g., pedals — resulting in broken ankles, etc.
3. Document the installation and use of restraint devices or tie down equipment. Seat belts, harness, floor hard points, cargo nets, etc. Note their use and effectiveness.
4. Note any failures in tie down chains to include deformation of the seat or flooring.
5. Document the rupture of any container of flammable material. Note type of container and how compromised.
6. Attempt to compute G loads on the exterior of the aircraft.
7. Document survival difficulties resulting from mishap; e.g., fire, ditching (note water temp.), remote areas, etc.

FUTURE TRENDS

The areas of great improvement appear to be composite technology and aerodynamic efficiency. The rotorcraft world has noticed the scarfed and swept tips on the newer machines. That swept tip does the same thing for the rotor blade it does for high performance aircraft with swept wings: it delays the onset of compressibility effects, including high drag rise. A hovering Bell 205 has a rotor tip velocity of approximately 814 FPS at hover. Add to that 150 FPS at cruise (90 KIAS) and you are getting very close to the speed of sound. Compressibility effects have a very large role in restricting the airspeed of the helicopter.

The rotor blade is of necessity long and slender, with weight constraints and rigidity requirements allowing rather limited types of blade construction. New construction techniques have allowed introduction of asymmetrical airfoils. Now airfoils can be self compensating and tailored for specific missions. Sikorsky, on the Army UH-60 Blackhawk, has gone to a titanium spar with a Kevlar tip, a Nomex-honeycomb core, fiberglass skin, a polyurethane-nickel-erosion cap and a graphite trailing edge. The SC 1095 (Sikorsky cambered 9.5-percent thick airfoil) has a -18° twist and a figure of merit (efficiency) of .76. The CH-53 blade has a maximum figure of merit of .69. Sikorsky is working on a composite blade, but chose not to use fiberglass at this time because the reduced torsional stiffness would result in a reduced figure of merit and speed. Aerospatiale has long since gone to the fiberglass blade, the most recent being on the AS-350C AStar. That blade has a symmetrical NACA 00 12 profile with a 12°27′ twist. The blade has a precured spar made up of glass-fiber strips. Strips are also wound around the spar and a foam core, then covered with a skin consisting of preimpregnated glass cloth. Bell also has new blades in development that will be all fiberglass filament wound for the Bell 214ST. Boeing Vertol has just announced that they have completed wind tunnel testing on a new airfoil that promises to give a 25 knot improvement to V_{ne}, along with a 6% increase in useful load and a 5% increase in best range speed.

These new blades are tough. I investigated an SA 341 Gazelle mishap where the helicopter had rolled over and was resting on one of the blades. That blade was bent up under the fuselage at an approximate angle of 120°. When the aircraft was righted, there was very little permanent set to the blade and no visible damage. All three blades had contacted the frozen tundra resulting in ground strikes that were 18-20 inches deep. The blades exhibited little or no evidence of ground contact. Blades with titanium spars and composite materials appear to be just as tough. Fatigue tolerance, notch resistance and corrosion resistance appear to be far superior to any blade currently in production. However, when it does occur, how is it recognized? It is my understanding that studies are currently underway to determine the crashworthiness of the composites. The doors on the Sikorsky S-76 are made from Kevlar while the hull on the AStar is polycarbonate. With the new blades and aerodynamics comes increased speed and the need for streamlining. Composite materials are more readily shaped, thus leading to greater application on future aircraft to reduce the drag of the fuselage.

Research aircraft such as the Sikorsky ABC (Advancing Blade Concept), Bell's XV-15 Tilt Rotor and the Canadian National Aeronautic Establishment's V/STOL Simulator (modified Bell 205) will provide information on the V/STOL machines of the future and how they are to be flown. Vertol studies show a reduction in the accident rate by about one-third due to improved human factors designs that will be incorporated into the machines of the future. These improvements will reduce the pilot's workload and, hopefully, the "pilot error" mishaps.

I am also happy to say that Sikorsky in the S-76 and Bell in the 222 have taken a giant step in the right direction by incorporating crashworthiness into their designs. While they do not go as far as the military machines, they do incorporate provisions for fuel containment, fail-safe components, energy absorption and reduced environmental hazards. Noses on the new machines are rounded with substantial keel structure to minimize plowing. Hughes, still the most crashworthy helicopter in my opinion, predicts that their 500D will be two to three times safer than the Hughes 500C. This is not to be accomplished through increased crashworthiness but through improvements in performance and reliability. Hughes is also working on eliminating the tailrotor, and an auxiliary device to impart energy to the rotor system in the event of an engine failure. More important for the near term, Hughes is offering as an option on the 500D a performance computer. This device can tell the pilot the capabilities of his machine at that moment. If any parameter is exceeded, the data is stored for the mechanic to evaluate. It also has the capability of displaying and recording the weight of an external load. This should go a long way toward keeping pilots honest. Properly utilized it should be a boon to maintenance. The prospect of on-condition maintenance becomes more of a reality with devices of this nature, so both the reliability and profitability of the machine will be enhanced. From an investigative point of view, I hope it has a self-contained memory that will retain all those nice parameters.

Lightweight avionics have made the cockpits of some machines as capable as the most modern widebody. In fact, the introduction of RNAV equipment and other off-airway guidance systems (VLF/Omega, LORAN C) have provided the catalyst for the IFR helicopter. Coupled with a TACAN transmitter, radar altimeter and onboard mapping/weather radar you can have an approach to anywhere. Recent operations in the Gulf of Alaska proved the feasibility of such operations with approaches of 300 feet and ½ mile visibility. North Sea operations with the Sikorsky S-61N and the Boeing Vertol Model 234 Chinook are planned into some of the world's worst weather conditions. In the near future, the FAA will probably begin certifying helicopters for operation in known moderate icing conditions. The Russians have been flying in Siberia with heated blades for years; the technology is available for a limited all weather helicopter.

The use of elastomeric bearings and devices is much more prevalent in new designs. Elastomeric bearings are much more tolerant to the environment of the helicopter, need no lubrication, have fewer components and have greater resistance to the effects of oil, sand and dirt. The characteristics of the material are such that it literally can be molded to produce the best results for the particular application; design actually controls the amount of rigidity and damping action of the material. The Starflex head developed by Aerospatiale has elastomeric articulation, weights 121 pounds and has only 64 parts. Research and development is currently underway in the United States and Europe on bearingless composite heads where all blade motions are resolved through elastomerics.

With the trend toward higher speed and all weather capability, individual helicopters are being designed with one market in mind. As an example, the OGE hover ceiling for the Sikorsky S-76 is only 1300 ft., the IGE hover is 5100 ft. while the single engine service ceiling is a respectable 4800 ft. However, it will cruise 400 nm at sea level at 125 KIAS and still have a 30 minute reserve at the end of the flight, all on internal fuel. The helicopter has been optimized for a specific mission: long range high speed flights at low altitude.

For the investigator, the future holds many unknowns. The higher speeds and IMC environment have ominous overtones, which is offset somewhat by the prospect of more twin-engine aircraft and increased reliability of the single-engine machines. The integrated avionics systems that do not retain information, autopilots, forced trim and stability augmentation systems are all unknowns, in that the evaluation of these components will be difficult if not impossible after a mishap. Incorporation of a small computer/FDR in these machines appears to be necessary if an accident investigation is to be accomplished with any degree of accuracy.

SUMMARY

You, the investigator, have the responsibility to know everything about all things. Right or wrong, that is the way others look at you. My only advice is to document everything that you see, touch, taste, hear or smell. If you don't know how or why something happened, make a complete record of the facts and circumstances; perhaps someone else will be able to solve the mystery at some future date armed with additional knowledge or experience. There cannot be pride of authorship in this profession, just as there is no possible way that you can know everything about all things.

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Cockpit and Visual System Limitations to See and Avoid

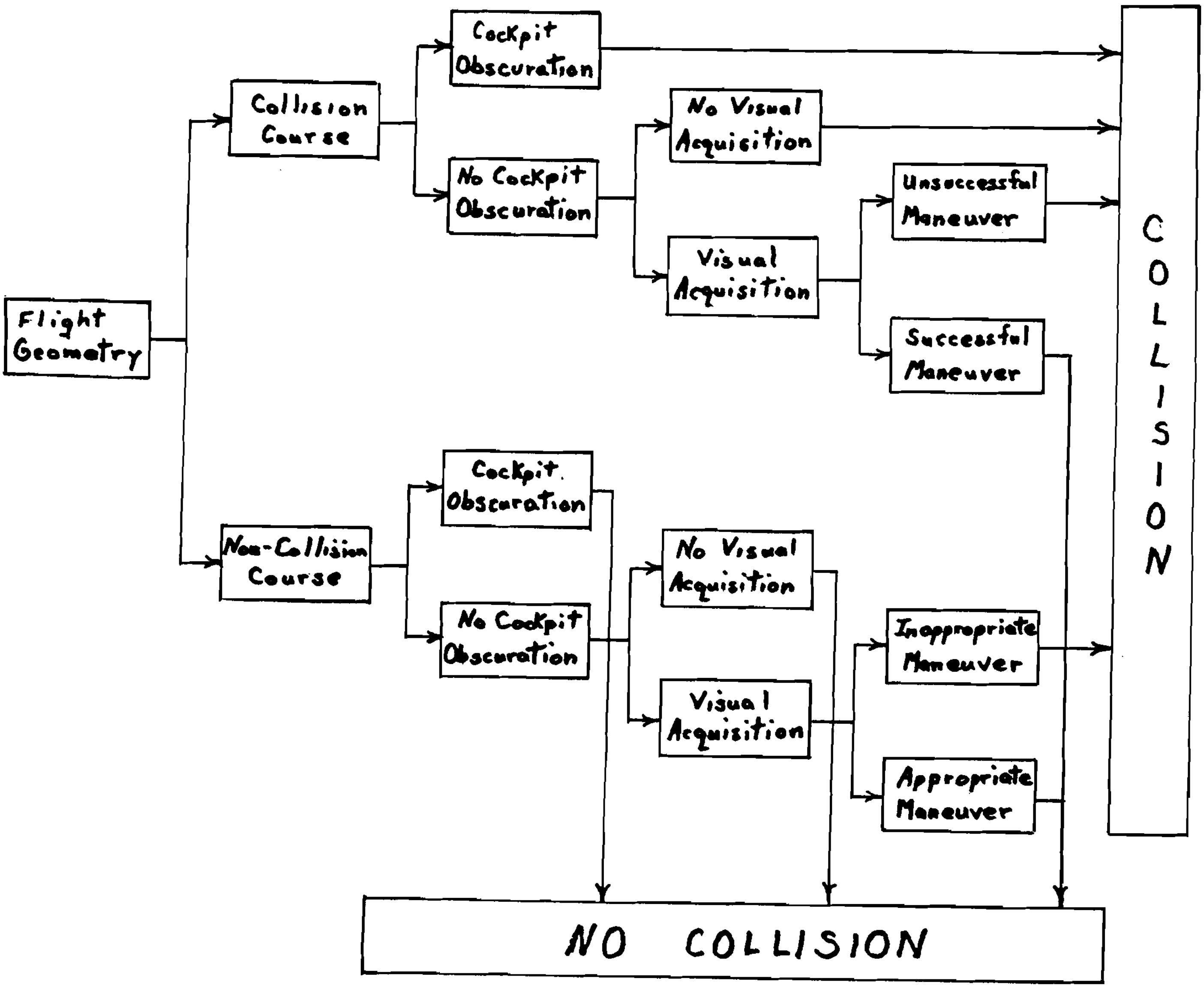
James L. Harris, Sr. *A00216*
Visibility Consultant
7169 Forum Street
San Diego, CA 92111

Introduction

The prevention of midair collisions by the process of seeing and avoiding other aircraft is an essential component of aviation safety. For that reason it is important that the process and its limitations be well understood. This paper is an attempt to review the principal factors which determine how well the see and avoid doctrine can be expected to achieve the desired result.

The occurrence of a midair collision is the result of a number of separate and distinct events. Chart 1 is an attempt to depict the various branches which are associated with such an occurrence. Each of these branches have associated with them a probability. The overall probability of having a collision is the composite of these individual probabilities. There are three principal ones which will be discussed in this paper.

Chart I



The first is "What Is The Probability Of Having Two Aircraft on a Collision Course?" The second is "If Two Aircraft Are On A Collision Course What Is The Probability That Neither Will See The Other In Time To Perform A Successful Evasion Maneuver?" The third is "If Two Aircraft Are On A Collision Course And Visual Acquisition Is Achieved By One Or Both Aircraft In Time To Perform A Successful Evasive Maneuver What Is The Probability That A Successful Evasive Maneuver Will Actually Be Performed?"

Collision Course Geometry

Let's start by considering the probability that two aircraft will be on a collision course. Quite obviously this is an extremely complex matter. However some feeling for the magnitude of the answer may be achieved by resorting to a very much simplified example. Consider the geometry shown in Fig. 1. A cylindrical region is depicted. The cylinder has a radius of five statute miles and a height of 3,000 feet. In the numbers which follow substantial liberty has been taken to reduce all values to round numbers for the ease of the reader. Such rather severe rounding is in keeping with the spirit of this greatly simplified example.

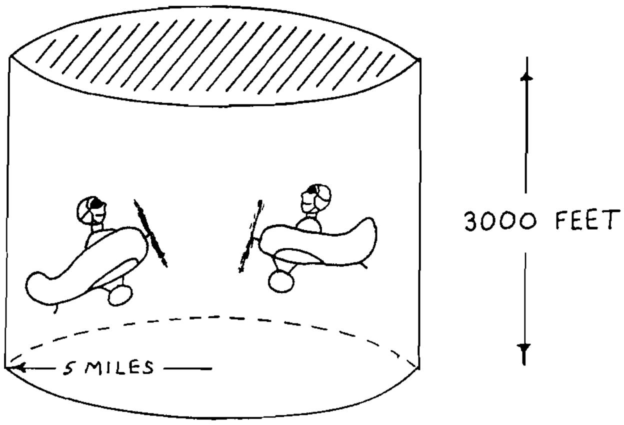


Figure 1

The volume of the cylinder is in excess of 6 trillion cubic feet. The volume of a small aircraft might be on the order of 600 cubic feet. This means that if we were able to achieve an efficient packing we could get approximately 10 billion such aircraft into the cylinder.

Let's now place two aircraft into the volume as depicted in Fig. 1. The pilot of each aircraft is blindfolded. They are instructed to continue flying at random within the airspace. They will be informed anytime that they approach any of the boundaries of the cylinder so that they can perform a maneuver which will keep them from leaving the cylinder. How long will it be before they collide? If each aircraft is traveling at a speed of 100 feet per second it will be occupying a completely new position about 5 times per second.

The mathematical question is then "How Long Will It Be Before The Two Aircraft Try Out The Same Position At the Same Moment In Time?" The answer of course is statistical in nature. The mean time between collisions will be approximately 500,000 hours.

Suppose now that we add a third aircraft to the volume. What happens to the probability of collision? Let's designate the aircraft as A, B and C. The probability that A will collide with B is not altered by the presence of aircraft C and is identical to that in the example in which two aircraft were present. However aircraft B can also collide with C so from A's point of view his probability of collision has doubled by the insertion of the third aircraft into the volume. From the system point of view however the probability that a collision will occur also includes the probability that B will collide with C. Overall then the addition of the third aircraft will increase the probability of a collision by a factor of three to one. For those who are mathematically inclined the equation is

$$P(N) = P(2) \times N/2 \times (N-1)$$

Where P(N) is the probability that a collision will occur with N aircraft present. P(2) is the probability that a collision will occur with 2 aircraft present. And N is the number of aircraft present. Table 1 shows probability values per flight hour and the corresponding mean times between collision for number of aircraft up to 10. Both the equation and the table make it clear that the probability of a collision is not linearly proportional to the number of aircraft present. This fact has been sometimes overlooked in discussions related to the meaning of near miss reports. For example the 5 to 1 increase in number of aircraft which occurs between 2 and 10 results in a 45 to 1 increase in collision probability.

I have also included in Table 1 two columns which pertain to cases in which two aircraft will pass within 100 feet of one another at time of closest approach. In this numerical example there are 300 such "near misses" for every single collision.

TABLE I

	COLLISION		100 FOOT CLOSEST APPROACH	
Number of Aircraft	Probability per Flight Hour	Hours Between Collisions	Probability per Flight Hour	Hours Between Collisions
2	.000002	500,000	.0006	1,700
3	.000006	167,000	.0018	560
4	.000012	83,000	.0036	280
5	.000020	50,000	.0060	170
6	.000030	33,000	.0090	110
7	.000042	24,000	.0126	80
8	.000056	18,000	.0168	60
9	.000072	14,000	.0216	50
10	.000090	11,000	.0270	40

Clearly such crude modeling falls far short of representing the true flight environment. Flight is not random and, except for instrument students, pilots do not wear blinders in the real world. In spite of the crudeness of the model however some element of truth emerges. Having two aircraft at the same point in space and time is a low probability event. As with any low probability event if enough trials are made there will be an occasional success. The probability of a potential collision encounter rises rapidly with increase of traffic density and the number of close approaches will be large compared with the number of actual collision encounters.

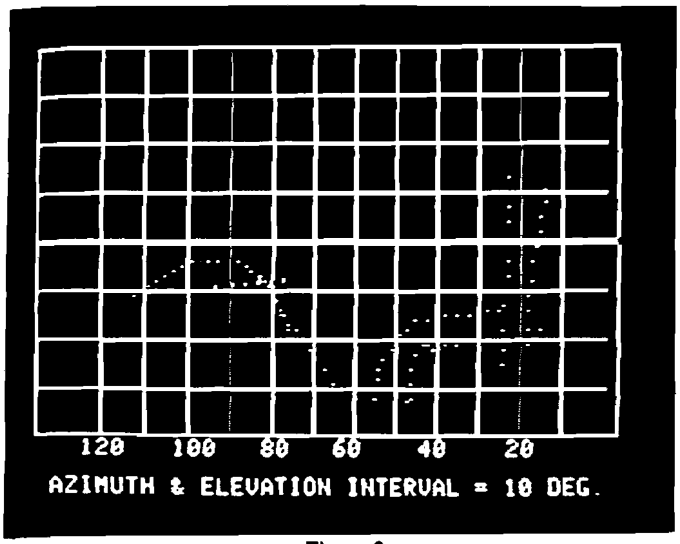


Figure 2

Cockpit Visibility

Assume that two aircraft are on a collision course. What is the probability that visual detection will take place? I previously stated that pilots do not wear blinders; however, pilots do wear cockpits and cockpits are partial blinders. Most air safety investigators are familiar with the binocular camera pictures shown in many NTSB reports involving air collisions(1). These pictures generally have the calculated positions of the other aircraft at various times prior to impact superimposed so that it can be seen whether the aircraft structures would have blocked the view of the other aircraft. There is no question that these representations of cockpit visibility are extremely helpful in understanding the visual aspects of a midair collision.

I have recently acquired a small computer system which includes a color display. Figure 2 shows a black and white photograph of the color display. The graph is the result of a computation of cockpit visibility. The grid structure lays out the angular field in 10 degree intervals in both azimuth and elevation. The heavy horizontal line is the horizon. A series of dots trace out cockpit constraints to the angular field of view from an aircraft. The direction of view is about 50 degrees to the left of nose-on. The window post between the windshield and the left side window can be seen at about 20 degrees in azimuth. Just to the left of the post is the outline of a small framed window within the left side window. The left wing can be seen to block the view almost up to the horizon at 90 degrees. A series of 6 dots can be seen to intersect the left wing at the leading edge a little less than 10 degrees below the horizon. These dots represent the position of a threat aircraft at 5 second intervals during the course of a collision encounter. The dot furthest to the right is the position of the threat aircraft 30 seconds before impact and the dot furthest to the left is the position 5 seconds before impact. The computer program allows the insertion of roll and pitch and can provide the threat aircraft position in real time so that the sense of timing and movement can be seen. Cockpit visibility data for different aircraft can be called from memory when needed.

The documentation of cockpit visibility need not and should not be confined to after the fact investigation of accidents. These same tools can be used to explore the general aspects of the problem. The angular position of a threat aircraft will depend upon the velocity, heading and rate of climb or descent of each aircraft. Figure 3 shows an illustrative calculation. The angular field of view is depicted from -50 to +50 degrees in azimuth and from -30 to +30 degrees in elevation. In this example it is assumed that the threat aircraft has an airspeed of 100 knots and may nave a vertical airspeed anywhere between a climb of 1,000 feet per minute and a descent of 1,000 feet per minute. The observing aircraft is assumed to be straight and level. Results are shown for three different assumptions as to the airspeed of the observing aircraft, i.e., 200,150 and 125 knots. For example, the line labled V1 = 200 knots forms the boundary within which all 100 knot threat aircraft will be found if the observer aircraft is travelling at 200 knots. As the airspeed of the observer aircraft is decreased the angular field required to see the threat aircraft expands as shown for the 150 and 125 knot cases. A hypothetical front left windshield is shown as a dashed line. When the airspeed of the observing aircraft becomes equal to or less than the airspeed of the threat aircraft the field of view expands to cover all angular space, i.e., a slower aircraft can be overtaken and struck from any direction. As a practical matter this lays a responsibility on the faster of the two aircraft. Figure 4 shows a similar calculation except that the observing aircraft is descending at 1,000 feet per minute. The field of view required to see the threat aircraft shifts down as might be expected.

Most documentation of cockpit visibility is accomplished using the design eye position. It is important to recognize that there is no requirement for a pilot to place himself in design eye position. His own physical characteristics, personal bias, etc., will dictate his positioning. Furthermore the pilot throughout his flight will be moving his body, his head, his eyes and even the aircraft for the specific purpose of expanding his useful field of view. These factors need to be considered in any cockpit visibility study. Even after such consideration, however, it is clear that two aircraft can be brought together in a collision encounter in such a way that neither has the opportunity to see the other because of obscuration by the physical features of the aircraft. The probability that this will occur is determined by the mix of aircraft speeds, headings and climb or descent rates.

Visual Search

To continue the chain of events, assume that two aircraft are on a collision course and that the collision geometry is such that the physical constraints of cockpit visibility will not block the path of sight of the

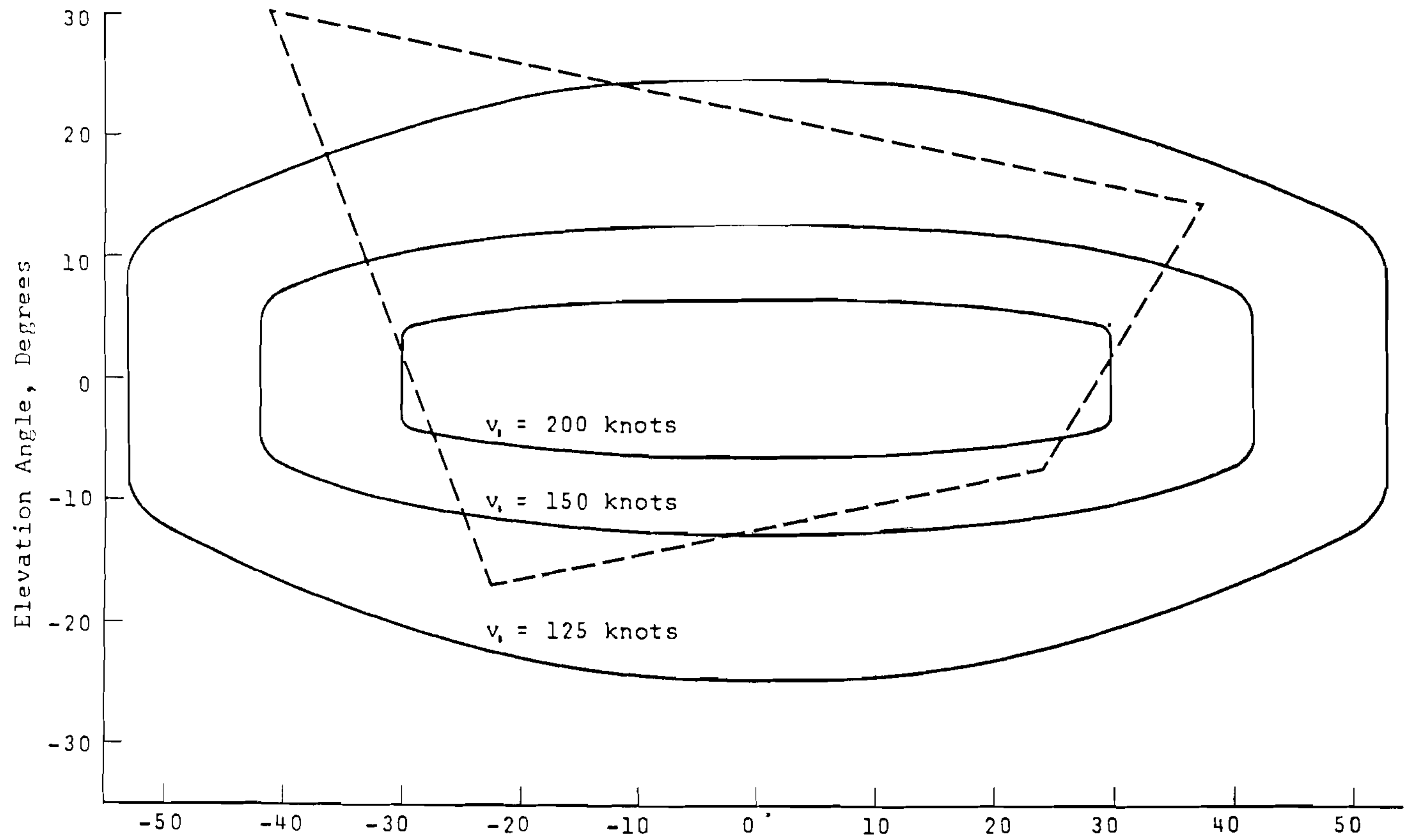


Figure 3 Azimuth Angle, Degrees

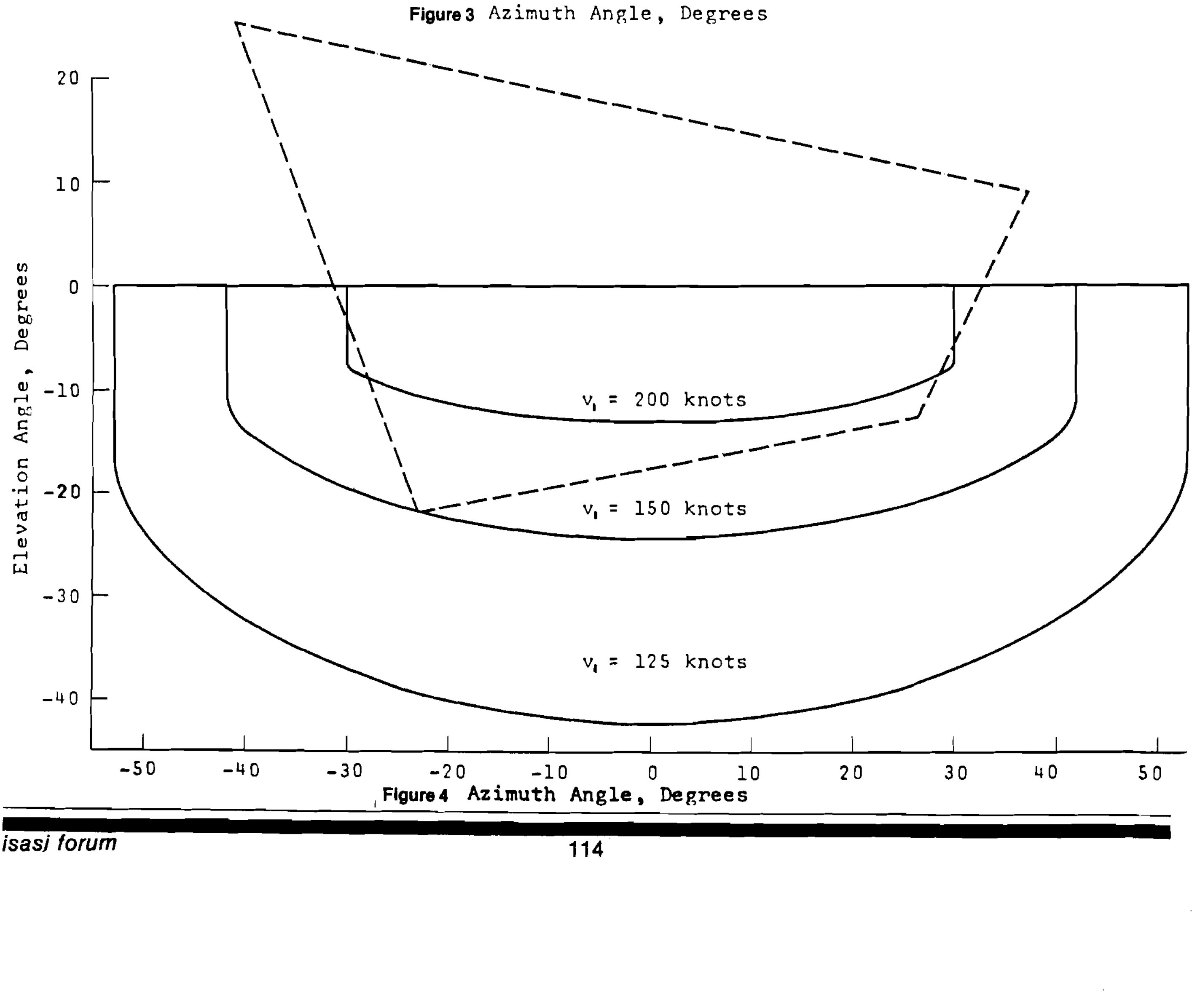


Figure 4 Azimuth Angle, Degrees

pilot in the observer aircraft. Does that mean that the threat aircraft will be visually detected? The answer to that question requires consideration of the properties of the human visual system.

Experiments have been performed to determine the limitations of human visual performance(2). In one set of experiments observers were positioned to view a uniformly illuminated screen. A buzzer sounded four times to mark off four time intervals. During one of these intervals chosen at random a circular spot of light was added to the screen by means of a rear screen projector. The observer's task was to push one of four response buttons to indicate which of the four time intervals contained the spot. When the output of the rear screen projector is high the observer's task is an easy one and the observer performance score is 100%. If the rear screen projector output is decreased a point is reached at which the observer performance will drop below 100%. The probability of detection will decrease continuously as the projector output is decreased until the observer score approaches 25% showing that the choice of interval is a guess. The point at which the score is 50% is referred to as limen and the contrast which the spot has relative to the background is called liminal contrast.

The liminal contrast value will depend upon the size of the spot. The size is traditionally measured in terms of the angular diameter of the spot as viewed from the observer's eye. The experiments described were repeated for a wide range of spot sizes with the experimental results shown in Fig. 5, which shows the relationship between angular subtense and liminal contrast. This same set of experiments explored one other important variable. The curve in Fig. 5 is the performance achieved when the observer knows exactly where the object will be located and therefore looks directly at the object. Therefore the observer is using the central fovea of the eye which is the most sensitive region of the eye during daylight light levels. In performing visual search the observer does not know where to look and the object will most often be sighted first peripherally followed by an eye movement to bring the object to the central fovea. The previously described experiments also explored the decrease in sensitivity as the object is moved away from the central fovea. Figure 6 shows the manner in which the threshold increases as a function of the angular distance from the central fovea. The graph shows that the contrast required to achieve detection at 12 degrees peripheral to the fixational center is approximately 10 times that required for direct viewing.

Atmospheric visibility is another factor important to determining visual detection performance. It is important to recognize that a reported visibility of 5 miles does not mean that the contrast of an aircraft will not be reduced at distances shorter than 5 miles. Figure 7 shows the relationship between the contrast reduction and distance. Note that for 5 miles visibility an aircraft viewed at 2 miles suffers a contrast reduction of a little greater than 3 to 1.

The windshield is an additional source of contrast reduction. Dust and dirt and grease and scratches and abrasions all scatter light and therefore reduce con-

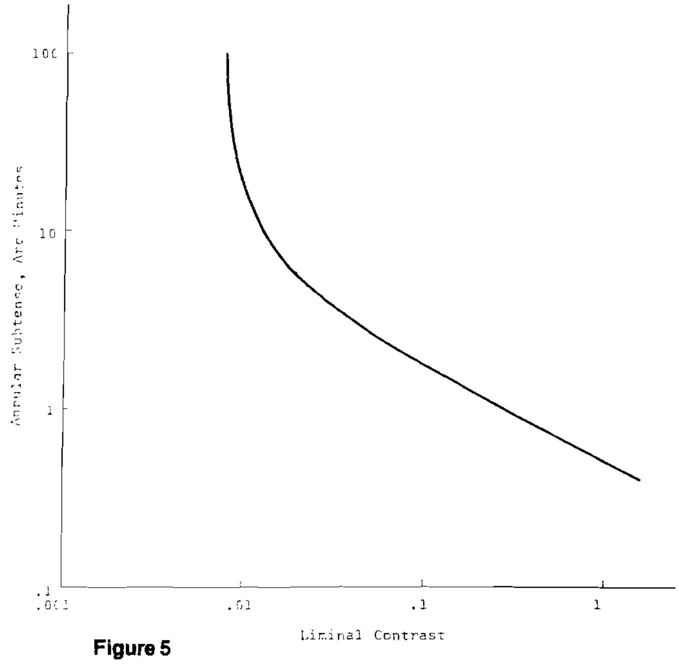


Figure 5

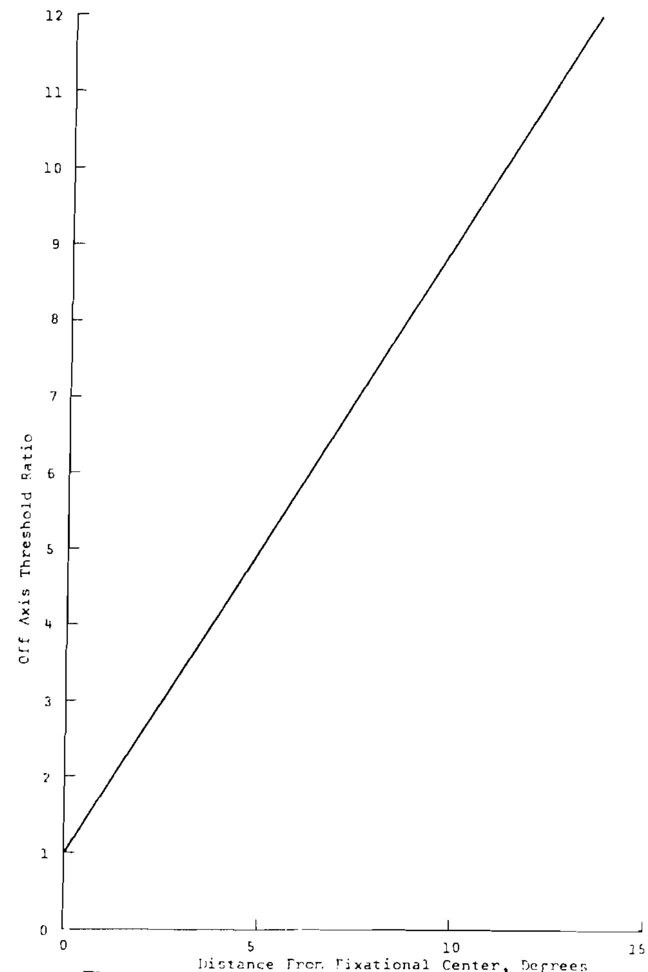


Figure 6

trast by the same processes which take place in the atmosphere. These effects are present at all times but are particularly noticeable when the sun is low and located within the azimuth of the field of view. It would be desirable to have suitable safety standards for windshield quality and cleanliness. Sunglasses and prescription glasses should be kept clean and scratch free for exactly the same reasons.

The basic threshold data on the human visual system and the contrast reduction produced by the atmosphere can be combined to produce what is called a visual detection lobe. An example is shown in Fig. 8. The aircraft to be viewed is assumed to have a cross-sectional area of 35 square feet which is something like the nose-on or tail-on cross-section of a Cessna 150. The range of the aircraft is assumed to be 2 nautical miles and the object is seen as a silhouette (very dark compared with the background) so that the contrast is -1. The graph is a plot of the probability of detection as a function of the position of the aircraft within the visual field relative to the central axis of the eye. Three different values of atmospheric visibility were used resulting in the three curves labeled 5, 10 and 25 nautical miles. Even though the visibility is numerically large compared with the viewing distance its effect upon the usefulness of peripheral vision is apparent in these curves. Figure 9 is a similar graph

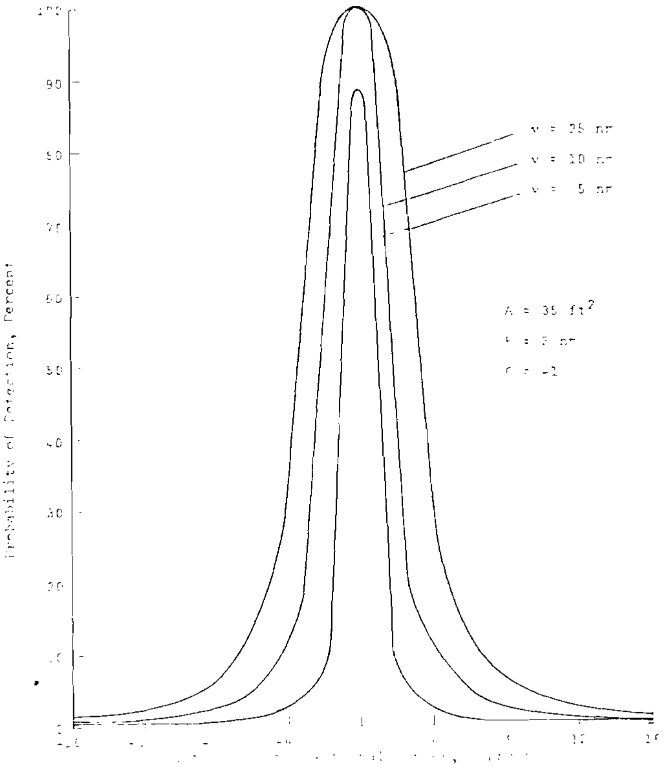


Figure 8

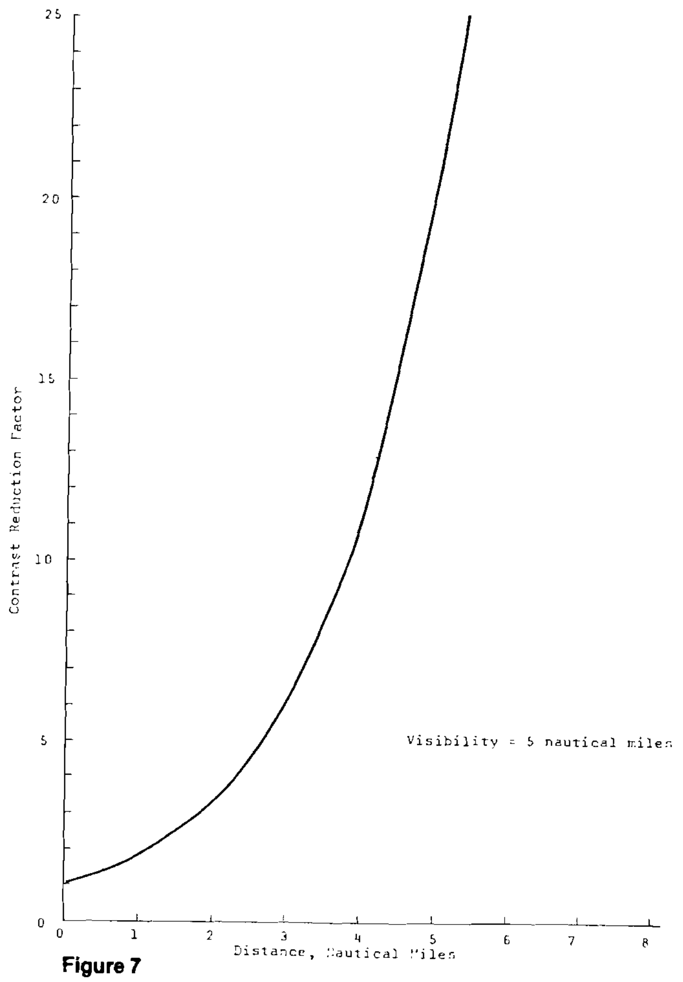


Figure 7

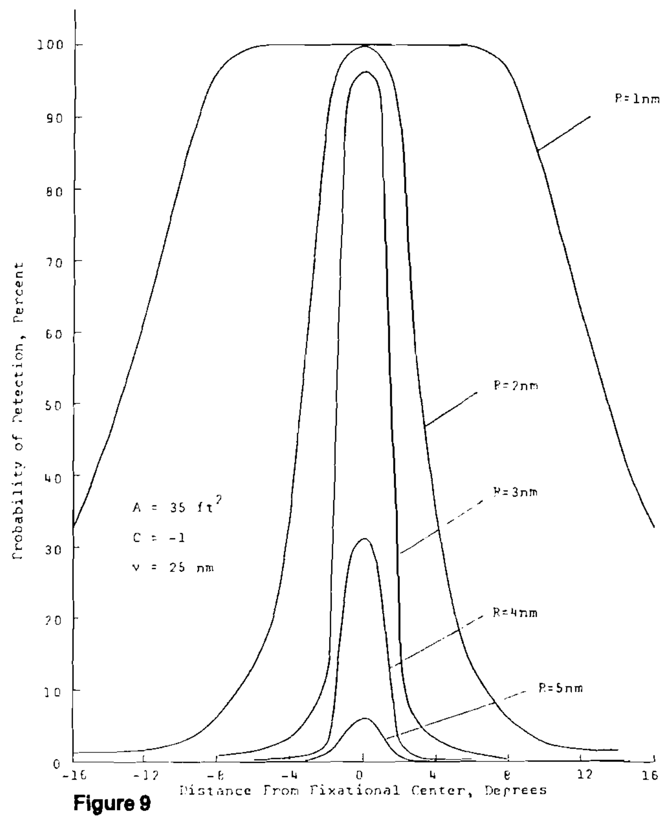


Figure 9

this time fixing the atmospheric visibility at 25 nautical miles and showing visual detection lobes for aircraft ranges of 1, 2, 3, 4 and 5 nautical miles.

The needle-like structure of the visual detection lobe at limiting ranges helps to give understanding to everyday occurrences. For example assume that we have visually followed an aircraft of the cross-sectional area used in this example out to a distance of 3 miles. The visual detection lobe for 3 miles shows that since we are looking directly at the aircraft (the distance from fixational center is zero) the probability of detection is high. Suppose now that our attention is directed to some remote part of the visual field and we then decide to look again at our receding aircraft. We may be surprised at the difficulty which we have in doing so. The reason for the difficulty is shown clearly by the visual detection lobe. It indicates that we must direct our vision to within a degree or less of the correct line of sight in order to have any appreciable probability of detection. That is likely to be very difficult if there is no nearby landmark to guide us. It will be necessary to perform visual search in which we make a series of eye movements, each followed by a fixation, attempting in the process to cover the region of uncertainty in the hope that one of these fixations will fall close enough to the aircraft to produce a detection.

It should be apparent that where the field of view to be searched is large the search task becomes more difficult. For example, suppose we attempt to search a field which is 180 degrees wide and 30 degrees high. That is 5,400 square degrees. If we have a visual detection lobe that covers a solid angle of 2 square degrees then even if we were capable of performing a totally systematic search there would be 2,700 individual fixations which must be made before the field has been searched effectively. Experiments have shown(3) that in performing such a search each fixation will take approximately ⅓ second. Therefore the time required to make 2,700 fixations is on the order of 900 seconds or 15 minutes. Such a search time is not available in normal flight operations. By comparison the visual detection lobe for a range of 1 nautical mile has a solid angle of something on the order of 300 square degrees. Once again if we were able to be completely systematic in our search the 5,400 square degree field of our example could be covered with 18 fixations which would require only 6 seconds at ⅓ second for each fixation. Such a search time is quite appropriate to the flight environment.

The very rough kind of calculations just described were intended only to give insight into the nature of the visual search task. Proper calculations take into account the statistical nature of the visual detection lobe and the quasi-randomness which will be inherent in any real search pattern. Figure 10 shows a computation of the cumulative probability of detection for a closure rate of 60 knots and for a total search field of 80 degrees by 20 degrees which is 1,600 square degrees. The three curves are labeled in terms of the percent of time spent in search chosen for this example to be 20%, 50% and 100%. The 20% figure was included because a study indicated that this value typified air line crew search time under certain phases of flight.(4) The closing velocity is a sensitive variable because it determines directly the time which is avail-

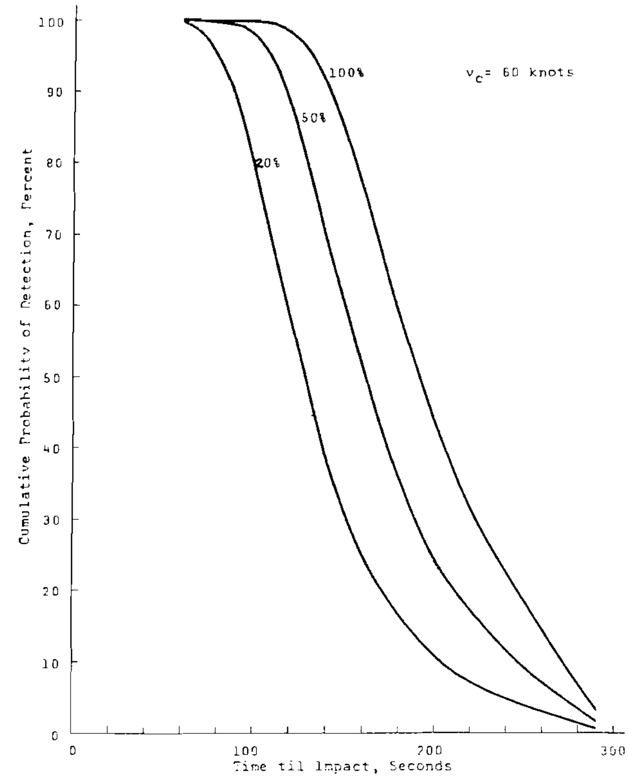


Figure 10

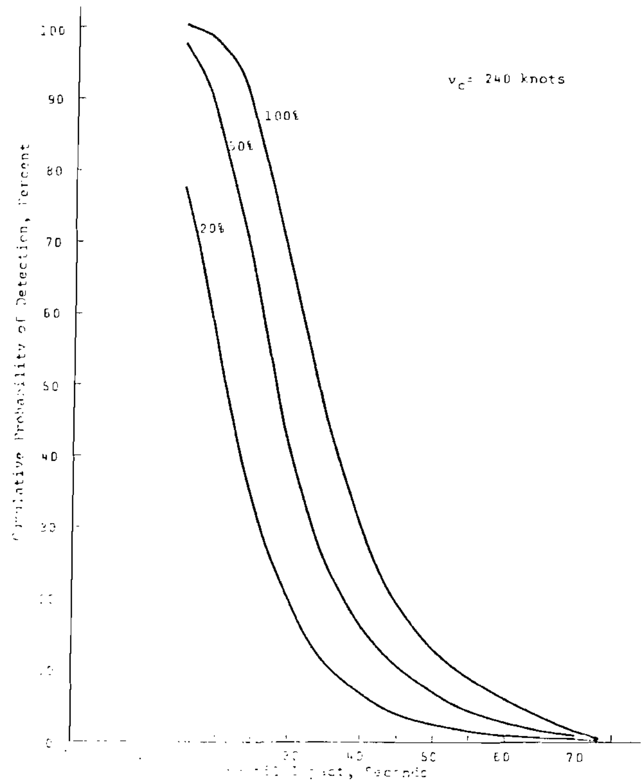


Figure 11

able for search prior to impact. The sensitivity is illustrated by Fig. 11 which is the identical calculation with the exception that the closing velocity is now 240 knots. Note that the time scale has been dramatically changed and that with 20% time devoted to search the probability of detection is only about 80% at a time 15 seconds before impact.

It is extremely important that these examples be viewed as purely illustrative. The 35 square foot cross-section is a minimum. Even for the smallest aircraft it may be 75 square feet on side view and 210 square feet for top and bottom views. Then of course there is the whole spectrum of aircraft types. The 747 has a nose-on projected area of approximately 900 square feet. It has approximately 5,250 square feet cross-section from the side and 9,250 square feet from the top or bottom. The contrast of the aircraft was assumed to be -1 in the example (very dark compared with the background against which it is viewed). That is frequently the case where the sun is to the rear of the aircraft so that the surfaces viewed by the observer are not sun illuminated and the background is sky. One has only to stand at an airport and watch an aircraft in the pattern on a sunny day to see that it undergoes dramatic changes from dark to bright sometimes almost disappearing in transition between the two. We also see occasional sun glints from glass or polished surfaces. Except in the silhouette situations the paint reflectance will directly determine the contrast.

Variations of aircraft cross-sectional area and contrast will produce corresponding variations in computed cumulative probabilities. The examples shown in this paper have been purely illustrative and not necessarily typical. They do demonstrate however that while it has long been apparent that a pilot who does not look will not see, the converse is not necessarily true. There can be cases in which the pilot performs reasonable search and still fails to make visual acquisition.

Search Strategy

The computations in the preceding section assumed that there was a defined field of view and that it was the plan of the searcher to spend equal amounts of time in each portion of that field. Is this a reasonable assumption? Figures 3 and 4 give some insight into how a reasonable field of view is determined. If the pilot had no other basis for knowing where to expect traffic then the information defined in Figs. 3 and 4 would be suitable grounds for establishing a search field. Frequently, however, a pilot will have other information available. One very important example is when the pilot has had traffic called to him via radio. Most traffic advisories will include information which localizes the aircraft within the search field. Once that localization has taken place it is highly appropriate that he spend a large portion or even all of his time looking for that one aircraft with the decision being based on the estimated urgency of the situation. This concentration of the search effort will substantially increase his probability for acquiring that traffic. It should be carefully noted however that while his search is thus localized his probability of detecting other traffic has been reduced or even eliminated. For this reason it is important that traffic advisories be issued only when the traffic represents a genuine collision threat and that the advisories be as accurate as possible in terms of defining the location within the pilot's visual field. It is also important for the pilot to terminate the localized search as quickly as possible either by visually acquiring the traffic or by requesting additional information.

Traffic advisories are by no means the only type of information which should cause the pilot to alter his search pattern. Other examples would include knowledge of the existence of traffic acquired by monitoring appropriate radio frequencies, and knowledge or experience as to the general flow of traffic within the area of flight.

It is also important to note that traffic density will alter visual search performance. The more aircraft which are visually acquired and visually monitored the less the time which is available for normal search. More than one midair collision has probably occurred while the pilot was watching a threat aircraft but not the one with which he collided.

Complex Structured Background

The vision data used in the preceding section on visual search was acquired in experiments involving the visual detection of stimulus presented on a uniform background. The data and the calculations based upon this data do not apply to the case of complex structured backgrounds such as terrain, metropolitan areas, cloud patterns, etc.

A principal difference between uniform and complex backgrounds is the role played by peripheral vision. Peripheral vision has poor resolution. This means that we do not recognize detail to any appreciable degree. For example, we cannot read with peripheral vision. To recognize words we must make a visual fixation within a small angular distance of the word itself; i.e., look almost directly at the word. In the search of a uniform background we detect an unrecognizable "something" peripherally and react with an eye movement to bring the "something" to the central fovea of the eye where we identify it by examining the fine detail of its image.

In a complex background there are "somethings" everywhere and since they cannot be identified peripherally the central fovea must be used to examine each one to determine if it is an aircraft. This can cause a dramatic slowdown of the visual process. Of course there is a continuous scale of background complexity. In the most extreme background complexity situations search for an aircraft must involve "reading" the background by examining each and every region with the central fovea. Since the central fovea is on the order of a few square degrees and since time on the order of a second or more may be required for the brain processing the area, search rate can be as little as a few square degrees per second. A 40 degree by 20 degree search field (800 square degrees) could therefore take on the order of 10 minutes to search. Such a search time is inconsistent with the timing of the sequence of events associated with most collision encounters.

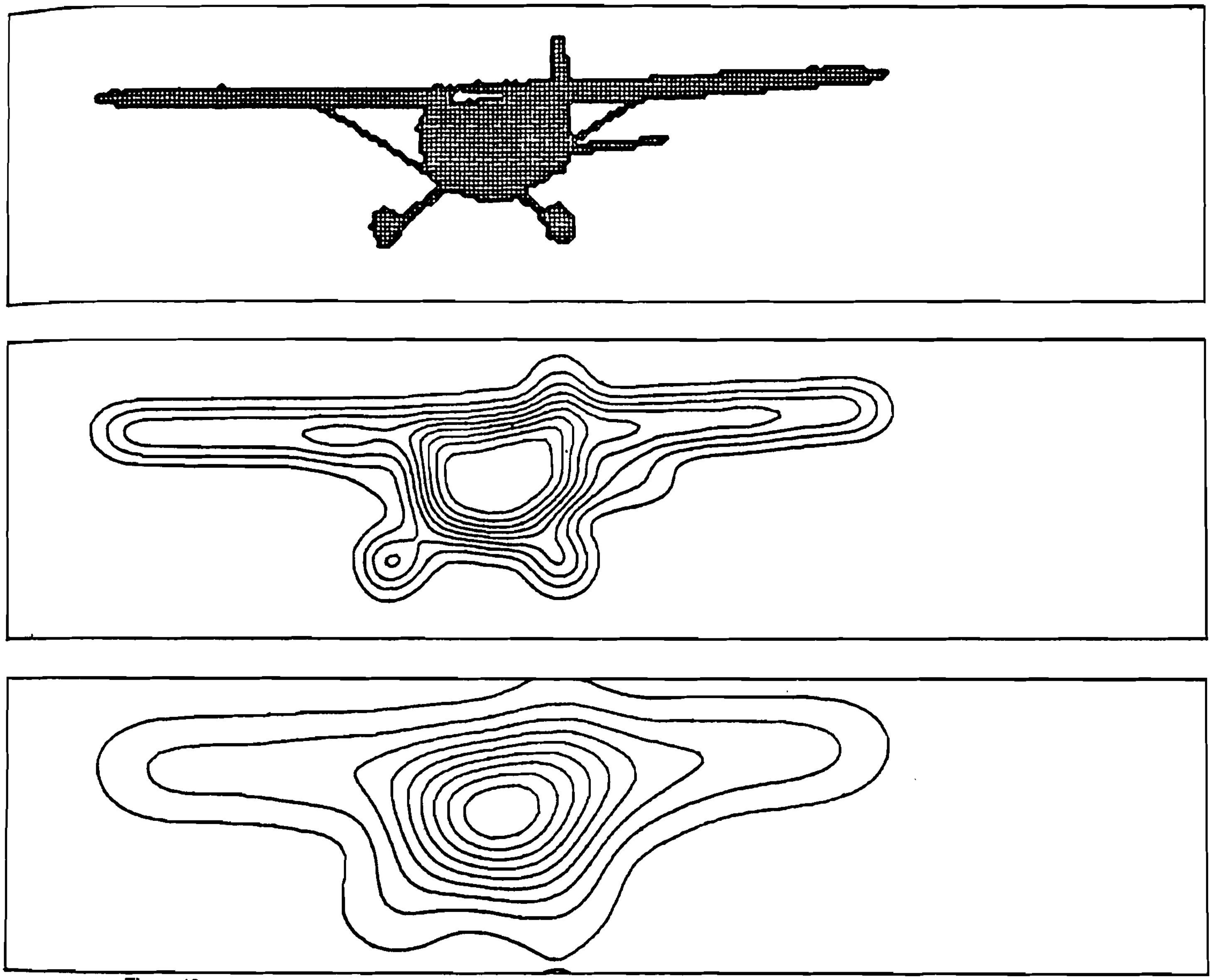


Figure 12

There are cases in which peripheral vision can still be effective even though the background is highly structured. One of these is if the threat aircraft is in rapid angular motion relative to the background. Unfortunately the majority of collision encounters will not involve such rapid relative motion. Another case is when the aircraft produces some rapid change of brightness as for example because of a sun glint. The peripheral vision is quite sensitive to such stimulus and perception of a sun glint will likely be followed by an eye movement and foveal inspection. Unfortunately sun glints are sporadic and cannot be counted on as a solution to the problem. A strobe light with sufficient power to be useful during daylight hours would be effective in making substantial improvement in visual search performance for complex structured background.

There is yet another aspect of the complex structured background which should be noted. The inference of the preceding paragraph is that the presence of the structured background will slow the search process by negating the usefulness of the peripheral vision. It is inherently implied that once direct foveal inspection is made of the region containing the aircraft, visual acquisition will take place. This may not be the case for reasons which will now be outlined.

Eye charts are used to document the resolution capabilities of the human visual system. On the last line that we can read the letters are just big enough to allow us to recognize them. On the line below that the letters are too indistinct or too fuzzy to allow recognition.

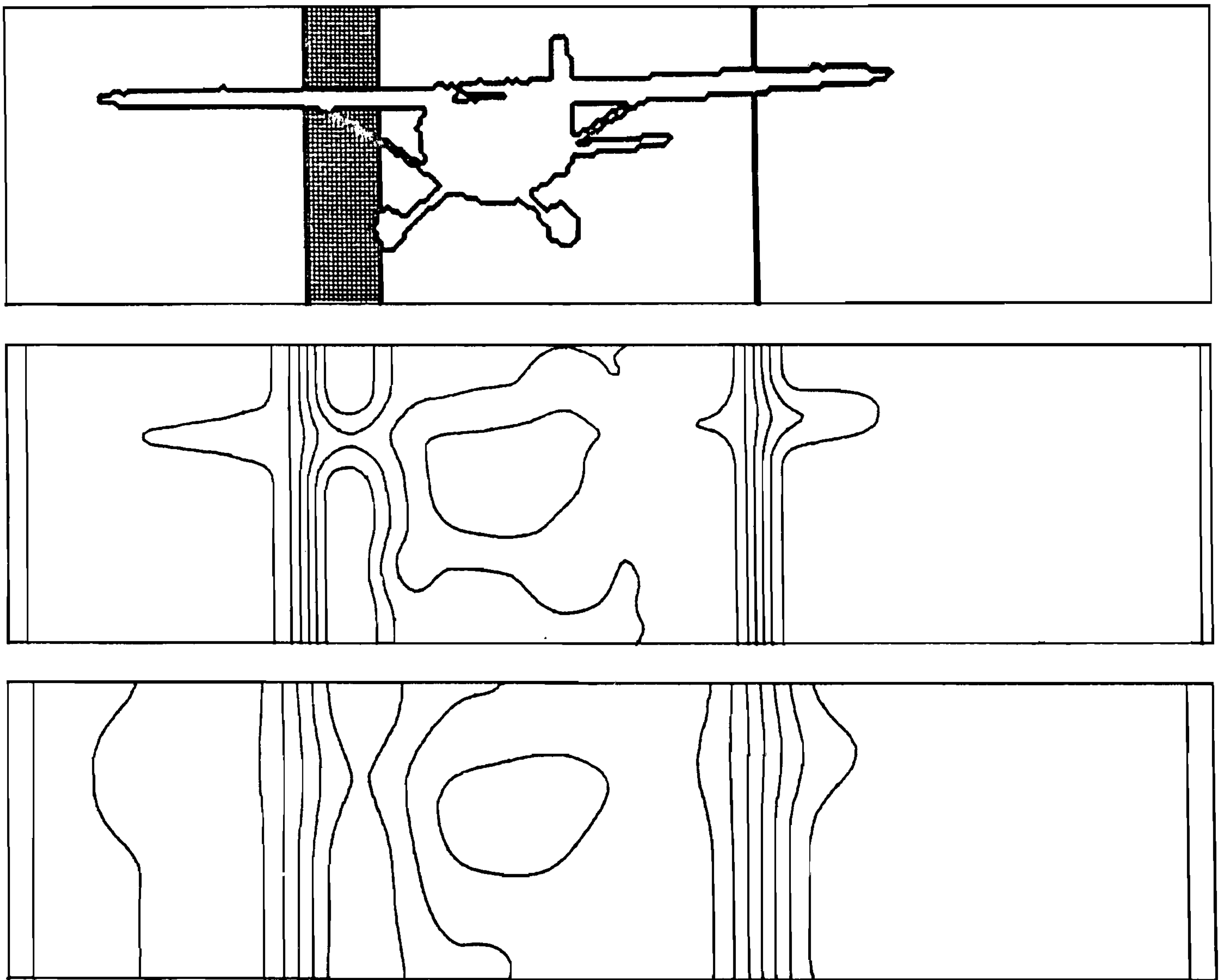


Figure 13

If an eye chart was to be constructed for viewing at one nautical mile instead of across the doctor's office the letters on the 20/20 line would have to be about 9 feet tall. Most small aircraft are less than 9 feet tall and therefore smaller in height than the 20/20 line letters. Such an aircraft viewed at 1 nautical mile will therefore be somewhat fuzzy. I have made a computer simulation to illustrate the fuzziness. The results are shown in Fig. 12. The top picture shows the silhouette of a small aircraft viewed almost nose-on. The middle picture is a contour plot of the image which would be produced on the retina of the human eye if the aircraft was viewed at 1 nautical mile. The computer simulation incorporates the optical properties of the lens system of the human eye. While the fuzziness is apparent the image certainly has sufficient detail to be able to visualize that it is a high wing single engine aircraft. The bottom picture is a similar computer simulation except that the viewing distance is now 2 nautical miles. The image was magnified by a factor of 2 to make it comparable to the dimensions of the previous picture. The increased fuzziness is apparent but recognition that it is a high wing aircraft is certainly plausible.

The next step in the computer simulation was to repeat the process for a non-uniform background. The result is shown in Fig. 13. The top picture shows the aircraft viewed against a background of several different brightness levels. It might be visualized as a series of building fronts with a dark shadowed gap between the left hand pair. The choice was purely arbitrary and not intended to portray any specific situation. As before the middle picture is a contour image associated with viewing at 1 nautical mile. Note how the background interacts with and contaminates the image of the aircraft. The wing tips are still visible as is some semblance of the fuselage. The bottom picture shows the 2 nautical mile case. There is little remaining which would be interpretable as an aircraft. Direct foveal inspection would probably not result in the recognition required to achieve visual acquisition.

In my opinion the complex background problem is a serious one. If I was asked to single out a specific set of circumstances most likely to produce a midair collision it would consist of the overtaking of a slower aircraft by a faster aircraft descending rapidly for an impending landing. The slower aircraft is quite likely to have no visibility in the direction of the faster aircraft and the faster aircraft will be viewing the slower aircraft along a downward path of sight which is very likely in the neighborhood of many airports to terminate in a complex structured background where acquisition may be too time consuming or nonexistent.

The Evasive Maneuver

The final element of the probability chain is the probability of a successful evasion maneuver. The question is "if two aircraft are on a collision course such that the cockpit did not obscure the threat aircraft and visual search did result in acquisition in time to allow a successful evasive maneuver, what is the probability that a successful evasion maneuver will actually be performed?"

The subject of evasive maneuvers is quite complex and cannot be adequately addressed in the present paper. Limited studies have been made of the visual system capabilities for properly assessing air collision threats(5). The study concluded that for nonaccelerating flight visual acquisition 10 seconds before impact was probably adequate to allow the performing of a successful evasive maneuver providing that the evading pilot knows how to choose the proper evasive maneuver and provided that the threat aircraft does not perform a negating maneuver.

For nonaccelerating flight the cleanest indication of a collision course is the absence of any angular movement of the threat aircraft. The fact that no angular motion is sensed however does not prove conclusively that a collision course is involved. It simply means that whatever level of angular motion does exist is below the threshold of motion detection. A too early maneuver response may very well result in increasing the risk of collision, particularly if the maneuver is such that further visual threat assessment is impossible, as for example in the case of a steep turn. It is my personal impression that many pilots have given little or no meaningful consideration to the question of what to look for in order to decide upon an appropriate maneuver. Their first experience with an actual collision encounter is a poor time to become educated. I am confident that there have been midair collisions which have been caused by an inappropriate last second maneuver. One striking example is that in the case of a head on encounter, a right bank by both aircraft just prior to reaching the point of closest approach will increase the probability of collision by a factor of from 3 to 5 because the collision cross-section has been increased by that amount. I think it is also fair to speculate that some cases in which a pilot believes he has performed a successful evasive maneuver were near misses rather than collision courses. In my opinion a training film could be very effective in teaching pilots what to look for in a collision encounter and how to respond with an appropriate maneuver.

The task of assessing a collision threat for accelerating flight paths including turns or changing airspeed is a more difficult visual task and has received little study to the best of my knowledge.

Concluding Comment

A midair collision is a low probability event which sometimes occurs. Undoubtedly one of the most difficult tasks facing anyone concerned with matters of safety is the development of an objective perspective as to the significance of a particular type of accident and a judgment as to the severity of the preventive measures which are justified. It is my opinion that a continuing search for a true understanding of the underlying causes will help to guarantee that such corrective actions as are taken are both necessary and responsive.

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The Search and Rescue Satellite Mission — A Basis for International Cooperation

Dr. William N. Redisch
Bernard J. Trudell
NASA Goddard Space Flight Center

There are two elements to the basic problem of how to reduce the heavy loss of life which occurs in an aircraft crash or when a vessel suffers a disastrous casualty such as breaking in two or exploding. First, there must be a means for immediately alerting potential rescuers that a distress situation exists. Second, an effective method for guiding rescue forces to the scene of the distress is necessary. Time is of the essence. The probability of surviving is inversely related to time elapsed subsequent to the casualty. Department of Transportation studies have shown that the chances of survival in a crash are lower than 10% after two days whereas they can increase to 50% if the survivor is located within eight hours.[1]

In 1970, the Congress recognized the deficiency which existed in locating the scene of an aircraft crash by passing legislation which required general aviation aircraft to carry an Emergency Locator Transmitter (ELT). Following implementation of Federal Aviation Administration (FAA) regulations, approximately 170,000 ELT's have been installed on U.S. civil aircraft. Subsequent Coast Guard and FCC rulemaking brought approximately 1700 U.S. vessels under mandatory regulations requiring carriage of Emergency Position Indicating Radio Beacons (EPIRB's). Both the aviation ELT's and the maritime EPIRB's transmit a distinct "wow-wow" modulated tone signal on the emergency distress frequencies of 121.5 and 243 MHz. The radio characteristics of both are identical. The differences, which are not of significant concern in designing an alerting and locating system around the devices, are: 1) in the case of the ELT, automatic activation on impact by means of an accelerometer ("g-switch") and 2) for the EPIRB, an ability to float free of the vessel and automatically activate. Both devices have the capability of providing both an immediate alert and a homing signal to assist rescue forces in locating the site of the distress. To be effective the ELT or EPIRB signal must be detected (Figure 1). The satellite system discussed in this paper would be capable of detecting and locating ELT's and EPIRB's operating at 121.5 and 243 MHz, as well as experimental ELT/EPIRB's operating on the 406 MHz frequency authorized for ground to satellite search and rescue use by the last World Administrative Radio Conference.[2]

For both the aviation and maritime communities, major deficiencies exist in the present ELT/EPIRB systems: transmitter malfunctions, equipment misuse, lack of DF equipment, and receiver coverage. Although most of these deficiencies can be overcome by educating operators and improving the equipment, locating the source of the signal presents a far greater problem. Each ELT signal must be treated as a Mayday call until the source is located and proven otherwise.

At the request of the FAA the Radio Technical Committee for Aeronautics (RTCA) formed a special committee (RTCA S.C. No. 127) to develop an improved Minimum Performance Standard for the ELT. Special Committee No. 136 was also formed to address the problems of installation and mounting. In conjunction with these two committee actions the FAA in a cooperative program with NASA will develop the specific technology to improve the second generation ELT's with the objective of improving their reliability and minimizing the false alarm problem. The effort by the RTCA and the FAA should result in substantial improvement of the ELT equipment.

The use of satellites to monitor and locate the source of distress transmissions has been the subject of discussions and studies for many years. In a letter to the NASA Administrator the FAA requested NASA to determine the feasibility of monitoring and locating the ELT's. Coast Guard and NASA studies have also investigated the potential for satellites to locate ELT and EPIRB transmissions and a study conducted by the Interagency Committee for Search and Rescue (ICSAR) concluded that a satellite demonstration for monitoring and locating ELT's and EPIRB's should be implemented to provide operational and cost-benefit data to user organizations.[3]

An examination of the various approaches to obtaining position location of a distress incident will show that all of the methods examined, except one, the doppler technique, could be accomplished by synchronous satellites. The natural advantage of using synchronous satellites is, of course, the value of immediate alert and location of the distress incident and it would seem logical that any satellite system for aiding in search and rescue would use a synchronous satellite approach. There are, however, basic physical and geometric limitations which offer strong offsetting disadvantages. These are distance, view angle to the satellite, and the lack of sufficient doppler for position location. These factors, coupled with the strong motivation to develop a system which could operate with the existing ELT's and EPIRB's now in wide use, led NASA to the selection of a low orbiting system for a satellite-aided search and rescue demonstration.

While the NASA Goddard Space Flight Center was conducting these studies, the Canadian Department of Communication (DOC) was conducting independent studies[4] for the Canadian Department of National Defense and their studies led to almost identical results and conclusions. These factors, coupled with the natural commonality of the search and rescue problems of both countries, led NASA and the DOC to join forces in defining a joint satellite-aided search and rescue system demonstration program plan in the Fall of 1976. This joint program was expanded into a trilateral program in December 1977 when the French Centre d'Etudes Spatiales (CNES) joined the effort by providing the on-board processor for an advanced emergency

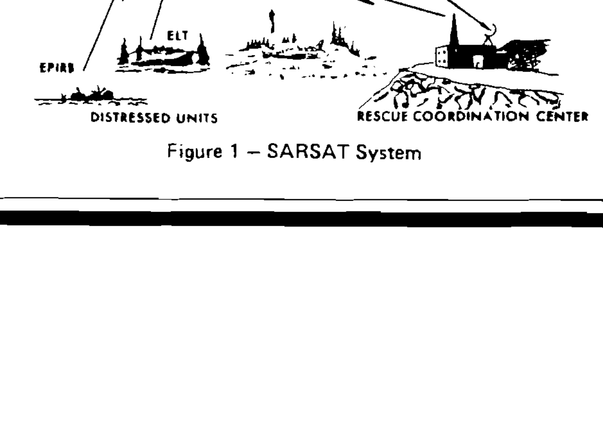

Figure 1 – SARSAT System

beacon system. This trilateral program, designated SARSAT, has been approved by the three countries and calls for a flight demonstration of the system commencing in 1982 using suitably instrumented operational satellites operated by the National Oceanic and Atmospheric Administration (NOAA).
The SARSAT system will consist of placing instrumentation on-board three spacecraft of the TIROS-N series of NOAA operational environmental satellites. Canada will furnish the communications repeater for receiving distress signals in the 121.5, 243 and 406 MHz bands and for real time relay of the search and rescue (SAR) data to the ground at 1543 MHz. France will provide a spaceborne processor for on-board processing of the signals received from the experimental 406 MHz ELT/EPIRB's. The 406 MHz spaceborne processor will detect these signals, measure the doppler frequency, and this doppler information together with the SAR message from the 406 MHz ELT/EPIRB will be fed to the real time 1543 downlink and will be recorded in parallel on-board the NOAA satellite.

Due to the low power (75 milliwatts) and modulation techniques being employed by the existing ELT/EPIRB's operating on 121.5 and 243 MHz, the processing of these signals will be accomplished on the ground. By employing four local users terminals located at Scott Air Force Base, Illinois; San Francisco, California; Kodiak, Alaska and Ottawa, Canada excellent coverage (Figure 2) of the U.S. and Canadian inland areas and large portions of the maritime regions can be achieved. Figure 3 shows the areas of SAR responsibility for the U.S. and Canada. The local user terminal (LUT) concept uses small antennas driven automatically to track the satellite by a mini-computer program. As the satellite is in view of both the distress transmitter and the ground terminal, the ELT/EPIRB signal would be detected and tracked to extract the doppler data which would then be used to calculate the position of the distress incident. A minimum of four minutes of mutual visibility of

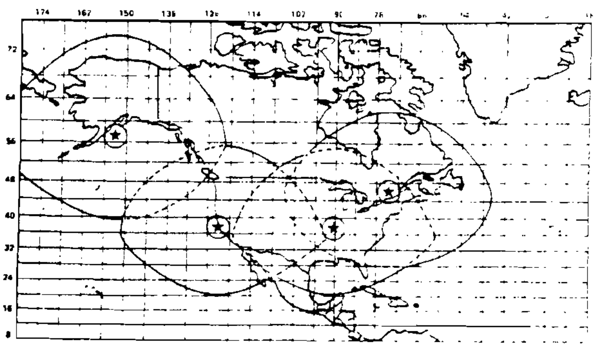

Figure 2 — SARSAT Ground Coverage Contour With Four Local User Terminals

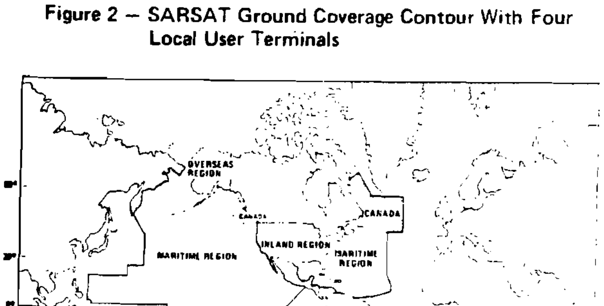

Figure 3 — Search and Rescue Areas of Responsibility for the United States and Canada

distress transmitter, LUT and satellite is required to obtain a location by doppler tracking (six to ten minutes of data are better). Depending upon the stability of the ELT/EPIRB oscillator, the effect of the earth's rotation upon the doppler frequency can be used to resolve the location of ambiguity. If not, a second satellite pass or other apriori information can be effectively used to resolve the ambiguity.

The operation of the system is depicted in the data flow diagram (Figure 4) of the SARSAT demonstration. The ELT's and EPIRB's in all three bands will transmit their signals to the orbiting spacecraft. Within each band, there can be one or more simultaneous ELT/EPIRB emissions as well as other non-ELT/EPIRB emissions. The spacecraft instrument will multiplex each band into a composite signal and relay the composite signal, in real time, to the LUT's.

In addition the spacecraft instrument will partially process signals from 406 MHz ELT/EPIRB's on-board the spacecraft. In this mode, the spacecraft instrument will look for and accept only valid ELT/EPIRB 406 MHz emissions and subsequently determine the identification of the user and measure the frequency of the doppler-shifted signal. The doppler frequency measurement, appropriately time tagged and including the SAR message, will simultaneously be transmitted in real time and also stored on-board the satellite for later transmission to the NOAA ground station. This approach will allow the 406 MHz ELT/EPIRB's to be received and partially processed when the satellite is not in view of a LUT, thus providing a total global coverage. The partially processed data will be stored for subsequent readout and transmission to the U.S. Mission Control Center (MCC) co-located at the Scott Air Force Base Inland Rescue Coordination Center near St. Louis, Missouri.
At the LUT the composite signal from the spacecraft will be demultiplexed into the three individual bands. Each ELT/EPIRB signal will be individually detected and processed to determine position location information, which will be displayed at the LUT control console for subsequent forwarding to the appropriate RCC where the SAR forces will be alerted and deployed.

The LUT's will use a three meter diameter parabolic antenna with program tracking of the satellite. The relayed ELT/EPIRB signals will be available for processing to determine the position location of the distress incident only when the satellite is mutually in view of both the ELT/EPIRB and the LUT. Note that, for the 406 MHz ELT/EPIRBs, in either the real-time or stored data mode, the data will be processed to compute the position location of the distress, to identify the person/vehicle in distress, and to display a message concerning the distress situation (e.g., ship on fire, sinking, or medical emergency) or the elapsed time from occurrence of the distress. The location accuracy for the 121.5/243 MHz ELT/EPIRB's will be 10 to 20 km; for the 406 MHz ELT/EPIRB's will be 2 to 5 km.

The concept for the future envisions the deployment of an operational four satellite system which would provide service for the existing ELT/EPIRB's operating at 121.5/243 MHz and allow for gradual phase-in of the 406 MHz ELT/EPIRB as new and replacement units are bought by the users. The 406 MHz experimental ELT/EPIRB system being developed by NASA in cooperation with the FAA and the Coast Guard will be designed to allow for encoding the country of origin, class of user, identification of the user and, as options, a situation code or elapsed time indication. The experimental 406 MHz ELT/EPIRB will also be designed with sufficient power such that if an operational system in the future were to utilize synchronous satellites they would be compatible for detection purposes. Also, recognizing that the SAR forces currently employ 121.5 MHz direction finding equipment for locating the distress, this frequency will also be built into the experimental ELT/EPIRB units.
The first spacecraft equipped with SAR instrumentation will be the NOAA-E spacecraft scheduled for launch in the first quarter of 1982. Because the NOAA spacecraft are launched on a replacement basis as required for the NOAA mission, the NOAA-E spacecraft could be launched as early as the first quarter of 1981

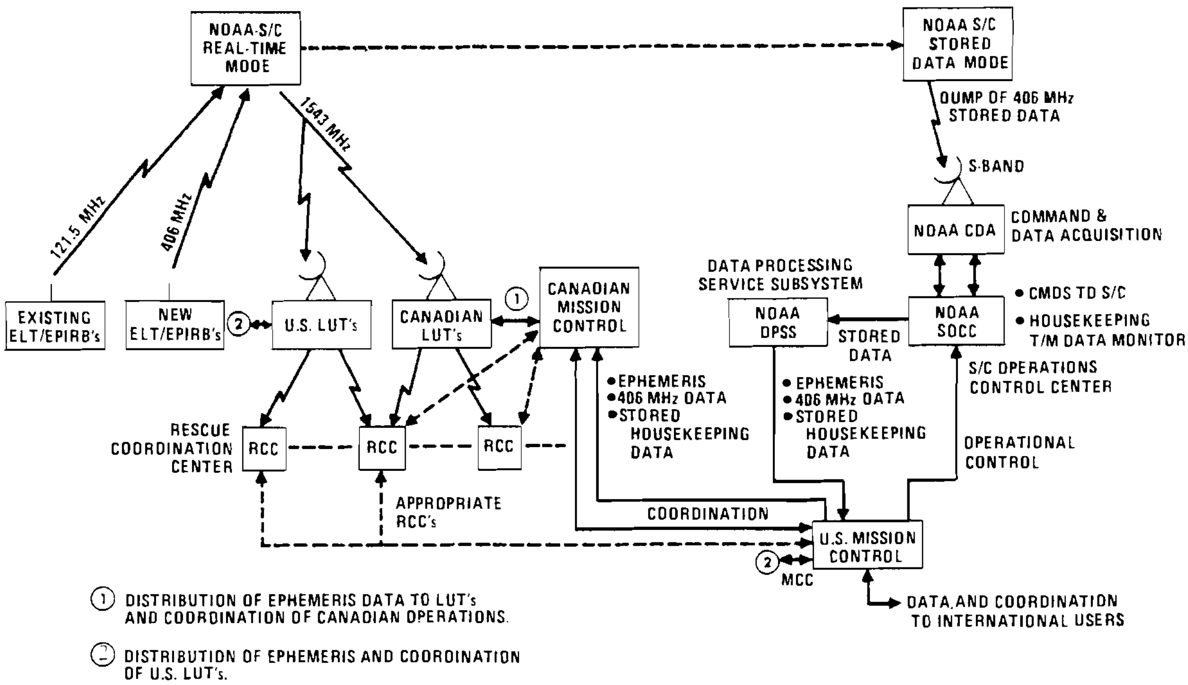

Figure 4 — SARSAT Data Flow for Normal Operations

or somewhat later than the projected launch date. The first three months after launch will be used for a technical checkout of the SAR system after which the system will be turned over to the U.S. Air Force and the U.S. Coast Guard for hands-on demonstration and evaluation. It is planned for the U.S. Coast Guard to operate the LUT's at Kodiak, Alaska and San Francisco, California and for the U.S. Air Force to operate the MCC and LUT at Scott Air Force Base. The use of SARSAT by the SAR Mission Agencies to detect and locate real distress incidents operating on 121.5 and 243 MHz and the simulation of distress incidents using the 406 MHz system should allow for a practical evaluation of the effectiveness of the satellite system.

The joint U.S./Canada/France (U/C/F) SARSAT demonstration project has attracted interest from other countries including the USSR, Norway, Australia, and Japan. The USSR recently met with the joint SARSAT parties to discuss a cooperative program whereby the USSR would place SAR instrumentation on one or more satellites of the "Meteor" class, and each country would use both the U/C/F satellite and the Soviet satellite to demonstrate the satellite-aided search and rescue capability. The participating countries would exchange data on the results of the demonstration/evaluation. Details on the exact nature and extent of a cooperative program with the USSR should be determined at the next joint working group meeting scheduled for early 1979.

The major benefit from any satellite-aided distress alerting and locating system will come from saving of lives. Operational savings from improved equipment and manpower utilization, although quite significant, would be smaller relative to the saving of lives. In addition to the saving of lives, a satellite-aided distress alerting and locating system has the potential to reduce costs incurred by civilian and military aircraft and ships searching for downed aircraft over land regions and for ships in distress on the high seas. It is also estimated that a significant dollar value of property damage would be avoided through improved rescue and salvage possibilities for commercial ships at sea. In summary, prompt notification of distress to search and rescue units can make a difference in life or death of aircraft and ship occupants. The advantage of using satellites to monitor large geographic areas holds great promise for reducing the time between occurrence and detection of a distress incident. In addition, the ability of a satellite system to provide a distress incident location will improve the efficiency of mission planning and operational response.

It is envisioned that an operational satelite-aided SAR system would employ four satellites in equally spaced near polar orbits. Such a system would provide an average waiting time in the continental U.S. of 1 hour with a maximum waiting time of four hours. In Alaska the waiting time would be 43 minutes average and three hours maximum. The use of geosynchronous satellites to provide alerting would reduce the alert time to the SAR forces to a few minutes with the later provision of location from a low orbiting satellite.

It is concluded that satellites should be employed to overcome shortcomings in the facilities for SAR purposes and to improve alerting, communications, and position determination in distress situations. To this end, geostationary and polar-orbiting satellites appear to have complementary properties with respect to service capabilities and coverage. The capability of geostationary satellites to relay instantly alarm signals with identification from alerting devices (ELT/EPIRB's) will be important when normal communications fail. Synchronous satellites appear to be beneficial to the maritime community world-wide in regions probably below 60°-70° latitude and may be of some benefit to the aeronautical community in regions below, say, 40°-50° latitude. The capability of satellites in a low polar orbit to monitor and locate existing EPIRB's and ELT's at intervals may enable a significant improvement to be demonstrated by the SARSAT project and could pave the way for a truly international operational system for the benefit of mankind.

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An Overview of the Canadian Experience with Emergency Locator Transmitters

Terry W. Heaslip and Max Vermij
Aviation Safety Engineering Aviation Safety Bureau
Department of Transport

INTRODUCTION

In the last few years the Canadian Department of Transport (DOT), the Military, and the aviation industry have become very concerned with the poor performance of the emergency locator transmitter (ELT). According to DOT statistics the ELT is less than 30% effective in the location of aircraft accidents and search and rescue (SAR) statistics fix the effectiveness of the ELT at 20% in air distress cases. The 17,000 ELT's with lithium battery packs carried in Canadian aircraft a few years ago, which were then considered a mandatory and vital part of the aircraft's survival kit, can now only be transported in an aircraft when packaged and labelled as "dangerous cargo".

This paper will describe the Canadian experience with the ELT. The ELT's history, reasons for its failures, its crash survivability and its role in search and rescue will be explored. Using Aircraft Accident Investigation (ASI) and SAR statistics and data from our Aviation Safety Engineering Facility (ASE) the ELT's performance as part of the search and rescue

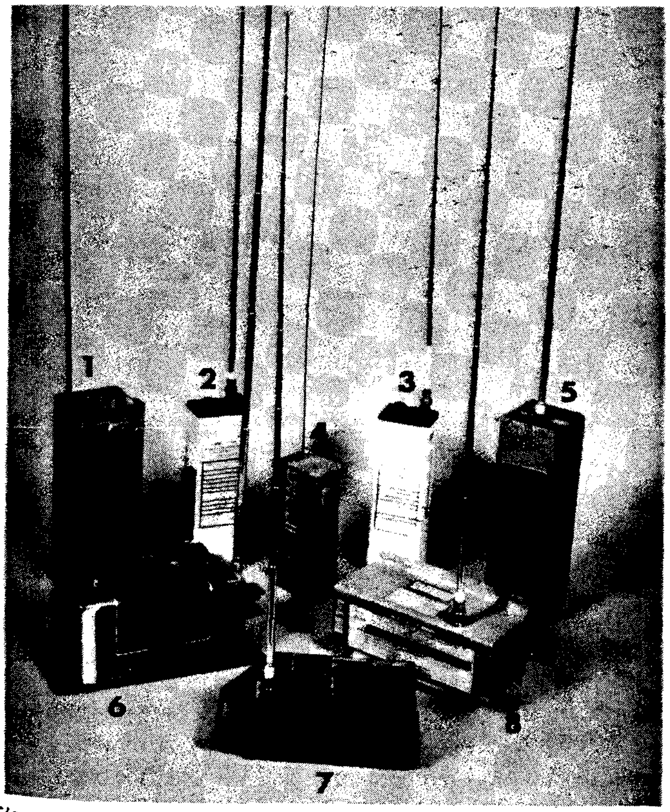
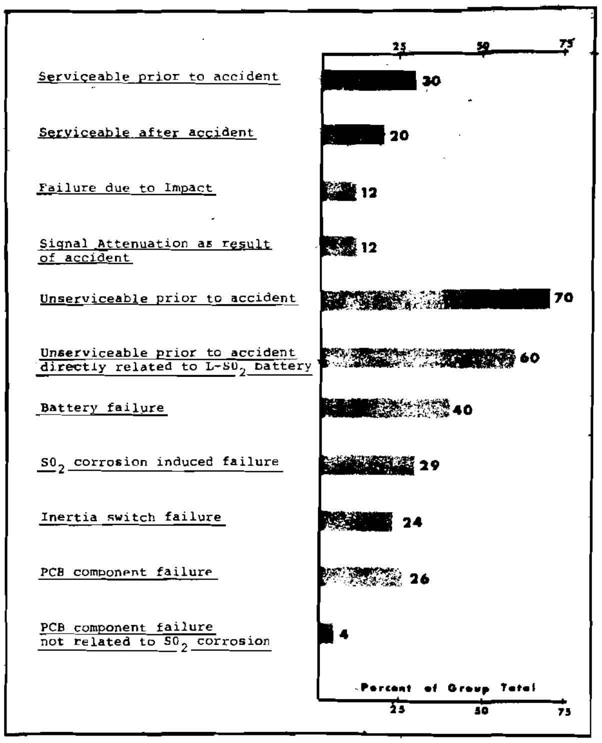


Figure 1:
A selection of emergency locator transmitters (ELT) typically found in Canadian general aviation aircraft. 1: Narco 10C; 2 and 3: Rescue 88; 4: Dart II; 5: Sharc 7; 6: Dorne and Margolin; 7: Pointer C4000; 8: Communication Component Corporation.



ELT Failure Modes of ASE Sample Group

Figure 2: Relative frequency of the various ELT failures encountered at the ASE Facility.

system will be examined. A better view of the areas of concern is gained through this systems approach. Of the five incidents recorded by ASE, where the ELT constituted a danger to the aircraft and/or its occupants by exploding or venting lithium batteries, three will be briefly discussed here. Data from SAR has been examined to acquire information about the ELT as a cost effective device. Figure 1 shows a collection of makes and models of ELT's encountered at the ASE Facility.

ELT HISTORY

Of the various failure modes of ELT's encountered at our Engineering Facility, two stand out. They are battery failures and failures due to SO_2 corrosion which is directly a result of the lithium - sulphur dioxide battery. It is now a well known fact that the lithium battery was (and still is) the major cause of ELT failures.

The lithium battery was chosen by the industry as the standard power supply for ELT's as the result of the minimum standard requirements layed out by DOT which required that the ELT be fully operational at temperatures down to 40° C below zero. Forty degrees below zero is a typical winter temperature for large regions in Canada and is generally believed to be the lowest temperature at which an unsheltered individual has a chance of surviving a 24 hour period. DOT postponed the compulsory compliance to these minimum standard several times during the ensuing years. Until September 1977 when these minimum standards were waived together with an airworthiness directive ordering the removal of all lithium batteries from Canadian registered aircraft.

The lithium battery was and still is the only practical primary battery which can supply the necessary power to operate the ELT transmitter for the duration and temperature range layed out in the original minimum standards. Its advantages over other type of primary and most secondary batteries are:

1) Very high cell voltage. (More than 3 volts)

2) Very long shelf life

3) Very high power to weight ratio

4) Very high energy to weight ratio

5) Very good low temperature characteristics

6) Moderate cost

Two types of lithium batteries which could satisfy The Canadian minimum standards were available at the time. Lithium Thionyl-Chloride ($LiSOCl_2$) batteries which are widely used in Pacemakers and very large emergency power installations and lithium sulphur dioxide ($LiSO_2$) batteries which were used in space applications. The industry chose $LiSO_2$ battery, because the space applications requirements had already produced a battery of the right size and power rating and little or no further development seemed to be required. But the $LiSO_2$ cell had a number of serious disadvantages at that time of which the industry was only partly aware:

1) Outgassing of sulphur dioxide (SO_2) which is a serious corrosive agent when it can react with moisture. Outgassing occurs due to internal vapour pressures and soft sealing. Excessive loss of SO_2 will deplete the cell.

2) Very high internal vapour pressures which increases dramatically with temperature:

   32 PSI at ambient 20°C
   180 PSI at 160° F 70°C
   415 PSI at 212° F 100°C

   Therefore temperature will accelerate the SO_2 loss.

3) Reverse current sensitivity. This can easily occur in a typical ELT battery configuration and can drive the internal temperature up and consequently the pressure of the cell to explosive proporations.

4) Lithium metal burns vigorously in air at 180°C. 1 gram of lithium burning in 10 seconds can produce 5000 watts of power.

5) Venting of the lithium cell which it is intended to do when the internal pressure reaches a design limit, causes the expulsion of SO_2 in large quantities. SO_2 is a disabling toxic gas.

6) A depleted $LiSO_2$ cell can produce a fair quantity of cyanide after it has been discarded.

Most of these undesirable characteristics of the $LiSO_2$ cell displayed themselves after the cell was generally accepted as the ideal power source for the ELT. When refering to lithium batteries or cells in this paper $LiSO_2$ batteries or cells are assumed.

Figure 2 is a bar-graph of the various failure modes of the ELT's examined at the ASE facility over a 6.5 year period. These are all failures as noted during examination or investigation. Often several different failures were detected in a single ELT, e.g. the failure of Inertia switch could have been caused by SO_2 corrosion which also caused damage to the circuit and originated in the battery which may have been depleted. The extent of SO_2 corrosion as the initial failure mechanism is clearly demonstrated by the two entries for PCB component failures. It is also shown in this graph that 85% of all ELT's that were unserviceable prior to the accident were so due to the presence of a $LiSO_2$ battery pack. This means that if a trouble free battery pack existed, that performed in accordence with the minimum standards, ELT's would be better than 90% reliable. For example Figure 3 is typical of advanced SO_2 corrosion damage to a printed circuit board and its components.

Table I shows, how a number of failure modes varied from year to year. The last entry shows the introduction and usage of $LiSO_2$ batteries. It is evident from this table that the first adverse effects of the lithium battery were felt in 1976 and continued unabated to the present.

TABLE I ELT FAILURE MODES BY YEAR

FAILURE MODE OR STATUS	74	75	76	77	78	79*	ALL 6.5 YEARS
Serviceable prior to Accident, %	43	75	30	19	60	27	30
Serviceable after Accident, %	14	50	25	13	60	7	30
Failure due to Impact, %	14	25	35	16	0	20	12
Signal Attinuation as a result of Accident, %	29	38	10	3	20	0	12
ELT's with Li-SO_2 batteries received, %	0	63	85	97	100	27	71
Unserviceable prior to Accident, %	57	25	70	81	40	73	70
Battery Failures, %	0	0	50	52	40	40	40
Failure due to SO_2 Corrosion, %	0	0	45	35	20	27	29
Failure due to Inertia Switch, %	43	57	25	35	16	0	24
Failure due to PCB Component, %	14	0	15	32	20	27	26
Failure due to PCB Component but not Related to SO_2 Corrosion	14	0	5	3	0	0	4

* FIRST HALF OF 1979

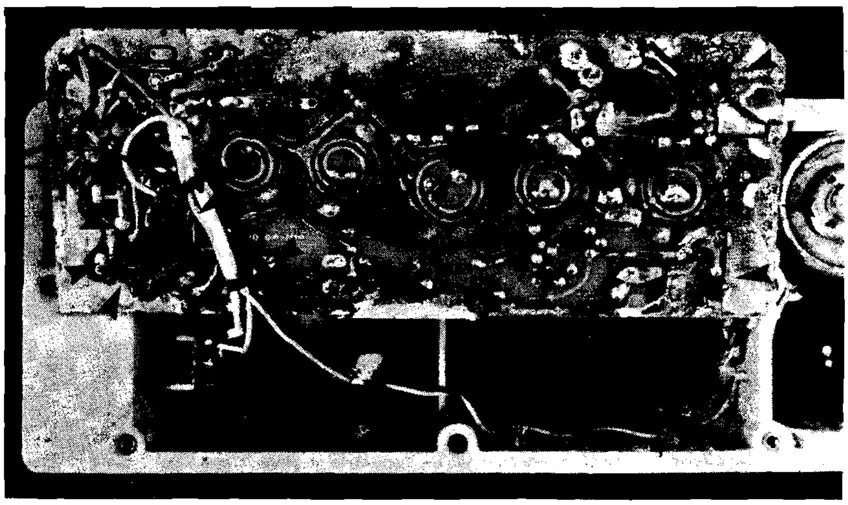


Figure 3: Typical PCB damage due to SO² induced corrosion.

Table II reflects the adverse effect of the lithium battery on the various makes and models that are in service. ASE has encountered nine different ELT makes.

TABLE II SOME FAILURE MODES BY ELT MAKE

MAKE	EXAMINED AT ASE	FAILURE DUE TO SULPHUR DIOXIDE CORROSION	FAILURE DUE TO INERTIA SWITCH
NARCO	13%	9%	0%
POINTER C4000	10%	33%	0%
RESCU 88	27%	22%	4%
SHARC 7	37%	47%	53%
OTHERS	13%	9%	9%
ALL	100%	29%	22%

NOTE: The five makes: Dorne and Margolin, Dart II, Emergency Beacon Corporation, Paracon and Communication Components Corporation were all less than 6% and are therefore grouped into one.

AVIATION SAFETY ENGINEERING DATA

A number of different types of inertia switches were used in the ELT's examined. Three of the most widely used ones which are shown in Figure 4 will be briefly discussed here. Switch 1 and 2 are of a type which can be in the closed position only during the short period that the inertia force exists. Therefore these switches work in conjunction with a holding transistor (SCR) which "holds" the transmitter in the "ON" position after impact, when the contacts of the Inertia switch are open again. Switch 1 works with an inertia mass, a coil spring and a set of contact points. Switch 2 is different in that the spring is replaced by a small permanent magnet which holds the inertia mass (a gold plated steel ball) away from the contacts. The Canadian minimum standards give exact specification as to the impact forces these inertia or "G" switches should close approximately 6 "G" for 15 milliseconds duration. A different type of "G" switch, one that does not require a holding transistor is shown in Figure 4 as switch 3. Here the inertia mass (the brass hollow cylinder) is held by a blade spring wrapped around it. Another blade spring is held, buckled, close to the two contacts. When impacted the inertial mass will cause the blade spring to buckle in the other direction when it will close the contacts and remain in this position. The inertia switch can only be deactivated when a force in the opposite direction is applied to the blade spring. A "Reset" button is provided for that purpose. Figure 4 shows the switch in the deactivated position.

The Sharc 7 ELT appeared to be the most sensitive one to SO_2 corrosion. This is for two main probable reasons. First, its large rather flexible casing, under the influence of significant varying atmospheric pressures as in A/C application can allow moist air to enter the interior at a regular basis. Unfortunately H_2O and SO_2 combine to form H_2SO_3 which is sulphurous acid and highly corrosive. Second, the inertia switch of the Sharc 7 has a sealed polymer casing that is permiable to SO_2. SO_2 can react with various

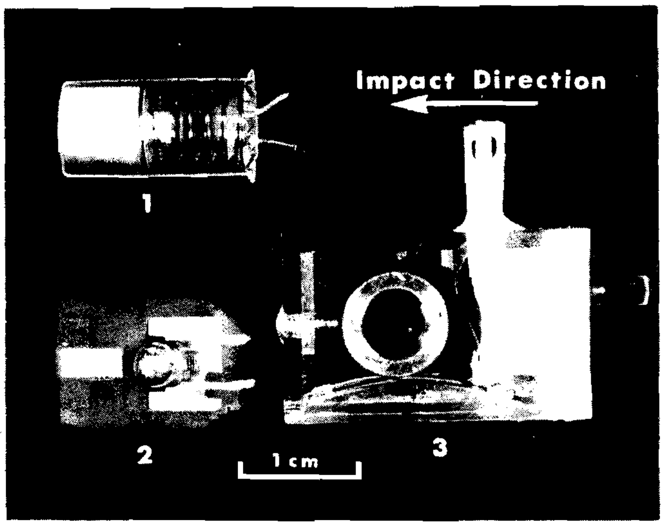


Figure 4: Cross-sectional view of three main inertia switches.

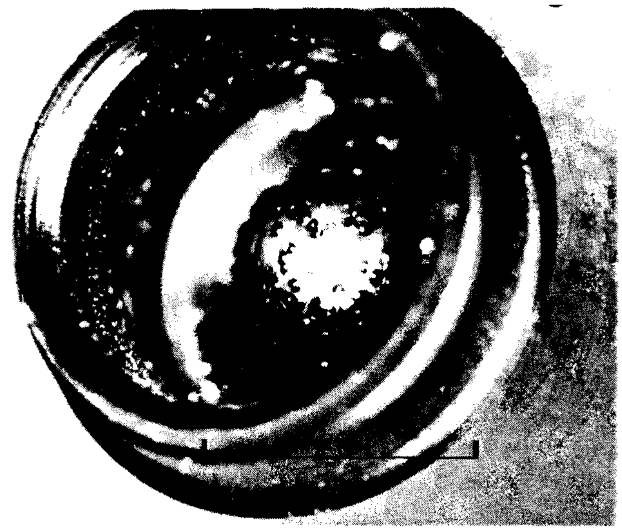


Figure 5:
Close-up view of the interior of an inertia switch showing droplets of a sulphurous compound on the gold plated steel ball (inertia mass).

organic molecules of the plastic casing to form a sulphurous compound which deposits itself in the interior of the Inertia switch. Evidence suggests that SO_2 and/or SO_3 have an affinity for a magnetic field and/or voltage potential field. Sulpherous compounds were also found to be conductive. This SO_3 compound can disable the inertia switch in two distinct ways. Its adhesive properties can effectively cement the inertia mass to the casing rendering the switch insensitive to even very high "G" forces. Or its conductive properties can short out the contacts, causing the ELT to activate. It is believed that a large percentage of inadvertent ELT activations can be contributed to this mechanism.

Figures 5, 6 and 7 show the various ways the Sharc 7 inertia switch can be affected by SO_2 corrosion. It should be noted that 22% of the Sharc 7 ELT's examined carried magnesium batteries. Therefore the actual failure rate due to SO_2 corrosion of Sharc 7 ELT's carrying $LiSO_2$ batteries was 60%. There is also another failure mode independent of SO_2 corrosion. The contact wires were cemented in position and could easily be loosened by bending stresses introduced during the installation of the switch on the PCB. Figure 8 shows how the switch is disabled in this manner.

The Pointer C-4000 and Rescu 88 ELT's cases were also found to be susceptible to atmospheric pressure changes, but not to the degree that the Sharc 7 was found to be. The Narco ELT 10C was the sturdiest with respect to pressure changes. It appeared that sensitivity to corrosive failure was a direct reflection of container design. It must be pointed out that an ELT case was only required to withstand short term water immersion. The inertia switch in the Rescu 88 is a metal cased glass sealed unit, shown in Figure 4, which is impermeable to SO_2. However a number of shorts were found on this unit too. In this case the problem is on the outside of the switch where the contact wire enters the unit through the glass seal as can be seen in Figure 9. The physical dimensions of the switch are quite small and the distance between the two contacts at the glass insulation is only .005 inch. This distance is apparently easily bridged by a sulphurous compound and inadvertent activation is the result. The Inertia switchs in the Narco and Pointer ELT's, (Switch 3 in Figure 4) are of the holding type

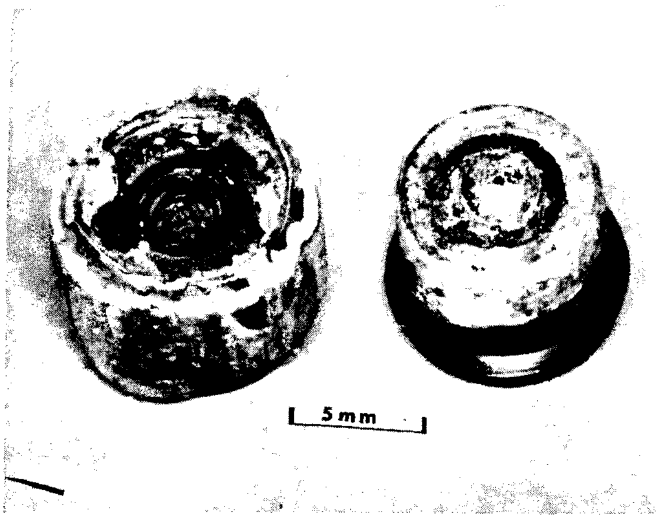


Figure 6:
the interior of an inertia switch showing more advanced SO^2 induced corrosion damage.

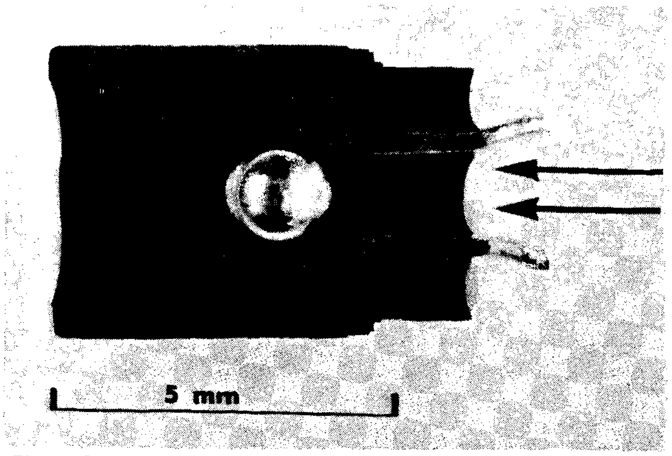


Figure 8:
Cross-section of an inertia switch with one contact pin too short.

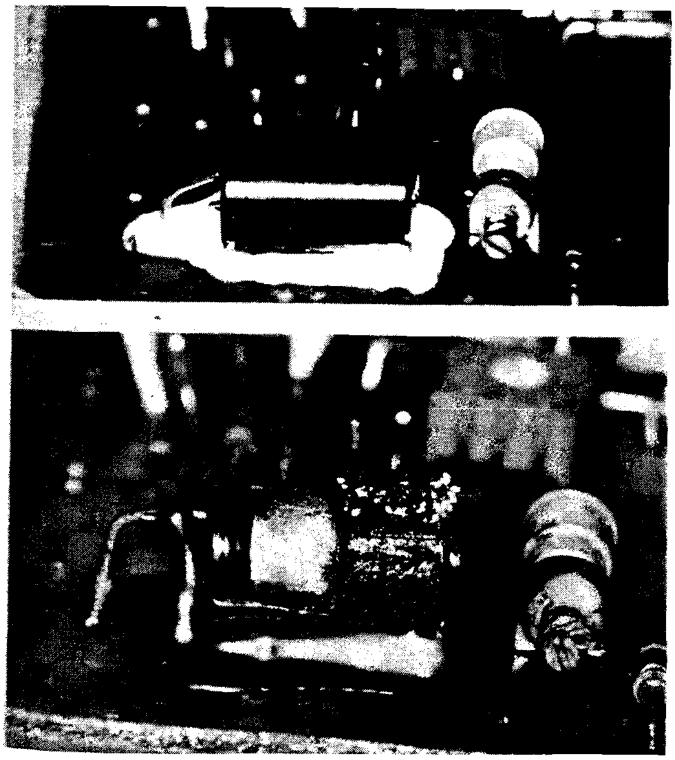


Figure 7:
The top photograph shows an undamaged inertia switch in position on the PCB. The bottom photograph shows the same type of switch damaged by SO^2. Most of the plastic casing has been leached away.

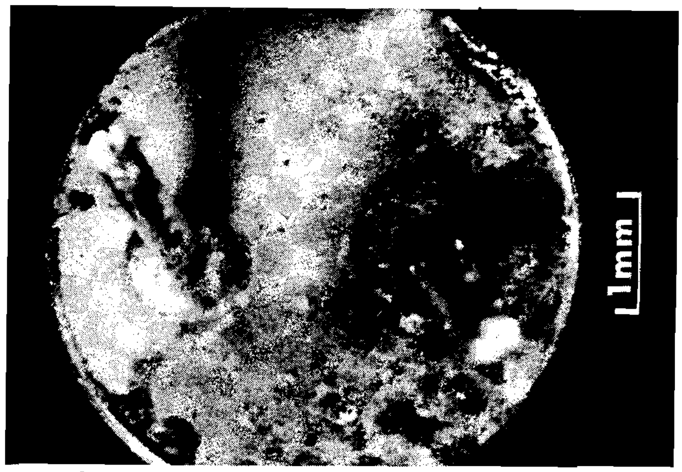


Figure 9:
The end cap of a metal cased inertia switch (switch 1 in Figure 4) showing SO^2.

Figure 10:
Exploded ELT (Narco 10C) as received at ASE showing damage to casing and original location of projectiled cell container.

and have never been found to be unserviceable or susceptible to SO_2 corrosion.

During 1977 two battery explosions and one battery venting which forced the occupants to evacuate the aircraft were reported to the Aviation Safety Bureau. This prompted Airworthiness Engineering to issue a directive ordering the immediate removal of all lithium battery powered ELTs from Canadian registered aircraft. Together with this directive a temporary waiver from all ELT requirements was issued.

The first battery explosion occured in a Narco ELT 10C which was stored in the basement of the residence of the owner. One lithium cell casing exposively broke through the ELT case. The cell casing reportedly exited the ELT with such force that after ricocheting off a cement wall it penetrated a standard laminated door to a depth of 3/4 inch before landing on the floor. It also ingited a number of small fires in its path. Figure 10 shows the ELT as received at the ASE Facility.

The second battery explosion incident occurred in an aircraft in flight. A Pitts Special was doing aerobatic maneouvers. When the Rescu 88 ELT located in the storage compartment behind the pilots head rest exploded. The explosion caused the compartment door/head rest to be forced out of its lock and hit the pilot on the head. Fortunately the pilot was not hurt and he was able to make a normal landing. As can be seen in Figure 11 the ELT's end cap was able to contain the cell case but burning lithium was spewed through the interior of the ELT causing severe burning on the PCB, see Figure 12. The intensity of the heat produced by burning lithium is evident from the damage to the inertia switch which has a steel casing.

The venting incident occurred in an aircraft with five people on board. Shortly before take-off the ELT ejected a large quantity of SO_2 gas. The pilot informed the tower of a Mayday situation and evacuated the occupants from the aircraft. The fire department on the scene required gas masks and asbestos gloves to remove the hot ELT from the aircraft. It was largely luck that these three incidents did not end tragically.

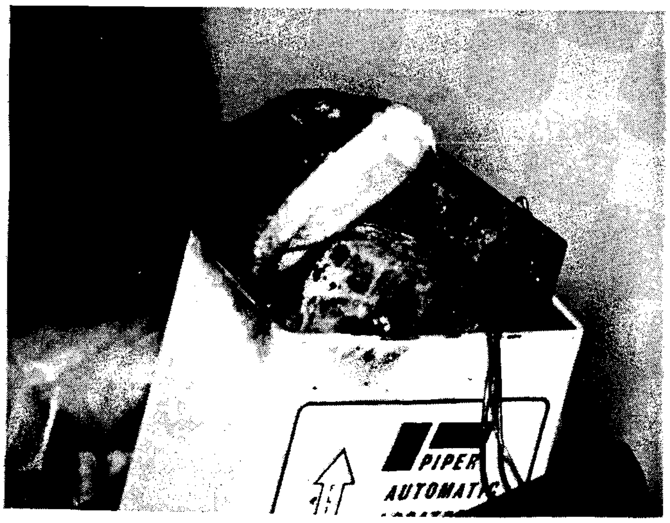


Figure 11:
Exploded ELT (Rescu 88) as received at ASE showing the protrusion of the exploded cell.

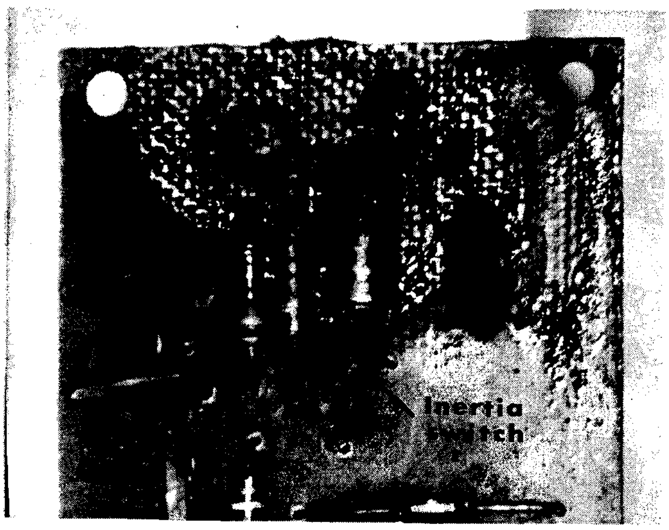
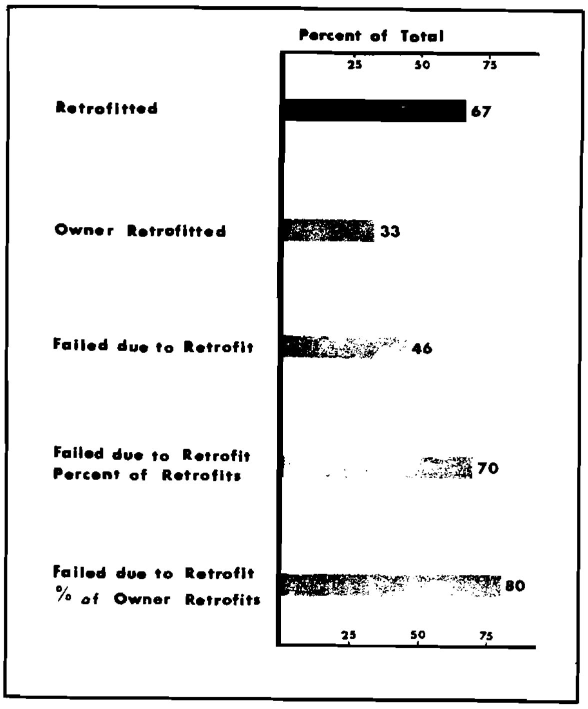


Figure 12:
Damage due to lithium burning to PCB and inertia switch of ELT shown in Figure 11.

In February 1978 a new airworthiness directive (AD) was issued. This AD had a more constructive content in that it suggested and approved a number of short and long term solutions for the ELT owner. It was suggested that if an approved battery was not available for any specific model ELT the owner could retrofit a battery pack of his own design. Some guidelines were provided as to the method of installation and choice of batteries.

In the beginning of 1979 the ASE Facility started to receive ELT's which were retrofitted by the manufacturer or owner in compliance with this AD. It was soon noted by ASE that the retrofitting of ELT's had created a new series of problems. Figure 13 shows the effects of retrofitting on ELT failures. A number of ELT's started to corrode badly after the retrofitting while prior to the retrofit and with lithium batteries the unit was just fine. What seemed to have happened is the following. Prior to the retrofit the unit was well sealed and its interior was relatively free of moisture. However the SO_2 outgassed by the battery combined with unknown molecules from the various polymers or residual soldering rosins to form a SO_2 compound. This compound is believed to be a relatively clear liquid and probably non-corrosive. Therefore when the unit was opened to change the battery and examined for corrosion the interior of the unit seemed to be clean and free of any corrosion deposits. It was apparently assumed that no SO_2 was present in the ELT. But during the retrofit (in a humid environment) moisture could easily have been introduced to the ELT. Now the SO_2 compound, still present in the unit, preferentially combined with H_2O to form H_2SO_3 compounds which are highly corrosive. Then when the



1979 Retrofitted ELTs

Figure 13: Bar-graph showing the effects of retrofitting ELTs with non-lithium batteries.

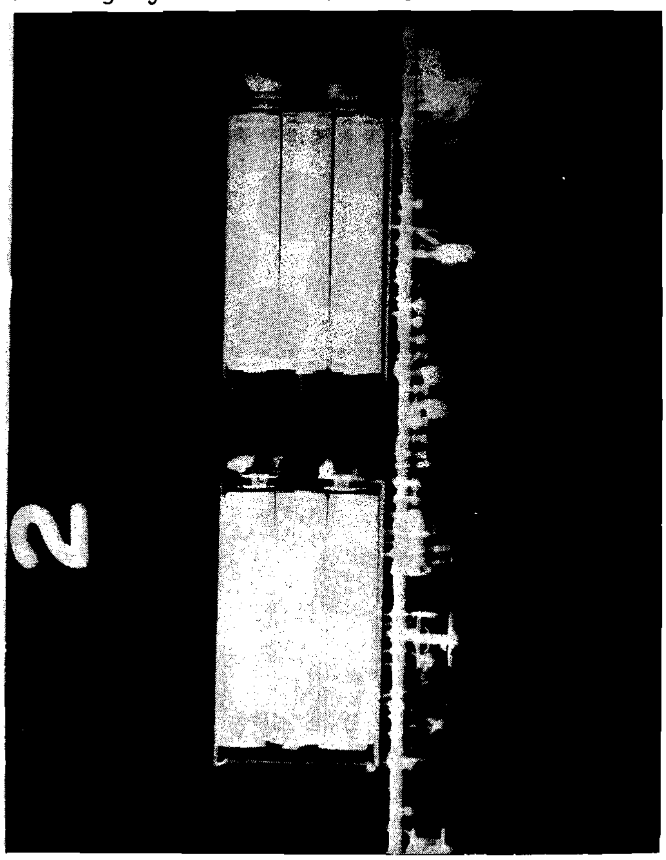


Figure 14: X-ray photograph of an "owner" retrofitted ELT (Rescu 88) showing the shorting of protruding PCB component wires with the battery casing.

unit was examined a time after the retrofit severe corrosion was discovered. It was then assumed that since this was "SO_2" corrosion it must have formed prior to the retrofit and the typical question asked was: "Why did the manufacturer, who performed the retrofit not see this obvious corrosive damage to the unit?".

Those ELTS that were retrofitted by their owner or maintenance workshop exhibited two typical problems. The first is shorting. An example of this problem is shown in Figure 14. Two 9 volt Alkaline batteries were fastened to the PCB with silicone cement which made a very sturdy mounting However the battery casing was aluminum and came into contact with a number of component connecting wires which protruded through the board as can be seen in the X-ray photograph. Figure 15 shows another case where, as a result of the retrofit, the ELT was damaged. Six 9 volt batteries were connected in parallel and taped together with electrical tape. In this case the electrical tape provided sufficient insulation from the PCB, but the battery "pack" was more than an inch shorter than the original $LiSO_2$ battery and therefore was loose in the ELT case. When the aircraft which carried this ELT crashed the inertia of the loose battery "pack" resulted in the pack impacting and breaking the function switch and antenna connection, rendering the ELT unserviceable. Finally Figure 16 shows a Sharc 7 retrofitted with a "clip" of four 1.5 volt Alkaline penlight cells, where one cell "jumped" out of the clip as a result of impact forces during a crash, causing the power to be disconnected.

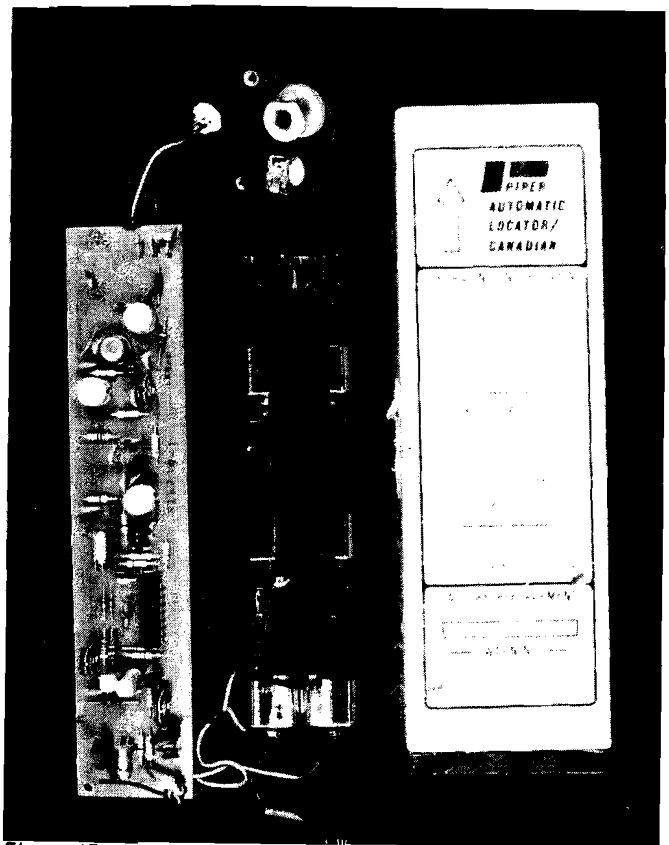


Figure 15:
A Rescu 88 ELT disassembled to show the "owner" retrofitted battery pack which could move in the casing. At impact this battery pack rendered the ELT unserviceable by breaking the on/off switch and antenna connection.

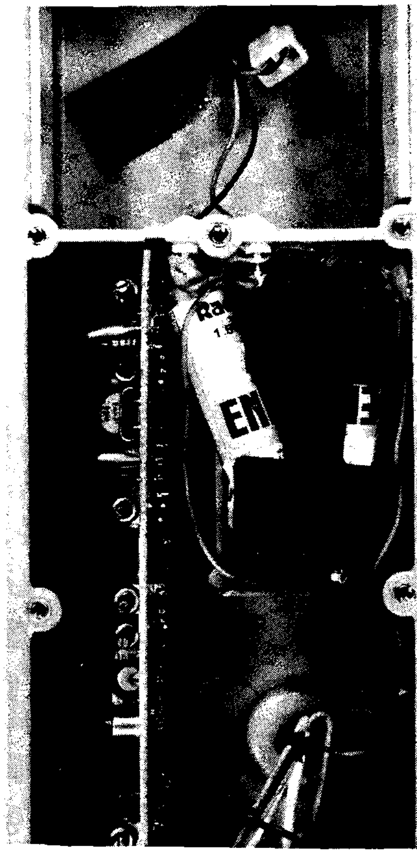


Figure 16:
The interior of a Sharc 7 ELT showing the "owner" retrofitted battery pack after impact. The penlight cell was dislodged from its clip by the impact force and rendering the ELT unserviceable.

SYSTEM ANALYSIS

The ELT which is conceptually a simple device becomes much more revealing and complex when analysed as part of the ELT Search and Rescue (SAR) System. The flow diagram in Figure 17 shows the complete ELT/SAR system in block form. Here it becomes clear that what originally was thought of as a single device "the ELT" is really a sub-system consisting of 6 different elements. Another sub-system consisting of 3 elements represents SAR, DOT and General Aviation. The two sub-systems are labelled transmission and receiving systems. The failure of any one of the elements in the system will cause total failure of the system. Except in the first three elements where some conditional redundancy is present, e.g. the pilot (if able) can override an inertia switch failure or an insufficient impact. Total failure of the system means failure to locate the aircraft in distress by means of its ELT signal.

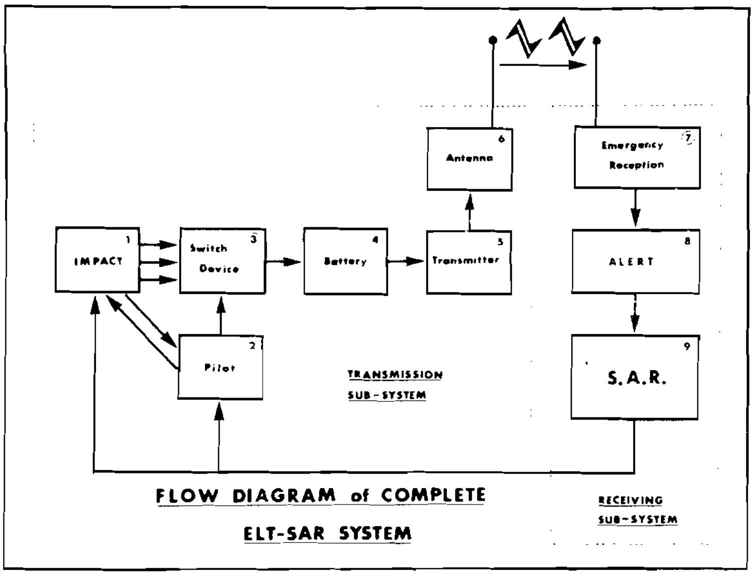


Figure 17: The ELT - Search and Rescue System.

In the ELT - SAR system, impact failure means all impacts that either damaged the ELT or were too weak to affect it. Pilot failure means the negligence of the pilot or owner to monitor the ELT properly or to install one in the aircraft. Switch device failure means the failure of the Inertia switch, the function switch or the SCR holding transistor. Battery pack failure means the failure of the battery to provide power for the transmitter or the damage to other system elements resulting from the battery outgassing, venting or exploding. Transmitter failure means all failures of any transmitter components, resulting from manufacturing or maintenance faults. Antenna failure means the failure to radiate a traceable signal due to terrain or wreckage signal attenation or an unserviceable antenna not related to impact damage. Emnergency reception failure means the failure of the operational aircraft population, DOT or SAR to pick up a real ELT signal. Alert failure means the failure of the operational aircraft population or DOT to inform DOT and/or SAR of the distress signal. SAR failure means the failure of a SAR and/or DOT search to locate the real ELT signal. Figure 18 is a bar-graph that shows the degree to which each element in the ELT-SAR systems was responsible for the systems failure over approximately the last five years. The ELT - SAR system Flow Diagram (Figure 17) and the System Element Failure Graph (Figure 18) shows clearly that the Transmission sub-system is responsible for 99% of all system failure. Considering the operating cost of each sub-system this is not surprising. The Transmission sub-system represents less than one million dollars in yearly effort, while the Receiving subsystem has a yearly budget of 20 million and can tap emergency resources from all over the country.

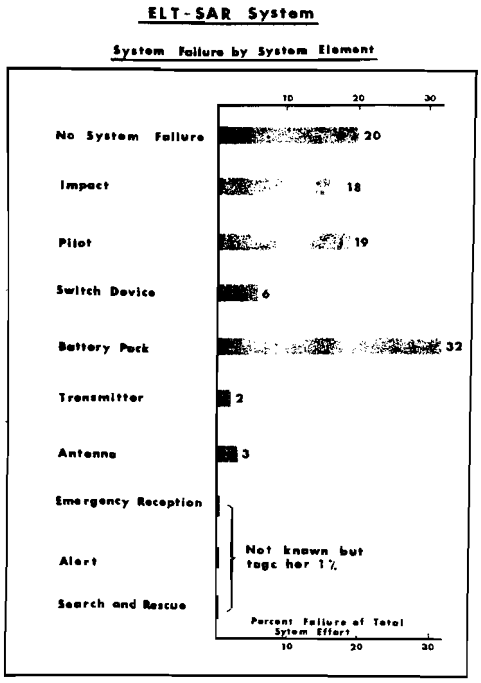


Figure 18:
ELT - SAR System failures acquired from Engineering (ASE), Accident Investigation (ASI) and SAR data.

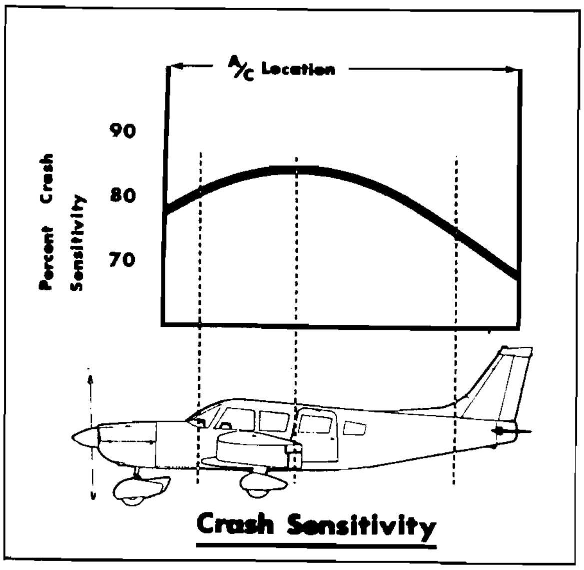


Figure 19:
Crash Sensitivity of the ELT as a function of its location in the fuselage (from ASI data).

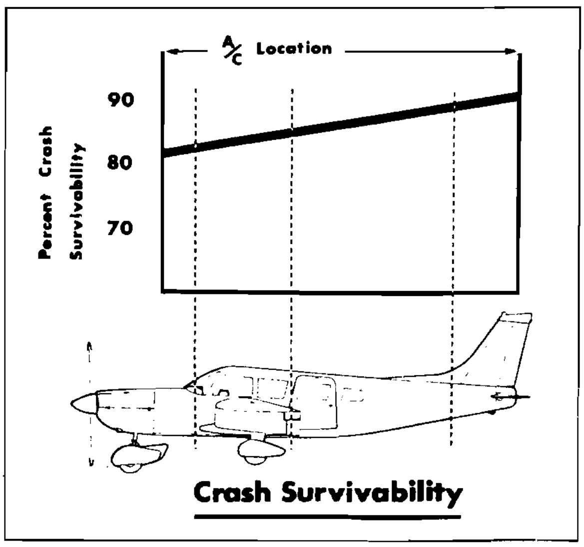


Figure 20:
Crash surviviability of the ELT as a function of its location in the fuselage (from ASE data).

ACCIDENT INVESTIGATION DATA

Data extracted from the accident files of the last 3.5 years gave the following information concerning the role of ELT's in accidents in Canadian airspace:

a) 8.5% of all Canadian aircraft accidents required some form of ELT location.

b) In 2.5% of all those accidents, an ELT signal was successfully used in the location of the aircraft.

c) 20% of those accidents which required ELT location were rendered unserviceable by impact related damage.

d) 50% of those accidents which required ELT location had a non-functioning ELT onboard, prior to the accident.

e) Therefore ELT location methods are only 30% effective and failures are almost entirely due to the aircraft system and largely due to the ELT's malfunctioning.

From accident data it was also possible to gain information concerning the effects of the mounting location of the ELT relative to the aircraft structure. It was found that the location of the ELT in the fuselage only had a moderate effect on crash sensitivity and crash survivability. Figures 19 and 20 show the findings from the data in graphical form.

SEARCH AND RESCUE DATA

Search and Rescue (SAR) which is operated by the Department of National Defence (DND) has maintained a large data bank on their search and rescue activities. Table III shows most pertinent ELT data over a 4.5 year period. It is shown that the share of the ELT in search activity is still only 20% over a 4.5 year period. It is clear that the role of the ELT dropped off sharply in 1978 which reflects the effects of the removal of ELT's from aircraft in compliance with the Airworthiness Directives concerning lithium batteries. A dramatic reduction in the number of false ELT Alerts was also noted and seems to carry right on into 1979.

TABLE III SEARCH AND RESCUE (SAR) ACTIVITY RELATED TO AIR DISTRESS CASES

	1975	1976	1977	1978	1979*
TOTAL AIR CASES	2538	2350	2171	1881	875
TOTAL AIR ALERTS	1210	1132	1004	564	310
REAL AIR CASES	174	140	149	172	68
REAL ELT ALERTS	22	25	19	11	12
REAL AIR CASES LOCATED BY ELT	37	36	35	16	13
% ELT CASES OF ALL REAL AIR CASES	21	26	23	9	19
REAL AIR CASES WITH ELT "ON"	54	50	48	23	15
REAL AIR CASES WITH ELT ON BOARD	108	93	108	74	32
FALSE ELT ALERTS	1188	1107	985	553	298
ELT ALERTS SUCCESSFULLY TRACED BY ANY MEANS	503	547	479	245	116
ELT ALERTS SUCCESSFULLY TRACED BY SAR AIR ACTION	232	243	229	113	58

TABLE IV SEARCH AND RESCUE (SAR) AIR ACTION HOURS

	1975	1976	1977	1978	1979*
TOTAL AIR ACTION HOURS	7310	7140	7830	7910	1720
AIR ACTION HOURS ELT ELT FALSE ALERTS	730	607	545	260	115
AIR ACTION HOURS	475	438	547	191	
AIR ACTION HOURS PER REAL AIR CASE	42	51	53	46	25
AIR ACTION HOURS PER REAL AIR CASE NOT INVOLVING ELTS	45	59	59	48	
AIR ACTION HOURS PER REAL ELT CASE	13	12	16	12	
HOURS PER REAL ELT CASE INCLUDING FALSE ALARM HOURS	33	29	31	28	
AIR ACTION HOURS SAVED PER REAL ELT CASE	12	30	28	20	
TOTAL HOURS SAVED	444	1080	980	320	

* FIRST HALF OF 1979

The Air Action hours distribution of SAR efforts are shown in Table IV. Also the hours per case which were calculated with data from Table III are shown. From this data the actual hours saved due to the ELT-SAR System could be calculated. Averaging over the 4.5 years tabulated, it becomes clear that ELT-SAR System, with all its problems and shortcomings affected a 10% saving in the cost of search and rescue. Some data from SAR could be compared with data from Accident Investigation giving the following results:

(a) SAR statistics show that the success of the ELT-SAR System in real air distress cases is 20% effective.

(b) Accident statistics show that the success of the ELT-SAR System in the location of aircraft accidents is 30% effective.

(c) 40% of all aircraft involved in real air cases did not carry an ELT on board.

(d) 21% of all aircraft involved in an accident did not carry an ELT on board.

DISCUSSION

The ELT was presumably introduced to the Search and Rescue system with two specific goals in mind. One, to reduce human suffering and two, to reduce the cost of the SAR system. This paper has not touched on the first goal for the obvious reason that it is a qualitative goal and cannot easily be translated into a quantitative form necessary for a meaningful analysis. However it has been demonstrated that despite the false alarms, despite the battery failures, despite the neglect of the pilot and despite the impact that is not just right and even in its worst days (1978) the ELT was and is a cost effective device. The ELT has saved money and lives ever since its introduction and will save a lot more when it's major problems are resolved.

From the system analysis it is clear that the major areas where improvements are needed are (1) the battery pack (2) impact (3) the pilot. At this time the battery industry has produced a hermetically sealed lithium battery that is supposed to have all the advantages of the past $LiSO_2$ cell and supposedly none of the disadvantages. This battery is being tested in the U.S.A. and will be tested against minimum standards here in Canada in the near future. However, it must be realized that any ELT which has at some time carried an old type $LiSO_2$ battery will have a drastically reduced life expectancy due to possible residual SO_2 compound deposits. These ELTs have to be replaced in the coming years, before it can be assumed that the problems created by the old lithium battery are behind us.

The desired improvements in the area of impact are: better impact sensitivity and crash survivability. These can only be affected by improving the design of the ELT and mounting package. In principle the location of the impact switch in the same container as the ELT transmitter and battery pack is not conducive to maximizing the above mentioned desired properties of the ELT. A provision could be made for the ELT to be activated by impact switches away from the ELT in areas of the aircraft structure where an impact can be better sensed, if so desired. However, portability and cost are also important considerations. Present minimum standards required the ELT to be able to withstand an impact force of 50

"G" over 25 milliseconds. The systems analysis here suggests that this is too low and that ELT's should be manufactured to withstand "G" forces closer to the typical severe impact forces of a crash.

The pilot should be made aware of the importance of the ELT in his transportation system. He should learn to realize that when he is down in unpopulated areas he becomes a burden on society and a costly burden at that (like the equivalent of a few years of welfare cheques per day) and this burden is there whether he cares for it or not. It has been demonstrated in this paper than the ELT is also a device which transfers very effectively some of the cost of search and rescue (actually while turning a profit) from the general tax payer to those who benefit the most from the system, this is the small aircraft owner/pilot. Therefore the pilot should not complain too much about the cost incurred by the past, present and future problems with ELT's. He should remember that a properly maintained ELT is very inexpensive insurance indeed.

The Emergency Locator Transmitter and the Investigator's Role in Safety Research

David S. Hall
Crash Research Institute
Box 968
Tempe, Arizona 85281

Background

An earlier speaker has described the National Aeronautics & Space Administration's (NASA) program to develop SAR-SAT, a satellite based search method for emergency transmissions from aircraft and ships in distress. As part of that effort, a major design task was undertaken for the electronics to be used on the aircraft Emergency Locator Transmitter (ELT) and the ship-borne type. This paper will discuss the development of data used to help design the installation, mounting and activiation criteria for this new ELT.

The original ELT was made mandatory by 1974 on most U.S. general aviation aircraft. It transmits on 121.5 MHZ and 243.0 MHZ and is activated by a switch designed to sense an acceleration pulse of 5G (+2/-0), for a period of 1 milleseconds or longer (Reg. A). These units experienced many problems in the field, including a false alarm problem wherein over 6,000 transmissions per year were not due to any aircraft distress. However, in many aircraft crashes, the unit did not transmit a usable signal when it was most needed. The Radio Technical Commission for Aeronautics (RTCA) at the request of the Federal Aviation Administration (FAA) wrote a new standard (Ref. B) which, among other things, specified a new crash pulse to be sensed. Based on studies of aircraft crashes and compilation of the average accelations of the whole aircraft, a crash pulse resulting in an acceleration of over 2G's and a velocity change of over 3.5 feet per second (fps) was selected for these changes, because several areas are still under study by RTCA. A detailed review of the history of the ELT is contained in Ref. C.

In an attempt to provide additional data for the development of a standard for the projected ELT (the 406 MHZ transmitter and satellite receiver system) NASA funded a detailed study of aircraft crash records. This paper discusses that study and, in particular, the quality of investigation reporting on ELT effectiveness.

THE STUDY

Althought the NASA study has many additional facets, a major portion consisted of the collection and analysis of detailed information from the U.S. and Canadian govemment files of aircraft accident investigation. The cases studied were all fixed wing, general aivation aircraft under 12500# gross weight. In order to select files with the most detail, the following source data sets were selected:

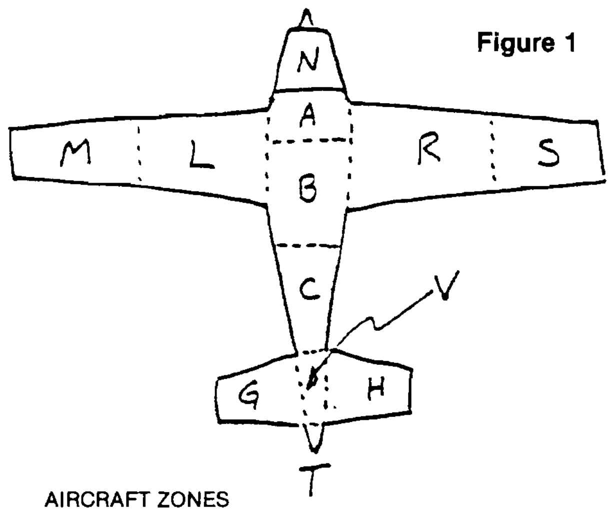
1. U.S.; Fatal; 1977. The most recent year with relatively complete files.
   U.S.; 1976, 1977, 1978 cases where the USAF
2. Search & Rescue Coordinating Center reported a successful ELT search.
3. Canadian; Fatal & Serious; 1976, 1977, 1978.
4. Canadian; Minor, No injury; 1976, 1977, 1978, where detailed ELT information was in the file.

For purposes of analysis, the follwing data sets were defined:

Basic File. (Groups 1 & 3 above) assumed to be a random set of accidents.
SAR File (Group 2 above)
ELT File. Any case where the ELT was known to operate and aid in search.

The bulk of the analysis was the interpretation of the photographic and narrative record to describe the aircraft damage in much greater detail. The aircraft was divided into twelve zones as shown in Figure 1, and each zone was described by the Location, Deformation and Attitude codes shown in Figure 2, as well as recording if the zone was involved in the fire.

Figure 1



AIRCRAFT ZONES

- N. Nose comp or engine/fwd of cabin bulkhead
- A. Instrument panel to bck of first seat
- B. Back of first seat to rear cabin bulkhead
- C. Tail cone from bulkhead to L.E. of horizontal
- T. Tail cone aft of horizontal
- R. Right wing from fuselage to mid wing
- S. Right wing mid to tip
- L. Left wing fuselage to mid
- M. Left wing mid to tip
- H. Right horizontal
- G. Left horizontal
- V. Vertical tail and tail cone below it

Figure 2 — Codes

LOCATION CODES

0 Unknown
1 Continuity of structure back to section A
2 Attached to next inboard section, but not back to A
3 Almost separated, most structural continuity gone
4 Separated Completely

DEFORMATION CODES

0 Unknown
1 Basically undamaged, minor dents and tears
2 Major dents, tears but still in near normal shape
3 Crushed/distorted/crumpled
4 Destroyed, pieces separated
5 Buried in wreckage/dirt/debris

ATTITUDE AT REST (PITCH OR ROLL)

1 ± degrees of upright/normal attitude in both pitch and roll
2 30 degrees — 90 degrees from normal in pitch or roll
3 90 degrees from normal (inverted)

CONFIDENCE LEVEL IN DATA

1 Estimated/guessed from photo or text
2 Clearly shown in photo
3 Detailed data in report
4 Personally observed at scene

Figure 3 Total File Contents by Injury, State & Year

Injury	State	C.Y. 76	C.Y. 77	C.Y. 78
Fatal	U.S.	26	572	36
Fatal	Canada	70	65	63
Serious	U.S.	3	3	2
Serious	Canada	55	48	38
Other	U.S.	8	10	8
Other	Canada	51	59	13

Basic Group Outlined

All of the data elements were subsequently coded and put into a computer file for analysis. The data discussed in this report is only the initial output of this very large and flexible data file. The file currently consists of 1134 cases (see Fig. 3). Of these, 915 cases are in the Basic set. The SAR file contains 107 cases, and there were 164 cases in the ELT set where the ELT was reported to have operated and aided in the search. These data sets overlap.

The Canadian file normally contains specific search information and specific ELT data (Fig. 4). The NTSB form only has two questions on ELT and Search (Figure 5). All additional data in the file was determined from narrative reports, and appended police or other reports. In addition, the NTSB computer data file has one entry for ELT data with 10 possible answers, shown in Figure 6.

ELT 1608	A	INSTALLED-FIXED-USED-EFFECTIVE IN RESCUE				
	B	INSTALLED-FIXED-USED-INEFFECTIVE/FAILED TO FUNCTION				
	D	PORTABLE-CARRIED-USED-EFFECTIVE IN RESCUE				
	E	PORTABLE-CARRIED-USED-INEFFECTIVE/FAILED TO FUNCTION				
	C	NOT INSTALLED/NOT CARRIED				
ELT ACTIVATION 1609	M	MANUAL	A	AUTOMATIC	X	DID NOT ACTIVATE
ELT LOCATION 1610	F	COCKPIT	C	CABIN	R	REAR OF AIRCRAFT	Y	OTHER
ELT TYPE 1611	A	A-AUTOMATIC EJECTABLE	F	F-FIXED	P	P-PERSONAL	W	W-WATER ACTIVATED
ELT NOT EFFECTIVE REASON	A	INSUFFICIENT G TO ACTIVATE	E	IMPROPER INSTALLATION	K	ANTENNA BROKEN OFF
	B	PHYSICAL DAMAGE IN CRASH	F	IMPROPER MAINTENANCE	L	NOT SWITCHED ON
	C	SHIELDING BY WRECKAGE	G	SWITCHED OFF BY CRASH	M	FIRE DAMAGE
	D	SHIELDING BY TERRAIN	H	SHORTED	N	WATER SUBMERSION
ELT MANUFACTURER 1613	▶		ELT MODEL	▶		

Figure 4 Canadian Investigation Form Question on ELT

EMERGENCY LOCATOR TRANSMITTER	ON BOARD	AIDED SEARCH/LOCATION	REMARKS
	☐ No ☐ Yes	☐ No ☐ Yes	

**Figure 5 NTSB Investigation Form
Questions on ELT and search**

Figure 6

Coded answers available for the single ELT entry in NTSB Computer File.

Operated — Used in Locating A/C
Operated — Not Used
Not Used — Not Armed
Not Used — Separated from Antenna
Not Used — Battery Malfunction
Not Used — Other Malfunction/Failure
Not Used — Impact/Fire Damage
Not Used — Operation Unknown
Not Installed
Not Applicable/Insufficient Impact
Unknown/Not Reported

Preliminary Results of the Study

The following tables and comments are a preliminary review and output of the data file. At this time (Sept. 1979) the file has just become operational and some corrections will still have to be made. However, the general results should not change significantly. The file permits tabulation of data elements of any subset of data, and so a wide variety of correlations and cross references can be obtained. No attempt has yet been made to explore the full range of potential data analysis, but those readers who have a particular question that might be answered from the file are invited to write the author with their specific request.

The first question of interest was the extent that the ELT is in use and the compliance with requirements to use it. During data acquisition, the question "ELT Required?" was answered based on the applicable national regulations and the recorded purpose of flight. Not all files contained data to answer this question. However, it appears from Fig. 7 that compliance is good. A summary of ELT data is provided in Figure 8. The high number of cases where the ELT is reported as not armed is of concern, since all benefit from this valuable device is lost. Discussions with search and rescue personnel indicates that they often turn the ELT off after arriving at the scene, to get the now unneeded signal off the air. They also report that they occasionally break off the antenna to silence the ELT. The accident investigator arrives later and unless he specifically asks the searcher (who may have left), he will see only an unarmed unit or a broken antenna.

Figure 7 ELT Regulation Compliance-Basic File

ELT Required and Installed	519
ELT Required, Not Installed	45
ELT Not Required, Installed	47
ELT Not Required, Not Installed	81
Either question not answered	223

Figure 8 ELT USAGE DATA-Basic File (915)

	Yes	No	Unk/Nr
ELT Required	669	202	44
ELT Installed	580	129	206
ELT Armed	287	43	250
ELT Activated	207	134	—
ELT Aid in Search	82	224	—

ELT Units with Expired Batteries 27

Method of ELT Activation Auto 200
Manual 3
UNK 4

A study of the ELT data in the basic file shows that the make/model of ELT was only recorded in 221 cases (24% of the file). Comparison of activation/non-activation and reasons associated with this have not yet been made. However, the small number of cases with this data, and the fact that only 5 of the 15 manufacturers show up more than 10 times, holds out little promise for detailed comparison between units. In the ELT success file the ELT make and model is recorded in only 47% of the cases.

Figure 9 lists the reasons given for ELT success or failure in the basic file cases. Multiple answers were permitted.

Figure 9 ELT Success & Failure Basic File

ELT AIDED IN SEARCH	**82**
Initial alerting	45
Detected by airborne SAR	19
Final homing	33
Voice Communication	2
ELT ACTIVATED BUT DID NOT AID IN SEARCH	**125**
Not Required	75
Battery went dead	1
Antenna Disconnected	23
Antenna Shielded	7
Searcher Not Equipped	2
Under Water	16
ELT DID NOT ACTIVATE	
Destroyed/Damaged by impact	119
Cause Unknown	24
Battery Dead	8
Corrosion Damage	13
Insufficient force to activate	5
Broke loose from mounting	11
Internal Malfunction	16
Tested OK After Accident	14

Figure 10 Aircraft Damage Data - Basic File See Fig. 1 & 2 for interpretation

	Burned	LOCATION 1	LOCATION 2	LOCATION 3	LOCATION 4	LOCATION UNK NR	DEFORMATION 1	DEFORMATION 2	DEFORMATION 3	DEFORMATION 4	DEFORMATION 5	DEFORMATION UNK NR	ATTITUDE 1	ATTITUDE 2	ATTITUDE 3	ATTITUDE UNK NR
COCKPIT	172						34	101	335	263	13	169	246	95	160	413
CABIN	175	362	5	168	205	175	52	129	312	239	12	171	243	95	160	416
NOSE	155	222	1	243	263	186	15	52	383	265	24	176	228	102	156	428
AFT FUS.	129	382	28	130	225	151	192	197	221	143	0	162	267	114	175	358
TAIL CONE	51	105	41	33	75	661	112	19	52	65	0	667	91	28	39	757
RT INBD WING	146	281	4	110	356	164	90	204	271	168	0	182	247	103	147	418
RT OTBD WING	97	249	189	60	243	174	84	187	305	150	0	189	239	98	149	429
LT INBD WING	143	267	3	134	348	163	91	209	269	165	2	179	233	99	157	426
LT OTBD WING	104	251	215	53	227	169	73	227	280	145	2	188	231	102	158	424
RT HORIZONTAL	80	369	183	38	153	172	372	148	98	97	5	195	271	108	184	352
LT HORIZONTAL	81	368	188	34	151	174	392	134	99	95	2	193	275	110	189	341
VERTICAL	80	374	173	54	131	183	372	159	100	91	3	190	278	104	196	337
ENG # 1	134	184	32	187	306	206	58	162	307	138	42	208	143	81	129	562
PROP # 1		141	169	30	270	305	41	158	285	83	67	281				

UNK/NR = Unknown or Not Reported

Figure 11 Aircraft Damage Data - Basic File ELT Activated (207 cases)

	Burned	LOCATION					DEFORMATION						ATTITUDE			
		1	2	3	4	UNK NR	1	2	3	4	5	UNK NR	1	2	3	UNK NR
COCKPIT	25						8	32	89	45	4	29	61	34	44	68
CABIN	26	101	2	44	30	30	16	37	80	41	3	30	63	34	44	66
NOSE	21	68	0	70	36	33	5	16	101	47	5	33	56	35	44	62
AFT FUS.	17	105	11	30	36	25	48	66	49	14	0	30	75	37	46	49
TAIL CONE	2	38	13	4	2	150	44	3	6	1	0	153	28	13	11	155
RT INBD WING	20	80	1	23	71	32	21	57	68	25	0	36	65	29	37	76
RT OTBD WING	11	68	48	9	47	35	17	57	75	21	0	37	64	27	38	78
LT INBD WING	19	75	0	34	70	28	20	60	69	25	0	33	58	31	42	76
LT OTBD WING	14	71	60	10	36	30	20	59	73	22	0	33	59	33	40	75
RT HORIZONTAL	7	100	50	7	19	31	103	46	12	8	0	38	73	35	47	52
LT HORIZONTAL	7	101	48	6	17	35	106	35	15	8	1	42	72	37	46	52
VERTICAL	7	100	47	13	15	32	105	46	12	7	0	37	76	34	49	48
ENG # 1	22	54	4	54	56	39	20	52	66	23	5	41	34	24	43	106
PROP # 1		39	41	6	60	61	7	46	76	11	14	53				

UNK/NR = Unknown or Not Reported

In our first look at the damage data, the mass of numbers may appear to be confusing. Figure 10 is a tabulation of the answers to the fire, location, deformation and attitude questions for each part of the aircraft for the basic file. (Recall that this file is only the Fatal & Serious injury index and is the random set of data). Figure 11 is the same tabulation for basic file cases where the ELT operated. Comparing figures 10 & 11 will permit assessment of differences that might have affected ELT operation. An additional table where ELT was installed but did not operate will also assist in this comparison. Note the high level of unknown/not reported answers. Figure 10 also helps answer the question of where to put the ELT for maximum survivability, and to assess the probability of survival.

The incidence of inflight breakup, inflight and ground fire, and the non-recovery of wreckage are shown in Figure 12. The tabulation of photo data only covers cases with two or less photos of the aircraft. It is difficult to make the assessments called for in this study without adequate photos, yet in over 180 cases involving fatal or serious injury where the aircraft was recovered (20% of the basic file) there were less than 3 photos of the wreckage. Additional studies of this damage data using combined location and damage indexes will permit studies of crashworthiness by aircraft type and model as well as overall considerations needed for the ELT study.

Figure 12 Miscellaneous Tabulations

	BASIC	ALL
Inflight Breakup	66	69
Inflight Fire	10	12
Ground Fire	207	211
Wreckage not Recovered — Land	4	4
Wreckage not Recovered — Water	46	48
Wreckage not Recovered Unknown Location	6	6
Zero Photos in File	220	
Only one Photo in File	13	
Only two Photo's in File	10	

At this point in the study, only preliminary reviews have been made of the data, and quality control checks are still being made to pick up input data errors, wrong codes, missing items, and to test the analysis programs. However, the data shown herein reveals that the data content of an accident investigation file is highly variable and often very incomplete. The constant focus on the "why" of the accident often obscures the value of a good investigation, especially when the cause is very obvious. This researcher personally reviewed about half of the NTSB files used in this study. This observation revealed that while most case files indicated that the investigator was at the scene, he often only took one or two pictures of the wreckage from a distance, and failed to completely document the scene and aircraft damage. The aircraft speed at impact was almost never calculated. The aircraft attitude at impact, the flight path angles, and the distance traveled during deceleration were often not recorded altho these items are crucial to proper design for crashworthiness and survivability.

Implications for the Accident Investigator

When the question is asked "How can we mount an ELT and sense the crash so that we have an acceptably high success rate of locating the crash?", where can a researcher turn except to the data of the accident investigator. Similar questions regarding human crash survivability have also been asked, as have questions on the specific form and magnitude of the deceleration pulse, the source of the post crash fire ignition and many other crashworthiness questions. In the past and present, controlled crashes have provided much good data relating to controlled environments, and these have led to many improvements, such as truly crashworthy fuel systems, seat systems, personal protective equipment, etc. However, the many variables of the real world are raised as arguments against design from controlled testing only. It is imperative that real world data be provided to the designer, to compare with the laboratory data, to validate the new concepts he is proposing.

Figure 13 (USAFRCC DATA Sept. 1979)

	WITH ELT	WITHOUT ELT
Time to Locate	22.2 HRS	4 Days 18 HRS
% Survivors	37	30
Hours Flown to Locate	19	127.3

In their "Safety Effectiveness Evaluation of the National Highway Traffic Safety Administration Passive Restraint Evaluation Program," (Ref. D) NTSB is very critical of NHTSA's plans for evaluation of a specific automotive safety feature. In particular, NTSB states "It is essential that the NHTSA evaluate the real-world effectiveness of the passive restraint standard." It is equally true that crashworthiness standards of FAA, ELT requirements and similiar safety efforts, should be evaluated in the real-world in accordance with specific evaluation plans for each part of the system. The NTSB, FAA, and the Canadian MOT should require specific plans of data collection to be prepared and implemented on a continuous and updated basis for areas under current consideration, such as;

ELT
Restraint systems
Crashworthiness of fuel systems
Collision avoidance systems
Ground proximity warning systems

All air safety investigators should be trained in the specifics of crashworthiness evaluation as well as accident cause determination, as are Canadian MOT investigators. Accident investigation forms and data storage programs should be growing and changing, not static. More detailed questions should be asked and answered, instead of relying on the investigators to remember to put it in the narrative. A requirement for specific, detailed photographs of certain items of equipment should be established and enforced by investigation managers. Accident reports and studies should do much more than count broken airplanes and people and cause factors. We need useable, statistically significant data to put into our development programs and help us find the way to a better aviation system. We need to prevent the accident as often as possible, but when we fail that, to prevent the injury and rescue the distressed as well as we possibly can.

NASA/FAA General Aviation Crash Dynamics Program — An Update

Robert J. Hayduk, Robert G. Thomson and Huey D. Carden
NASA Langley Research Center; Hampton, VA 23665

Abstract

The objective of the Langley Research Center general aviation crash dynamics program is to develop technology for improved crash safety and occupant survivability in general aviation aircraft. The program involves three basic areas of research: controlled full-scale crash testing, nonlinear structural analyses to predict large deflection elasto-plastic response, and load attenuating concepts for use in improved seat and subfloor structure. Both analytical and experimental methods are used to develop expertise in these areas. Analyses include simplified procedures for estimating energy dissipating capabilities and comprehensive computerized procedures for predicting airframe response. These analyses are being developed to provide designers with methods for predicting accelerations, loads, and displacements of collapsing structure. Tests on typical full-scale aircraft and on full- and sub-scale structural components are being performed to verify the analyses and to demonstrate load attenuating concepts.

A special apparatus has been built to test Emergency Locator Transmitters (ELT's) when attached to representative aircraft structure. The apparatus is shown to provide a good simulation of the longitudinal crash pulse observed in full-scale aircraft crash tests.

Introduction

In 1972, NASA embarked on a cooperative effort with the FAA and industry to develop technology for improved crashworthiness and occupant survivability in general aviation aircraft. The effort includes analytical and experimental work and structural concept development. The methods and concepts developed in this ongoing effort are expected to make possible future general aviation aircraft designs having enhanced survivability under specified crash conditions with little or no increase in weight and acceptable cost. The overall program is diagramed in figure 1 with agency responsibility indicated by the legend.

Crashworthiness design technology is divided into three areas: environmental, airframe design, and component design. The environmental technology consists of acquiring and evaluating field crash data to support and validate parametric studies being conducted under controlled full-scale crash testing, the goal being to define a crash envelope within which the impact parameters allow human tolerable acceleration levels.

Airframe design has a twofold objective: to assess and apply current, on-the-shelf, analytical methods to predict structural collapse; and to develop and validate new and advanced analytical techniques. Full-scale tests are also used to verify analytical predictions, as well as to demonstrate improved load attenuating design concepts. Airframe design also includes the validation of novel load limiting concepts for use in aircraft subfloor designs.

Component design technology consists of exploring new and innovative load limiting concepts to improve the performance of the seat and occupant restraint systems by providing for controlled seat collapse while maintaining seat/occupant integrity. Component design also considers the design of non-lethal cabin interiors.

Langley's principal research areas in the joint FAA/NASA Crash Dynamics program are depicted pictorally in figure 2. These areas include full-scale crash testing, nonlinear crash impact analyses, and crashworthy seat and subfloor structure concept development. Subsequent sections deal with these topics, as well as, Emergency Locator Transmitter (ELT) testing.

Full-Scale Crash Testing

Full-scale crash testing is performed at the Langley impact dynamics research facility (ref. 1) shown in figure 3. This facility is the former lunar landing research facility modified for free-flight crash testing of full-scale aircraft structures and structural components under controlled test conditions. The basic gantry structure is 73 m (240 ft) high and 122 m (400 ft) long supported by three sets of inclined legs spread 81 m (267 ft) apart at the ground and 20 m (67 ft) apart at the 66 m (218 ft) level. A movable bridge with a pullback winch for raising the test specimen spans the top and traverses the length of the gantry.

Test Method

The aircraft is suspended from the top of the gantry by two swing cables and is drawn back above the impact surface by a pullback cable. An umbilical cable used for data acquisition is also suspended from the top of the gantry and connects to the top of the aircraft. The test sequence is initiated when the aircraft is released from the pullback cable, permitting the aircraft to swing pendulum style into the impact surface. The swing cables are separated from the aircraft by pyrotechnics just prior to impact, freeing the aircraft from restraint. The umbilical cable remains attached to the aircraft for data acquisition, but it also separates by pyrotechnics before it becomes taut during skid out. The separation point is held relatively fixed near the impact surface, and the flight path angle is adjusted from 0° to 60° by changing the length of the swing cable. The height of the aircraft above the impact surface at release determines the impact velocity which can be varied from 0 to 26.8 m/s (60 mph). The movable bridge allows the pullback point to be positioned along the gantry to insure that the pullback cables pass through the center of gravity and act at 90° to the swing cables.

To obtain flight path velocities in excess of 26.8 m/s (60 mph) a velocity augmentation method has been devised which uses wing-mounted rockets to accelerate the test specimen on its downward swing. As shown in figure 4, two Falcon rockets are mounted at each engine nacelle location and provide a total thrust of 77,850 N. The aircraft is released after rocket ignition, and the rockets continue to burn during most of the downward acceleration trajectory but are dormant at impact. The velocity augmentation method provides flight path velocities from 26.8 to 44.7 m/s (60-100 mph) depending on the number and burn time of rockets used.

Instrumentation

Data acquisition from full-scale crash tests is accomplished with extensive photographic coverage, both interior and exterior to the aircraft using low-, medium-, and high-speed cameras and with onboard strain gages and accelerometers. The strain gage type accelerometers (range of 250 G and 750 G at 0 to 2000 Hz) are the primary data-generating instruments, and are positioned in the fuselage to measure accelerations both in the normal and longitudinal directions to the aircraft axis. Instrumented anthropomorphic dummies (National Highway Traffic Safety Administration Hybrid II) are onboard all full-scale aircraft tests conducted at LaRC. The location and framing rate of the cameras are discussed in reference 1. The restraint system arrangement and type of restraint used vary from test to test.

Tests Conducted

A chronological summary of the full-scale crash tests conducted at the Impact Dynamics Research Facility is represented in figure 5. The shaded symbols are crash tests that have been conducted, the open symbols are planned crash tests. Different symbols represent different types of aircraft under different impact conditions, for example the represents a twin-engine specimen impacting at 26.8 m/s (60 mph) while the represent the same twin-engine specimen, using the velocity augementation method, impacting at 40.2 m/s (90 mph). Various types of aircraft have been successfully crash tested at LaRC from 1974 through 1978 including CH-47 helicopters, high and low wing single-engine aircraft, and aircraft fuselage sections. Data from these tests are presented in references 2-4. The aircraft fuselage section tests are vertical drop tests conducted to simulate full-scale aircraft cabin sink rates experienced by twin-engine aircraft tested earlier. The response of the aircraft section, two passenger seats, and two dummies are being simulated analytically (see, Nonlinear Analysis Section). Some single-engine crash tests were conducted using a dirt impact surface while most crash tests were conducted on a concrete surface. The dirt embankment was 12.2 m (40 ft) wide, 24.4 m (80 ft) long and 1.2 m (4 ft) in depth. The dirt was packed to the consistency of a ploughed field. The variation of full-scale crash test parameters is not complete and does not consider such secondary effects as aircraft sliding, overturning, cartwheeling, or tree and obstacle impact.

Controlled Crash Test and Las Vegas Accident

On August 30, 1978, a twin-engine Navajo Chieftain, carrying a pilot and nine passengers crash landed in the desert shortly after taking off from the North Las Vegas Airport. All ten persons on board were killed. A comparative study of this Navajo Chieftain crash and a similar NASA controlled-crash test was made. The purposes of the study were to compare damage modes and estimate acceleration levels in the Chieftain accident with Langley tests and to assess the validity of Langley's full-scale crash simulation. The controlled-crash test chosen employed the velocity augmentation method wherein the aircraft reach a flight path velocity of 41.4 m/s (92.5 mph) at impact. The pitch angle was -12°, with a 5° left roll and 1° yaw. Figure 6 shows photographs of the two aircraft. The NASA specimen is a twin-engine pressurized Navajo, which carries from six to eight passengers, and although the cabin is shorter in length it is similar in structural configuration to the Chieftain.

Structural damage to the seats and cabin of the Navajo Chieftain and to the seats and cabin of the NASA test specimen are shown for illustrative purposes in figure 7. Much more corroborating structural damage is discussed in reference 5. The Chieftain apparently contacted the nearly level desert terrain at a location along the lower fuselage on the right side opposite the rear door. An instant later, the rest of the fuselage and the level right wing impacted. The Chieftain's attitude just prior to impact was concluded to have been the following: pitched up slightly, rolled slightly to the right and yawed to the left. The two aircraft differ in roll attitude at impact but are comparable. The structural damage to the cabin of the Chieftain was much greater than that exhibited by the NASA controlled crash test under correspondingly similar impact attitudes. The damage pattern to the standard passenger and crew seats of the Chieftain was similar to that in the NASA tests, but generally exhibited more severe distortion. The damage patterns suggest similar basic failure modes and in the case of the seat distortion a flight path impact velocity in excess of 41.4 m/s (92.5 mph) for the Chieftain. Acceleration time histories from the first passenger seat and floor of the controlled NASA crash test are shown in figure 8 where the first passenger seat corresponds to the damaged seat shown in figure 7.

Because of the similarity in the damage patterns exhibited by seats 6 and 8 of the Chieftain and the first passenger seat of the NASA controlled test, generalized conclusions can be drawn relative to certain seat accelerations experienced by those passengers in the Chieftain. The peak pelvic accelerations of passengers 6 and 8 in the Chieftain accident were probably in excess of 60 g's normal (to aircraft axis), 40 g's longitudinal, and 10 g's transverse.

Nonlinear Crash Impact Analysis

The objective of the analytical efforts in the crash dynamics program is to develop the capability to predict nonlinear geometric and material behavior of sheet-stringer aircraft structures subjected to large deformations and to demonstrate this capability by determining the plastic buckling and collapse response of such structures under impulsive loadings. Two specific computer programs are being developed, one focused on modeling concepts applicable to large plastic deformations of realistic aircraft structural components, and the other a versatile seat/occupant program to simulate occupant response. These two programs are discussed in the following sections.

Plastic and Large Deflection Analysis of Nonlinear Structures (PLANS)

Description. For several years LaRC has been developing a sophisticated structural analysis computer program which includes geometric and material nonlinearities (refs. 6 and 7). "PLANS" is a finite element program for the static and dynamic nonlinear analysis of aircraft structures. PLANS computer program is capable of treating problems which contain bending and membrane stresses, thick and thin axisymmetric bodies, and general three-dimensional bodies. PLANS, rather than being a single comprehensive computer program, represents a collection of special purpose computer programs or modules, each associated with a distinct class of physical problems. Using this concept, each module is an independent finite element computer program with its associated element library. All the programs in PLANS employ the "initial strain" concept within an incremental procedure to account for the effect of plasticity and include the capability for cyclic plastic analysis. The solution procedure for treating material nonlinearities (plasticity) alone reduces the nonlinear material analysis to the incremental analysis of an elastic body of identical shape and boundary conditions, but with an additional set of applied "pseudo loads". The advantage of this solution technique is that it does not require modification of the element stiffness matrix at each incremental load step. Combined material and geometric nonlinearities are included in several of the modules and are treated by using the "updated" or convected coordinate approach. The convected coordinate approach, however, requires the reformation of the stiffness matrix during the incremental solution process. After an increment of load has been applied, increments of displacement are calculated and the geometry is updated. In addition to calculating the element stresses, strains, etc., the element stiffness matrices and mechanical load vector are updated because of the geometry changes and the presence of initial stresses. A further essential ingredient of PLANS is the treatment of dynamic nonlinear behavior using the DYCAST module. DYCAST incorporates various time-integration procedures, both explicit and implicit, as well as the inertia effects of the structure.

Comparison with experiment. PLANS is currently being evaluated by comparing calculations with experimental results on simplified structures, such as, a circular cylinder, a tubular frame structure, an angular frame with joint eccentricities, and the same angular frame covered with sheet metal. Static and dynamic analyses of these structures loaded into the large deflection plastic collapse regime have been conducted with PLANS and compared with experimental data in references 8 and 9.

A analytical simulation of a vertical drop test of an aircraft section has recently been compared with experimental full-scale crash data in reference 10. Figure 9(a) shows the fuselage section prior to testing and figure 9(b) shows the DYCAST finite element fuselage, seat, and occupant model. The vertical impact velocity of the specimen was 8.38 m/s(27.5 ft/s). The 50-percentile anthropomorphic dummies each weighed 74.8 kg (165 lb). The occupant pelvis vertical accelerations compared with analysis are shown in figure 10. The DYCAST model predicted an accurate mean pelvis acceleration level. If the occupant had been modeled with several masses representing the lower and upper torso, the model would also have shown the oscillatory response exhibited by the test.

Modified Seat Occupant Model for Light Aircraft (MSOMLA)

Description. Considerable effort is being expended in developing a good mathematical simulation of occupant, seat, and restraint system behavior in a crash situation. MSOMLA was developed from a computer program SOMLA funded by the FAA as a tool for use in seat design, (ref. 11). SOMLA is a three-dimensional seat, occupant, and restraint program with a finite element seat and an occupant modeled with twelve rigid segments joined together by rotational springs and dampers at the joints. The response of the occupant is described by Lagranges equations of motion with 29 independent generalized coordinates. The seat model consists of beam and membrane finite elements.

SOMLA was used previously to model a standard seat and a dummy occupant in a NASA light aircraft section vertical drop test. During this simulation, problems were experienced with the seat model whenever the yield stress of an element was exceeded. Several attempts to correlate various finite element solutions of the standard seat with OPLANE-MG, DYCAST, and SOMLA using only beam and membrane elements, to experimental data from static vertical seat loading tests were only partially successful. Consequently, to expedite the analysis of the seat/occupant, the finite element seat in SOMLA was removed and replaced with a spring-damper system. Additional modifications to SOMLA added nonrigid occupant contact surfaces (nonlinear springs) and incorporated a 3-D computer graphics display. This modified SOMLA is called MSOMLA. A more complete discussion of MSOMLA, its computer input requirements, and additional comparisons of experiments and analysis can be found in ref. 12.

Comparison with Experiment. A comparison of full-scale crash test data from the -30 degree, 26.8 m/s (60 mph) crash test and occupant simulation using MSOMLA is presented in fig. 11 in two-dimensional graphics. Although three-dimensional graphics are available in MSOMLA, only two-dimensional graphics were chosen for the pictorial comparison in figure 11. Note the similarity between the response of the occupant in the simulation and the occupant as seen through the window of the aircraft during the crash test. Note also that in the simulation the dummy's head passes through the back of the seat in front of him, a fact that could explain differences in the computed and measured head accelerations as presented in fig. 12. The comparisons of this figure, between measured and computed acceleration pulses are excellent considering the seat and occupant were subjected to forward, normal and rotational accelerations. This comparison, using full-scale crash data, demonstrates the versatility of the program's simulation capability.

Crashworthy Seat and Subfloor Structure Concepts

The development of structural concepts to limit the load transmitted to the occupant is another research area in LaRC's crashworthiness program. The objective of this research is to attenuate the load transmitted by a structure either by modifying its structural assembly, changing the geometry of its elements, or adding specific load limiting devices to help dissipate the kinetic energy. Recent efforts in this area at LaRC have concentrated on the development of crashworthy aircraft seat and subfloor systems.

The concept of available stroke is paramount in determining the load attenuating capabilities of different design concepts. Shown in figure 13 are the three load attenuating areas which exist between an occupant and the impact surface during vertical descent: the landing gear, the cabin subfloor, and the aircraft seat. Attenuation provided by the landing gear will not be included in this discussion since it is more applicable to helicopter crash attenuators. Using the upward human acceleration tolerance of 25 g's as established in ref. 13, a relationship between stroke and vertical descent velocity can be established for a constant stroking device which fully strokes in less than the maximum time allowable (0.10 s) for human tolerance. This relationship is illustrated in fig. 13. Under the condition of a constant 25 g deceleration stroke the maximum velocity decrease for the stroking available is 12.2 m/s (40 fps) for the seats and 8.2 m/s (27 fps) for the subfloor. (Assuming 30 cm (12 in) and 15 cm (6 in) in general for a twin-engine light aircraft). For a combination of stroking seat and stroking subfloor the maximum velocity decrease becomes 15.2 m/s (50 fps). These vertical sink rates are comparable to the Army Design Guide recommendations (ref. 13) for crashworthy seat design.

Seat

Figure 14 shows a standard passenger and three load limiting passenger seats that were developed by the NASA and tested at the FAA's Civil Aeromedical Institute (CAMI) on a sled test facility. The standard seat is typical of those commonly used in some general aviation airplanes and weighs approximately 11 kg (25 lbm). The ceiling mounted load limiting seat is similar in design to a troop seat designed for Army helicopters (ref. 14) and weighs 9 kg (20 lbm). This seat is equipped with two wire bending load limiters which are located inside the seat back and are attached to the cabin ceiling to limit both vertical and forward loads. Two additional load limiters are attached diagonally between the seat pan at the front and the floor at the rear to limit forward loads only. The seat pan in the design remains parallel to the floor while stroking. The length of the stroke is approximately 30 cm (12 inches) in the vertical direction and 18 cm (7 inches) forward (Fig. 15(a)). The components of a wire bending load limiter are shown in the photograph of fig. 16. In operation, the wire bending trolley, which is attached to the top housing sleeve, translates the wire loop along the axis of the wire during seat stroking at a constant force. This type of load limiter provides a near constant force during stroking thus making it possible to absorb maximum loads at human tolerance levels over a given stroking distance.

The floor mounted load limiting seat weighs 10 kg (23 lbm) and employs two wire bending load limiters which are attached diagonally between the seat pan at the top of the rear strut and the bottom of the front legs. While stroking, the rear struts pivot on the floor thus forcing the load limiter housing to slide up inside the seat back (Fig. 15(b)). The third load limiting concept tested uses a rocker swing stroke to change the attitude of the occupant from an upright seated position to a semi-supine position.

In the dynamic tests conducted at CAMI, the sled or carriage is linearly accelerated along rails to the required velocity and brought to rest by wires stretched across the track in a sequence designed to provide the desired impact loading to the sled. A hybrid II, 50 percentile dummy instrumented with accelerometers loaded the seats and restraint system on impact. The restraint system for these seats consisted of a continuous, one piece, lap belt and double shoulder harness arrangement.

Time histories of dummy pelvis accelerations recorded during two different impact loadings are presented in figure 17 with the dummy installed in a standard seat and in a ceiling-mounted, load-limiting seat. The vertical impulse of figure 17 (a) positioned the seats (and dummy) to impact at a pitch angle (angle between dummy spine and direction of sled travel) of -30° and a roll angle of 10°. In the "longitudinal" pulse (fig. 17 (b)) the seats were yawed 30° to the direction of sled travel. The sled pulses are also included in the figure and represent the axial impulse imparted to the inclined dummies. The X and Z axis of the dummy are local axes perpendicular and parallel to its spine, respectively. The figure shows that for both impact conditions the load-limiting seat in general provided a sizeable reduction in pelvis acceleration over those recorded during similar impacts using the standard seat.

The impact condition associated with a dummy passenger in one of the full-scale NASA crash tests were quite similar to those defined by the sled test of figure 17 (a), particularly in terms of velocity change, thereby permitting a gross comparison of their relative accelerations. Figure 18 shows that comparison. The dummy acceleration traced from the two tests are similar in both magnitude and shape, however some phase shift is evident. This agreement suggests that sled testing provides a good approximation of dummy/seat response in full-scale aircraft crashes.

Subfloor Structure

The subfloor structure of most medium size general aviation aircraft offers about 15 - 20 cm (6 - 8 in) of available stroking distance which suggests the capability to introduce a velocity change of approximately 8.2 m/s (27 fps) (see fig. 13). Aside from that necessary for routing hydraulic and electrical conducts, considerable volume is available within the subfloor for energy dissipation through controlled collapse. A number of energy absorbing subfloor concepts have been advanced and figure 19 presents sketches of five prominent candidates. The first three concepts, moving from left to right, would replace existing subfloor structure and allow for: (a) the metal working of floor beam webs filled with energy dissipating foam; (b) the collapsing of precorrugated floor beam webs filled with foam; or (c) the collapsing of precorrugated foam-filled webs interlaced with a notched lateral bulkhead. The remaining two concepts eliminate the floor beam entirely and replace it with; a precorrugated canoe (the corrugations running circumferentially around the cross-section) with energy dissipating foam exterior to the canoe; and foam-filled kevlar cylinders supporting the floor loads. These five promising concepts are being tested both statically and dynamically to determine their load-deflection characteristics. Some examples of the static load-deflection behavior obtained from four of the five concepts are shown in figure 20.

After repeated testing and sizing (geometric optimizing) of these load limiting devices, the three most promising will be chosen for integration into complete subfloor units to be used as the subfloors in aircraft sections. Drop tests of these aircraft sections will then be conducted at velocities up to 15.2 m/s (50 fps) to evaluate their performance as compared to unmodified subfloor structure. A static crush test will also be performed on one of each of the subfloor units.

Emergency Locator Transmitter (ELT) Tests

General aviation airplanes are required to carry an Emergency Locator Transmitter (ELT) (normally crash activated) to expedite the location of crashed aircraft by searchers. However, the ELT is plagued with many problems that severely limit the usefulness of these potentially life-saving devices. The National Transportation Safety Board recently reviewed the ELT problems and efforts to find solutions, ref. 15. The ELT has a high rate of nondistress activation and failure to activate in a crash situation. Suspected problem sources are, among others, improper mounting and location in the aircraft, short circuits, vibration sensitivity, battery failures, and antenna location. NASA Langley is assisting the FAA and industry through Radio Technical Commission for Aeronautics (RTCA) Special Committee - 136 formed to study in depth the ELT problems and to seek solutions.

NASA Langley is demonstrating ELT sensor activation problems by mounting a sampling of ELT specimens in full-scale crash test aircraft and in a special test apparatus to simulate longitudinal crash pulses. This very definitive demonstration of some specific ELT performance problems and evaluation of the test results will increase understanding and lead to solutions. Langley is also studying the antenna radiation problem by fly-over examination of the radiation patterns emanating from ELT's mounted in situ.

An apparatus has been constructed to permit laboratory tests to be conducted on ELT's in a realistic environment. The test setup, shown in figure 21, consists of a large cylindrical section with an actual airplane tail section mounted in its interior. Wedges attached to the test apparatus shape the "crash" pulse upon impact in a bed of glass beads. The cylinder can be rotated relative to the wedges to vary the vector inputs. Decelerations at the base of the airplane section, responses of the bulkheads and webs, and the response of the ELT are recorded along with activation/no activation signals.

The test apparatus permits an extension of test data on ELTs acquired during crash tests of full-size aircraft at the Impact Dynamics Facility. For example, the data in figure 22 is a comparison of the longitudinal deceleration on an ELT in a recent crash test with a simulated crash pulse in the test rig. As indicated in the figure, both the characteristic shape of the crash pulse and structural resonances are reproduced by the test apparatus.

A representative sampling of in-service ELT's will be tested in this apparatus over the next six months. The effect of oblique-pulse input on the ELT activation will be studied, as well as, sensitivity of the crash sensor to structural vibration. Additional antenna radiation monitoring studies will be performed to determine the effect of ELT attitude on the radiation pattern. This test information will be used to assure ELT performance.

Concluding Remarks

Langley Research Center (LaRC) has initiated a crash safety program that will lead to the development of technology to define and demonstrate new structural concepts for improved crash safety and occupant survivability in general aviation aircraft. This technology will make possible the integration of crashworthy structural design concepts into general aviation design methods and will include airframe, seat, and restraint-system concepts that will dissipate energy and properly restrain the occupants within the cabin interior. Current efforts are focused on developing load-limiting aircraft components needed for crash load attenuation in addition to considerations for modified seat and restraint systems as well as structural airframe reconfigurations. The dynamic nonlinear behavior of these components is being analytically evaluated to determine their dynamic response and to verify design modifications and structural crushing efficiency. Seats and restraint systems with incorporated deceleration devices are being studied that will limit the load transmitted to the occupant, remain firmly attached to the cabin floor, and adequately restrain the occupant from impact with the cabin interior. Full-scale mockups of structural components incorporating load limiting devices are being used to evaluate their performance and provide corroboration to the analytical predictive techniques.

In the development of aircraft crash scenarios, a set of design crash parameters are to be determined from both FAA field data and LaRC controlled crash test data. The controlled crash test data will include crashes at velocities comparable with the stall velocity of most general aviation aircraft. Close cooperation with other governmental agencies is being maintained to provide inputs for human tolerance criteria concerning the magnitude and duration of deceleration levels and for realistic crash data on survivability. The analytical predictive methods developed herein for crash analyses are to be documented and released through COSMIC.

A new Emergency Locator Transmitter (ELT) test apparatus has been made operational at NASA Langley Research Center. Testing of a representative sample of in-service ELT's is underway. Results of this study will form the basis for specific recommendations by RTCA Special Committee 136. These recommendations to the FAA and industry will lead to improvements in ELT reliability.

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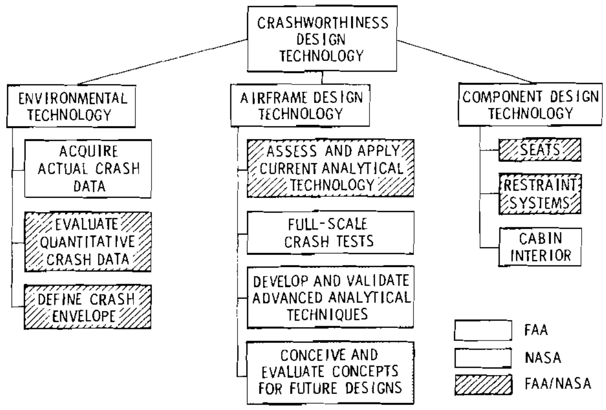

Fig. 1 Agency responsibilities in joint FAA/NASA general aviation crashworthiness program.

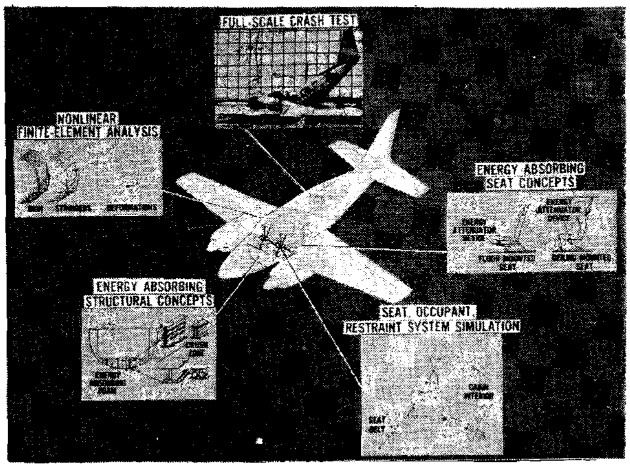

Fig. 2 Research areas in LaRC general aviation crash dynamics program.

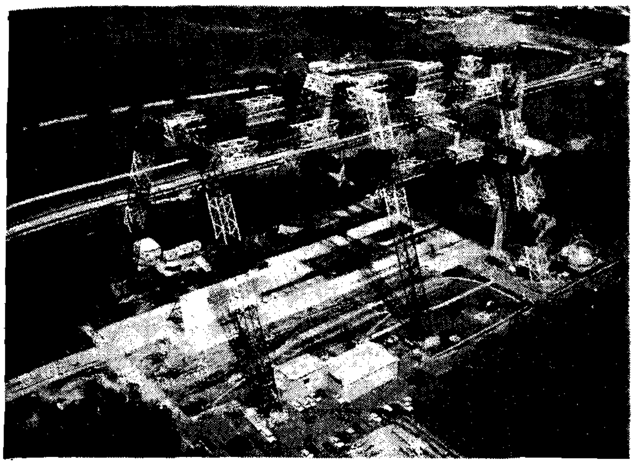

Fig. 3 Langley impact dynamics research facility.

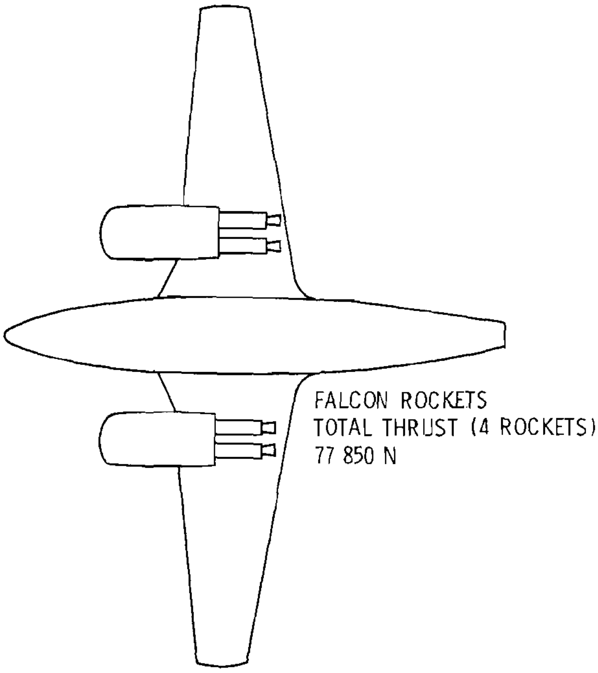

Fig. 4(a) Schematic of rocket location.

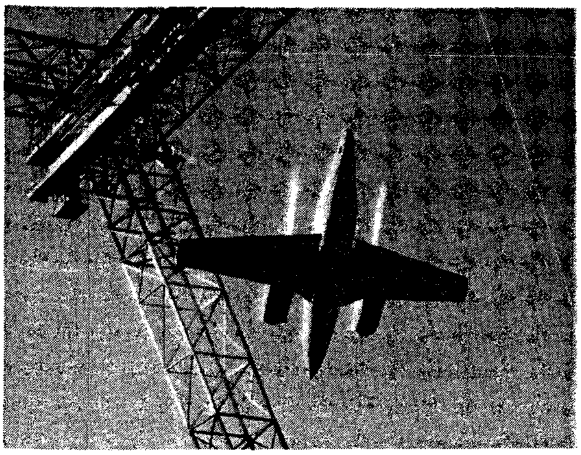

Fig. 4(b) Photograph of rocket ignition during test.

Fig. 4 Velocity augmentation crash test method.

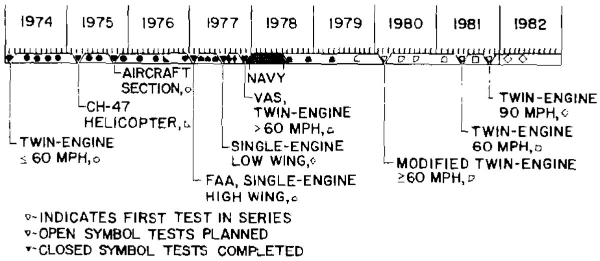

Fig. 5 General aviation crash test schedule.

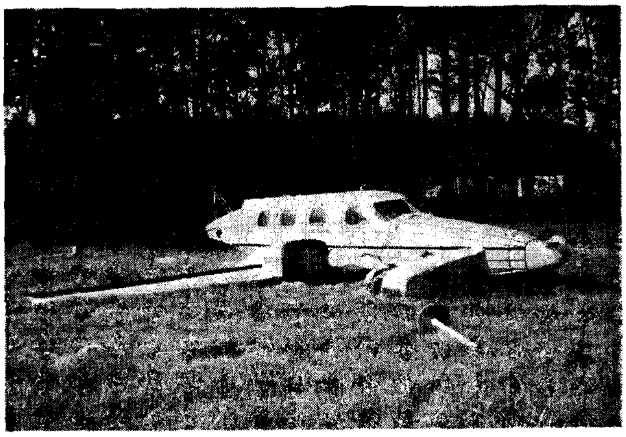

Fig. 6(a) Controlled crash.

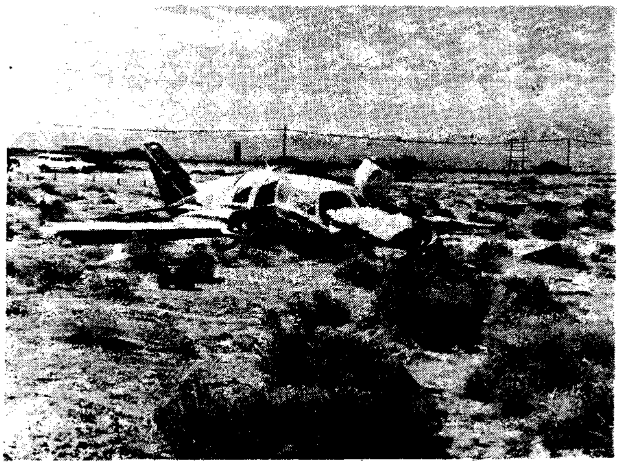

Fig. 6(b) Las Vegas accident.

Fig. 6 Controlled crash test and Las Vegas accident.

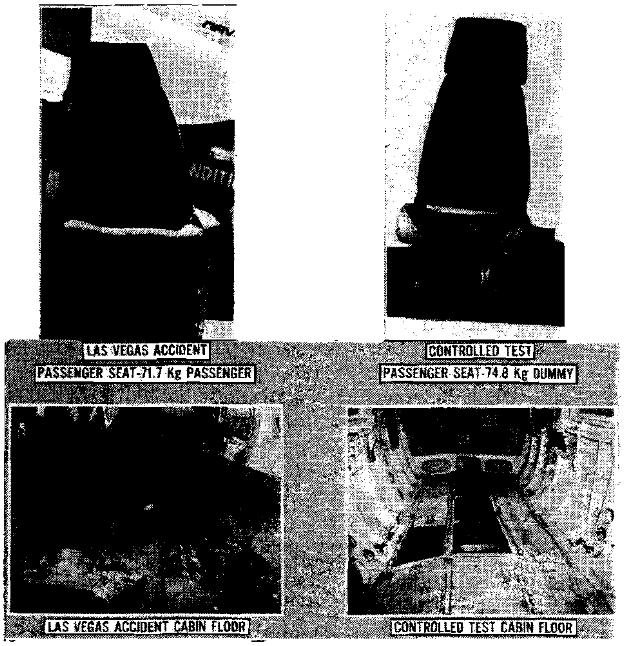

Fig. 7 Damage comparison between controlled test and Las Vegas accident.

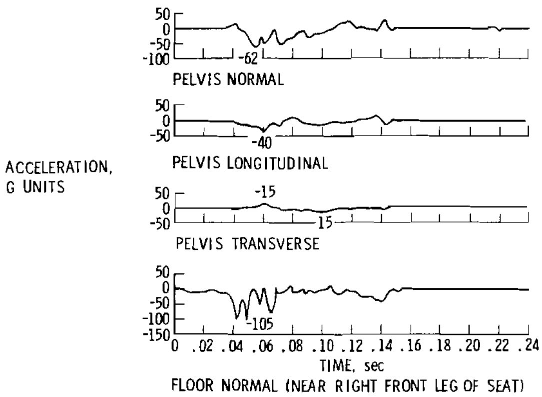

Fig. 8 Acceleration time histories from first passenger and floor of controlled crash test (-12° pitch, 41.4 m/s flight path velocity with 5° left roll, 1° yaw).

Fig. 9(a) Fuselage section drop-test specimen.

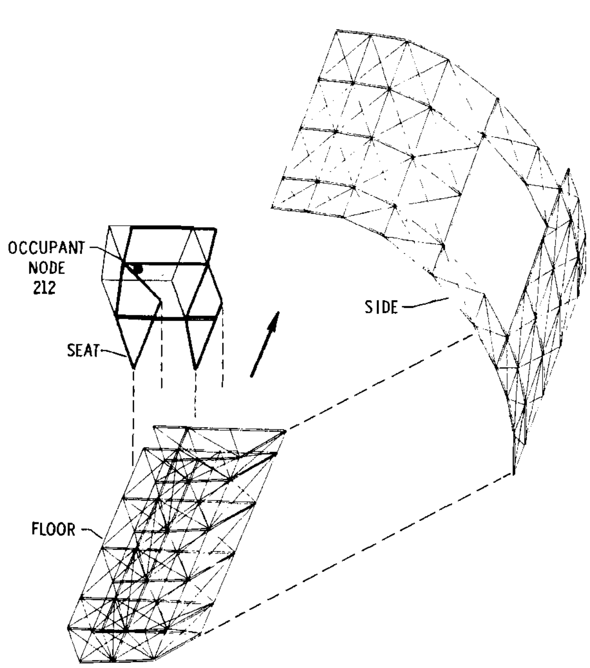

Fig. 9(b) DYCAST fuselage, seat, and occupant model.

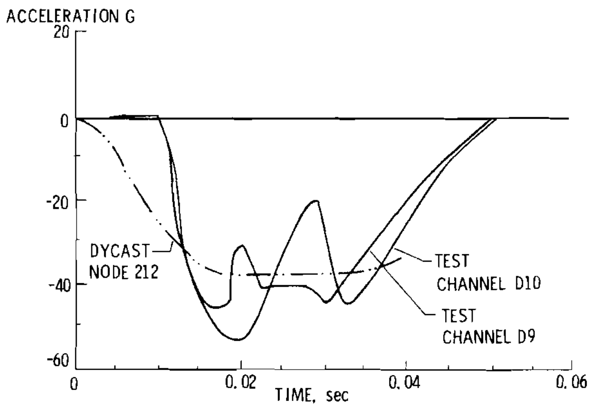

Fig. 10 Comparison of occupant pelvis vertical accelerations; Test versus analysis.

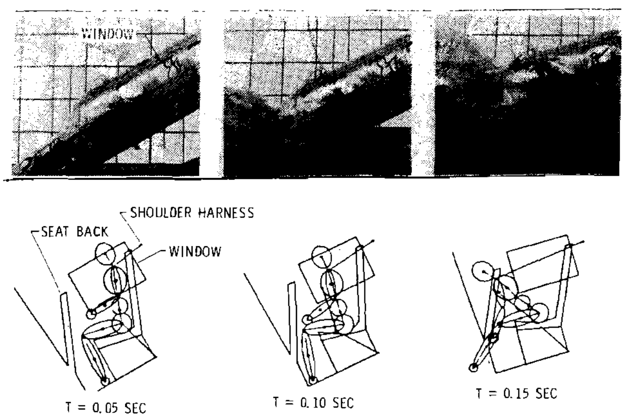

Fig. 11 Two-dimensional computer graphics display of the motion of the third passenger of the -30 degree, 27 m/s full-scale crash test.

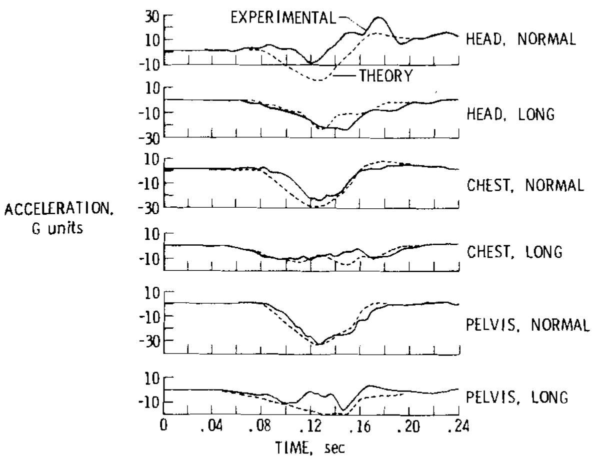

Fig. 12 Experimental and computer dummy accelerations for the -30 degree, 27 m/s full-scale crash test.

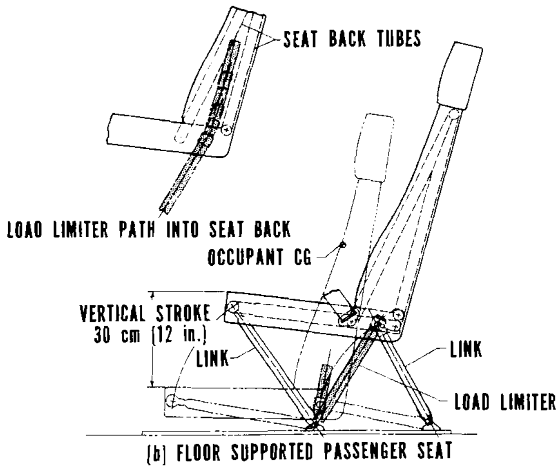

Fig. 15(a) Floor supported passenger seat.

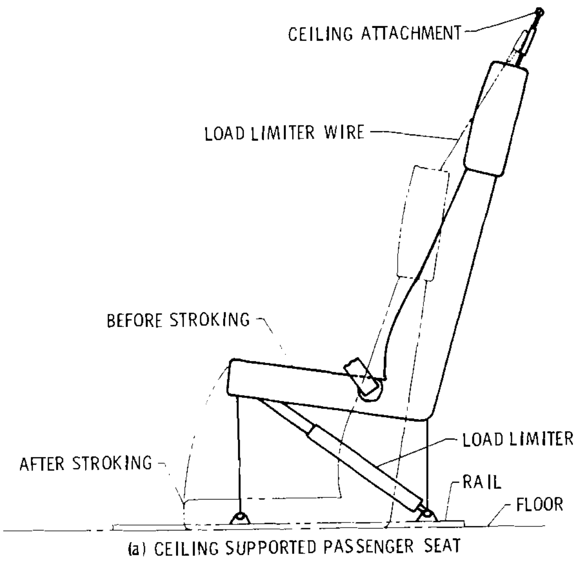

Fig. 15(b) Ceiling supported passenger seat.

Fig. 15 Passenger seats with wire bending load limiters.

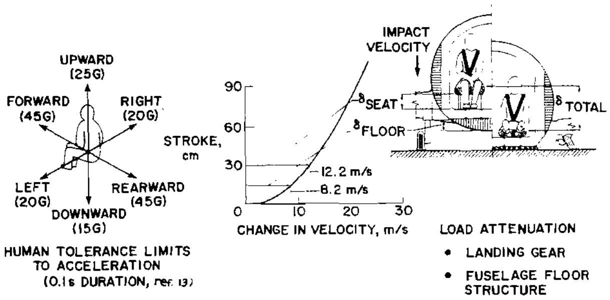

Fig. 13 Available stroke for energy dissipation in typical twin-engine general aviation aircraft.

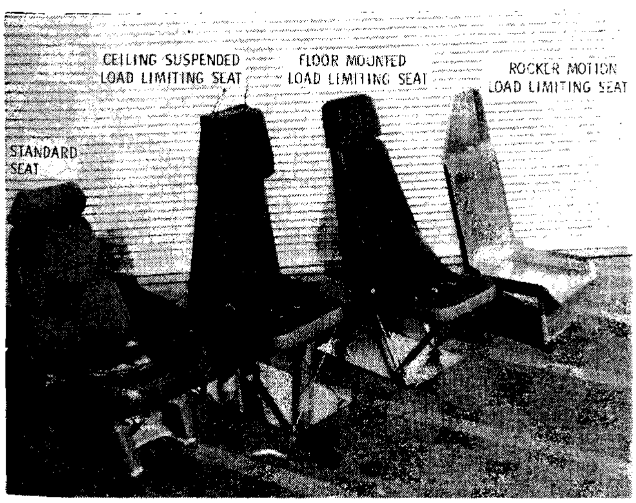

Fig. 14 Load limiting seat concepts.

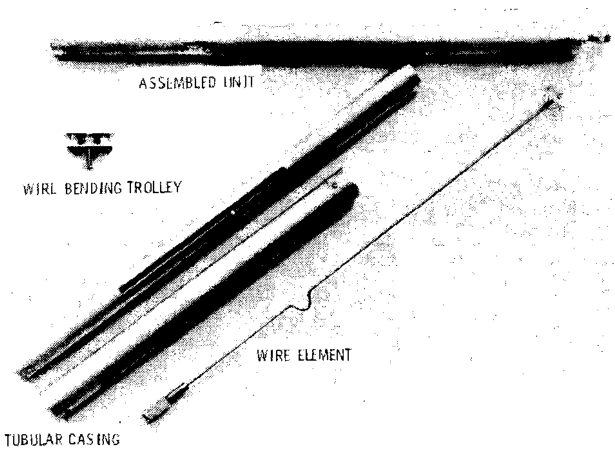

Fig. 16 Wire bending load limiter.

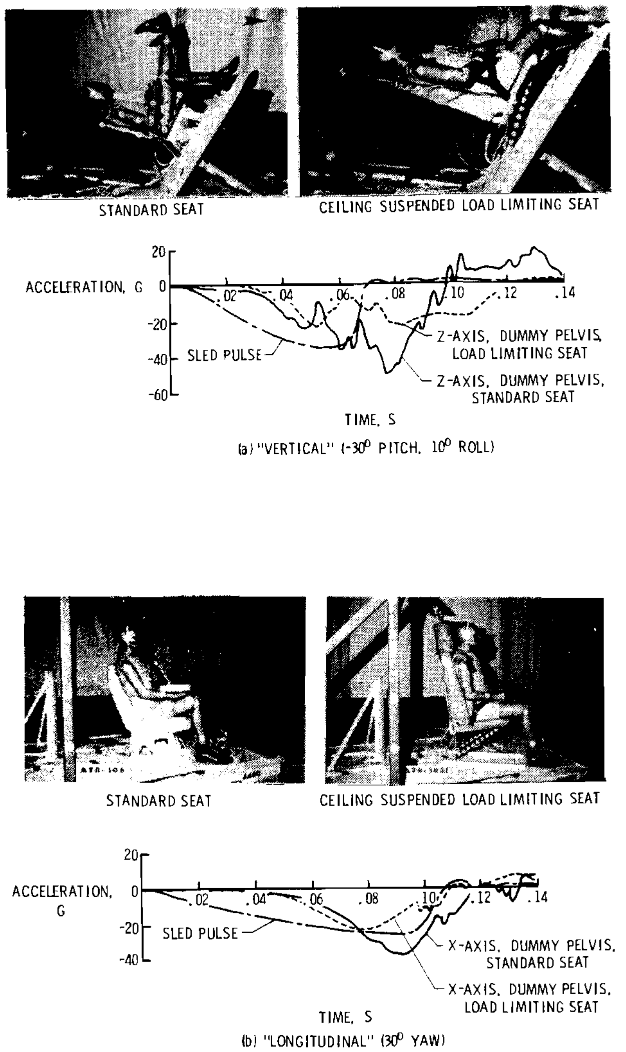

Fig. 17 Pelvis accelerations for dummy in standard and ceiling mounted (load limiting) seat subjected to "vertical" and "longitudinal" sled pulses.

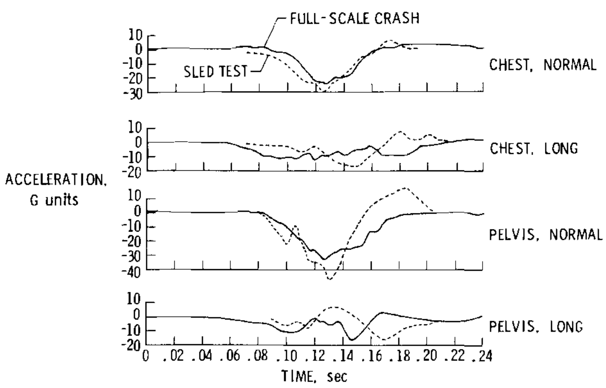

Fig. 18 Dummy accelerations from sled test and from a full-scale crash test under similar impact conditions.

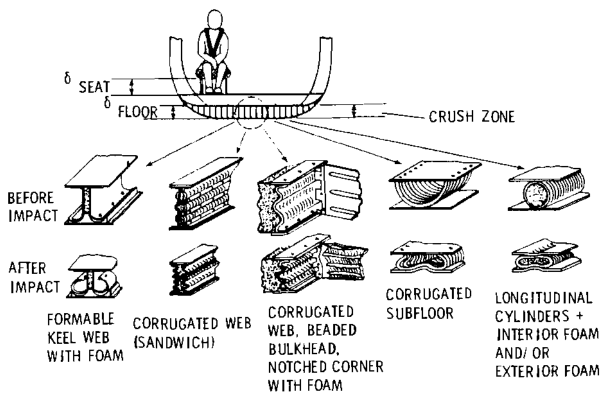

Fig. 19 Load limiting subfloor concepts.

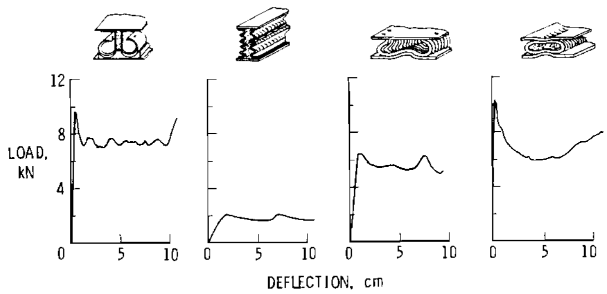

Fig. 20 Load-deflection curves for load limiting subfloor concepts.

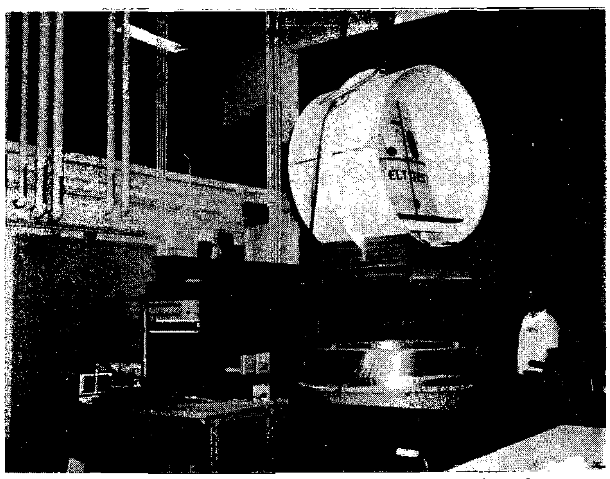

Fig. 21 Emergency Locator Transmitter (ELT) test apparatus.

ISASI SEMINAR '79
LIST OF PARTICIPANTS

* ABARBANELL, Oded
77 Bnayahu St., Tsahala
P.O. Box 10094
Tel-Aviv, Israel

* ALLARD, Robert L.
NTSB
784-D Fairview Ave.
Annapolis, MD 21403

* BAILEY, Joe
AMSI
Corp Plaza Las Colinas
4950 N. O'Connor Road, #265
Irving, TX 75062

* BARNHART, Rev. W.D.
Civil Air Chaplains Int'l.
629 Ransom St.
Ripon, WI 54971

* BARTEL, Richard
Human Factors Engineer
P.O. Box 153, Station H
Montreal, Quebec
Canada H3G 2K7

* BENDER, Dieter
815 Holzkirchen
Bergfried Str. 4
Federal Republic of Germany

* BENTLEY, V.
CALPA
3009 - 140th St.
Surrey, British Columbia
Canada V4A 4J5

BICKNELL, R.P.
CALPA
9675 Cote de Liesse #200
Dorval, Quebec, Canada

BISSONNETTE, Bob
Minnesota State DOT
8290 - 85th St. S.
Cottage Grove, MN 55016

BOARDMAN, W.
US Aviation Underwriters
110 William St.
New York, NY 10038

BROWN, Richard K.
University of Southern
California
Institute of Safety &
Systems Management
Office of Special Programs
Room 104
Los Angeles, CA 90007

* BRUGGINK, Gerard
2107 Centennial Drive
Dothan, AL 36301

BURGESS-WEBB, Roger
CALPA
35 - 1st St.
Orangeville, Ontario, Canada

CAIGER, B.
National Research Council
Box 921, Manotick, Ontario
Canada

CARPENTER, W.J.
Coroner Service of
British Columbia
700 West Georgia, 5th Floor
Vancouver, British Columbia
Canada

* CASSINGHAM, Delmar E.
4420 Majestic Circle
Pleasant View, UT 84404

CELLA, T.
AASC
8414 Hampstead
St. Louis, MO 63123

* CHIPPINDALE, R.
Office of Air Accidents
Investigations
Ministry of Transport
Wellington, New Zealand

* COLLINS, Thomas J.
6517 Allview Drive
Columbia, MD 21046

* CONLON, S.B.
Air Claims Inc.
2841 East Lee Ave.
Alexandria, VA 22306

* CORNELL, S.B.
Republic Airlines
Rialto Bldg.
Joliet, IL 60431

* COULTER, Charles M.
Allied Pilots Association
1736 Woods Drive
Arlington, TX 76010

* COWSER, Roland R.
Flight Manager
American Airlines, JFK
121 Rising Ridge Road
Ridgefield, CT 06877

CZOP, Michael
Aviation Marine Services Inc.
P.O. Box 319
Collegeville, PA 19426

* DAVIES, David E.
Westley & Callaghan
Suite 207
300 University Ave.
Sacramento, CA 95825

* DAVIS, Tom H., Esq.
Byrd, Davis & Eisenberg
214 Austin National Bank Bldg
Austin, TX 78701

* DE LAVISON, C.
Air Canada
5410 rue Charlebois
Pierrefonds, Quebec
H2X 2K4, Canada

DEMONE, G.A.
c/o Eastern Provincial Airways
Halifax, Nova Scotia, Canada

* DENNIS, Jerry T.
NTSB
SRA Box 1452A
Anchorage, AK 99502

* DIECKHOFF, Richard H.
US Aviation Underwriters Inc.
110 William St.
New York, NY 10038

* DONOVAN, D.A.
Republic Airlines
Rialto Blvd.
Joliet, IL 60431

DRABANT, Robert
Rust & Aimenis
555 Capitol Mall
Suite 1200
Sacramento, CA

* DRAKE, John B.
NTSB
12733 Builders Rd.
Herndon, VA 22070

* DUBE, F.
DOT Canada
1328 Fernwood Drive
Ottawa, Ontario
Canada K1V 7J9

DUBIN, Mr. Justice C.L.
Osgoode Hall, Toronto
Ontario, Canada

(c) * DYKHUIS, H.A.
United Airlines
1747 Crystal Lane
Mt. Prospect, IL 60056

* EDWARDS, Laurence S.
President, ISASI
31 Mallon Dene
Rustington
W. Sussex BN15 2JP, England

EIK, David
AMSI

* FERRY, Ted S.
University of Southern
California
44 Karen Place
Newbury Park, CA 91320

* FRITSCH, Olof
ICAO
602 Cote St-Antoine
Westmount, Quebec, Canada

GAGNON, Robert

* GALLAGHER, J.D.
CALPA
R.R. No. 1
Inglewood, Ontario
L0N 1K0 Canada

(c) GIORDANO, Robert
Federal Express
Box 727, Dept. 100
Memphis, TN 38194

(c) GOGILIA, John
Machinist Union-IAMAW
73 Auburn St.
Saugus, MA 01906

GOLZE, D.
CALPA
49 Aspen Lane
Box 51 Hudson
Quebec J0P 1H0 Canada

GOMAZ, Y.L.
Ministry of Civil Aviation
Cairo Airport, Cairo
Egypt

* GREEN, Robey
Private Investigator
477 West Charles Drive
Melbourne, FL 32935

* GRESHAM, Harry G.
Associated Aviation Underwriters
9203 Livenshire
Dallas, TX 75238

* GUINN, Render C.
Aviation Safety, Fort Rucker,
Alabama
Rte. 3, Box 212
Enterprise, AL 36330

* HARRINGTON, Jack G.
901 Central Road
Glenview, IL 60025

* HARRIS, James L.
Consultant
7169 Forum St.
San Diego, CA 92111

* HALL, David S.
Crash Research Institute
P.O. Box 968
Tempe, AZ 85281

HEASLIP, T.W.
Transport Canada
ASE Transport Canada Bldg.
Ottawa, Ontario K1A 0N8
Canada

* HNOT, Walter
Insurance Co. of North America
1600 Arch St.
Philadelphia, PA 19103

* HOGAN, Brian R.
U.S. Aviation Underwriters
111 E. Touhy Ave.
Des Plaines, IL 60018

(c) * HOGUE, P.
Boeing Aircraft Co.
Box 3707
Seattle, WA 98124

* HOHN, Otto
Ajusta Airclaims
106
P.B. 60118
Caracas, Venezuela

* HOWDEN, R.I.C.
Flight Operations Dept.
Cathay Pacific Airways Ltd.
Kai Tak, Hong Kong

HOWES, W.M.
Transport Canada
1248 Evans Blvd.
Ottawa, Ontario K1H 7T9
Canada

* HUGHES, G.V.
DOT, Australia
10 Rhodes Drive
Glenwaverley 3150
Victoria, Australia

* HUTCHESON, E.L.
Helicopter Association of America
1156 - 15th St., N.W.
Washington, DC 20005

(c) IWASA, Osamu
Japan Airlines Co. Ltd.
2-1-1 Haneda Int'l Airport
Ohta-ku, Tokyo, Japan 144

* JOHNSON, J.A.
Dept. of Civil Aviation
Ministry of Transport & Communication
Freetown, Sierra Leone

* JONES, R.M.
CALPA
Box 305
Nobleton, Ontario L0G 1N0
Canada

* JORGENSEN, Robert K.
Deputy Chief Executive for Operations
Philippine Airlines
P.O. Box 954
Manila, Philippines

* KIDD, Robert M.
CAE Electronics
15 Muir Park Rd.
Senneville, Quebec
H1S 2C1 Canada

* KELLY, Donald E., Esq.
Pennie & Edmonds
330 Madison Ave.
New York, NY 10017

* KENNEY, F.E.
Dept. of National Defence
1 Ashwick Cresent
Ottawa, Ontario

* KLEIMENHAGEN, V.
FAA
11206 Radisson Drive
Burnsville, MN 55337

* KOSMIDER, K.
657 Pepperloaf Cresent
Winnipeg, Manitoba
R3C 1E6 Canada

* LAKE, Peter
Writer
2 Ketch St.
Venice, CA 90291

* LAURITSEN, B.M.
Civil Aviation
Codanhus
60 Gammel Kongevij
DK-1850 Copenhagen V.
Denmark

* LAZOUSKI, J.C.
Canadian Armed Forces
1133 Sheppard Ave. W.
P.O. Box 2000
Downsview, Ont. M3M 3B9
Canada

* LEDERER, J.
EPRI & USC
468 Calle Cadiz
Laguna Hills, CA 92653

* LEE, Raymond C.
Raymond C. Lee & Associates
5164 E. Princeton Ave.
Englewood, CO 80110

* LEGGETT, James F., Esq.
The Law Offices of James Francois Leggett
Suite 2025
One Washington Plaza
1201 Pacific Ave.
Tacoma, WA 98412

* LINDEBOD, M.
SAS
35 Mosevangen
DK 3460 Birkerod
Denmark

* LOMAS, R.
British Airways
T326 Comet House
London (Heathrow) Airport
Hounslow, Middlesex, U.K.

* LYBECK, Wayne A.
Republic Airlines
Box 157
Belleville, MI 48111

MacWILLIAM, R.
CALPA
1300 Steeles Ave. East
Brampton, Ontario L6T 1A2
Canada

* MAEDER, H.P. Hubert
Federal Aircraft Accident Investigation Bureau
Bundeshaus Nord, Bern
Switzerland CH 3003

(c) * MARGWARTH, John
Lockheed Aircraft Corp
23983 Via Bocina
Valencia, CA 91355

MARTINEAU, M.
CALPA
4736 Victoria Ave.
Montreal, Quebec H3W 2N1
Canada

* McDONALD, John R.
Aviation Accident Consultant
196 June Drive
Cocoa Beach, FL 32931

* McINTOSH, W.
Penderson, Toronto

McLEOD, R.K.
Transport Canada
ASE Transport Canada Bldg.
Ottawa, Ontario K1A 0N8
Canada

* McWHORTER, J.
John L. McWhorter & Associates
1454 S.W. First St.
Miami, FL 33135

* MEBIUS, Lars H.
SAAB-SCANIA Aerospace Division
7 Batvagen
Wreta Kloster
Sweden S59061

* MERRITT, H.G.
Canadian Armed Forces
995 Goyer
St. Bruno, Quebec
Canada

* MILLIGAN, Ian S.
Air Safety Investigation Branch, DOT, Australia
14 Kerry Close
Doncaster, East Victoria
Australia, 3109

(c) NISHIMURA, Yoshihide
All-Nippon Airways Co. Ltd.
1-6-6 Haneda Airport
Ota-Ku, Tokyo, Japan

* NOBERT, Gilles
Brouer & Co.
7185 Blondin
St. Leonard, Quebec
H1S 2C1 Canada

* NYBORG, Ore
Dept. of Accident Investigation Bureau
Birche Meyer Lauritsen
G.L. Kongerei 60
DK 1850 Copenhagen
Denmark

* O'BEIRNE, Larry E.
1365 Chateauguay
St. Bruno, Quebec J3V 3A7
Canada

OKADA, S.
The Aircraft Accident Investigation Bureau, MOT
Kasumigaseki,
Chiyoda-Ku, Tokyo, Japan

* ORR, Robert G.
The Boeing Co.
252 Arbour Cresent
N. Wales, PA 19454

* PAPADAKIS, M., Esq.
Delta Airlines
6106 Morning Crest
Spring, TX 77373

(c) PARKER, George B.
University of Southern California
3407 Sea Breeze Lane
Corona Del Mar, CA

* PAUL, Olaf
Canadian Air Safety Investigator
2306 Hillside Dr.
Burlingame, CA 94010

* PHILLIPS, Samuel M.
US Army Safety Center
P.O. Box 585
Daleville, AL 36322

* PLENGE, Lisbeth
SAS
Fagerlunden 32
2950 Vedbaek, Denmark

* PRENDAL, B.
SAS
Stationsvej 10A
3520 Farum, Denmark

REES, Linden
Canadian Aviation Ins. Managers Ltd.
Royal Bank Plaza
P.O. Box 2
Toronto, Ontario M5J 2J1
Canada

REYES, Reynaldo
ALPA-Philippines
Manila, Philippines

* RHODES, G.H.
ATS Incorporated
6596 Maplewood Dr.
Cleveland, OH 44124

(c) RIDDERBUSCH, H.C.
Sundstrand Data Control
Overlake Industrial Park
Redmond, WA 98052

* RIMSON, I.J.
System Safety Associates Ltd.
4507 Wakefield Drive
Annandale, VA 22003

* RUBENS, R.G.
Republic Airlines
Rialto Bldg.
Joliet, IL 60431

* RUDICH, Robert
Air Transportation Consultants
Box 7351
Alexandria, VA 22307

SAITO, H.
The Aircraft Accident Investigation Bureau, MOT
Kasumigaseki,
Chiyoda-Ku, Tokyo, Japan

* SALAS PARRA, J.A.
FAA
Country Club Calle el Valle Quinta
La Lomita, Caracas
Venezuela, S.A.

* SATTERFIELD, James E.
J.E. Satterfield & Associates
10215 Quiet Valley Lane
Houston, TX 77075

* SAYERS, Daniel C.
Daniel C. Sayres Associates
37 Sea Breeze Road
Massapequa, NY 11758

* SCHLEEDE, Ronald L.
NTSB
10255 E. 25th Ave.
Suite 14
Aurora, CO 80010

SCHNEIDER, Dr. G.F.
Chief of Investigation Bureau, MOT
Elizabeth Str. 9
1010 Vienna, Austria

SCOTT, Ronald C.
Kursen, Evans & Byrne
Public Ledger Building
Independence Square
Philadelphia, PA 19106

* SERRA, Jaime D.
Associates Int'l Inc.
401 Bonnie Brae Way
Hollywood, FL 33021

* SHULTS, E.H.
Private Investigator
821 E. Providencia Ave.
Burbank, CA 91501

SILVA, Wayne
Casey Corp. of California
9495 Rogers Road
Sacramento, CA 95823

SIMPSON, D.
Texas International Airlines

SLANGEN, Arnold
CAN Airclaims Ltd.
P.O. Box 304
Montreal Airport
Dorval, Quebec, Canada

* SMITH, Reg H.
CALPA
9675 Cote de Liesse Road #200
Dorval, Quebec
H9P 1A3 Canada

* SMITH, Roger
CANADAIR Ltd.
70 Thurlow Rd.
Hampstead, Quebec H3X 3G9
Canada

* SNYDER, R.G.
Biomedical Dept.
University of Michigan
Ann Arbor, MI 48109

SOLIMAN, Amado
ALPA-Philippines
Manila, Philippines

* SPROGIS, H.L.
117 Peaceable Hill Road
Ridgefield, CN 06877

STALLKAMP, Roger
Hartzell Propeller Co.
350 Washington Ave.
Piqua, OH

STEWART, R.
CALPA
9675 Cote de Liesse Rd. #200
Dorval, Quebec H9P 1A3
Canada

(c) STUART, Keith
* Pratt & Whitney Aircraft Ltd.
C.P. 10
Longueuil, Quebec
J4K 4X9 Canada

* SUZUKI, Toshiro
5-90-14 Ikeda-Cho
Yokosuka, Japan 239

* SWEENEY, W. Michael
Insurance Co. of North America
691 Hallow Road
Radnor, PA 19087

* SWEET, John, Esq.
Sweet, Dussault & Neff
219 E. Galer
Seattle, WA 98102

WALTON, M.
Dept. of National Defence
Quality Engineering
Test Establishment
Ottawa, Ontario K1A 0K2
Canada

* WARREN, G.R.
CALPA
9675 Cote de Liesse #200
Dorval, Quebec
H9P 1A3 Canada

* WILKEN, Frederic
American Aviation Services Corp.
10534 Natural Bridge Rd.
St. Louis, MO 63134

* WILKINSON, R.W.
CALPA
9675 Cote de Liesse #200
Dorval, Quebec
H9P 1A3 Canada

* WOOD, Richard H.
University of Southern California
12711 - 9th Street
Yucaipa, CA 92399

* WOODRUFF, B.
Associated Aviation Underwriters
30 Adrienne Place
Staten Island, NY 10308

(c) WU, Yung-Chuan
* China Airlines Ltd.
26, 2nd Floor, Sec. 3
Nanking E. Rd.
Taipei, Taiwan

* YATES, Andy D.
7413 Park Terrace Drive
Alexandria, VA 22307

YUMAR, J.
ALAV
Asociancion de Lineas
Aereas en Venezuela

* YURMAN, Allan
AMSI
352 Perrine Ave.
Piscataway, NJ 08854

* ISASI Member
(c) Corporate Representative

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West Building, Room 168
Washington National Airport
Washington, DC 20001

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