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ANALYSIS OF WRECKAGE

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IT IS THE PURPOSE of this paper to discuss and to demonstrate the procedures and philosophy of accident investigation and to demonstrate some of the techniques, first in a general or philosophical way, and then by case studies showing an application of the general approach outlined.

There exists in our literature an extremely vast body of information and there have been many years of experience in the investigation of aviation accidents and incidents of all kinds and the literature, published in both America and abroad, is a first starting point for anyone interested in understanding, following, and using the results of an aircraft accident investigation. Some of the literature in this field is cited in the attachments to this paper and will not be reviewed at this time.¹ Most of the written accident investigation material has as its central theme the investigation of aircraft accidents for the purposes of accident prevention and a determination of the causative factors contributing to an accident is essential to this goal. This goal, however worthy, is not identical at all times with the goals of those who would seek to assign and enforce responsibilities to others who may have been willing or unwilling participants in the accident in question.

As you will learn from some of the attached literature, the Na-

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¹ Dr. Packer recommends the following authorities for further reference: Address by Frank G. Andrews, AVAILABILITY OF INVESTIGATION INFORMATION, Aircraft Accident Investigation, A.B.A. NAT. INSTITUTE ON SMALL AIRCRAFT ACCIDENT LITIGATION, Dec. 7, 1973; DEP'T OF TRANSP., F.A.A., AIRCRAFT ACCIDENT INCIDENT INVESTIGATION & REPORTING 8020.1A (1968); W. GEIGER, FIELD GUIDE FOR AIRCRAFT ACCIDENT INVESTIGATION, Univ. So. Cal., The Safety Center (Rev. ed. 1973); W. HALNON, NAT. TRANSP. SAFETY BD., AIRCRAFT ACCIDENT INVESTIGATION METHODOLOGY (19—).

tional Transportation Safety Board, operating under the Department of Transportation, is charged with the responsibility of investigation of aircraft accidents and the determination of probable cause. Certain categories of investigative activities are delegated to the Federal Aviation Administration. The missions of each body, the role of interested parties, and the degree of involvement allowed the owner, operator, manufacturer, and component manufacturer for a particular aircraft are controlled through these groups and their charter.

Techniques for the investigation of accidents have evolved to a high level of sophistication, as have the organization and training of investigative teams. Figure 1 shows the prescribed make-up for such a team or specialty group. Note that the primary data gathering will follow the same organizational structure, whether the group is military, civilian, or government-body-controlled and whether the investigative team is comprised of one man or many. The principle areas of investigation include: (1) operations (2) witness (3) Air Traffic Control (4) weather (5) human factors (6) structures (7) systems (8) power plants (9) maintenance records (10) flight recorder and in-flight records.

Once one has become enamored by the desirability of investigation of accidents and the assignment of cause and responsibility and has educated himself in the broad realm of available materials, the time to start the planning for the approach to investigating a specific accident is not at 4 a.m. on some foggy morning when Flight 748 has augered in from 12,000 feet in a blinding rain-storm. The engineering investigator who you will hire will not be interested in spending a great deal of time establishing rapport with an attorney, as much as he will be interested in getting to the scene, finding the artifacts of the wreckage, establishing or learning the factual information on a first-hand basis, if possible. This procedure is essential from both a technical efficiency viewpoint and from the cost effective viewpoint, which we will discuss shortly. He should be available to put his time and attention where it is most needed within the first few hours of the accident. It is essential that you know how to make your expert a member of the investigative team as an interested party. This may or may not be possible depending on who you might represent or the nature of the acci-

TEAM INVESTIGATION ORGANIZATION

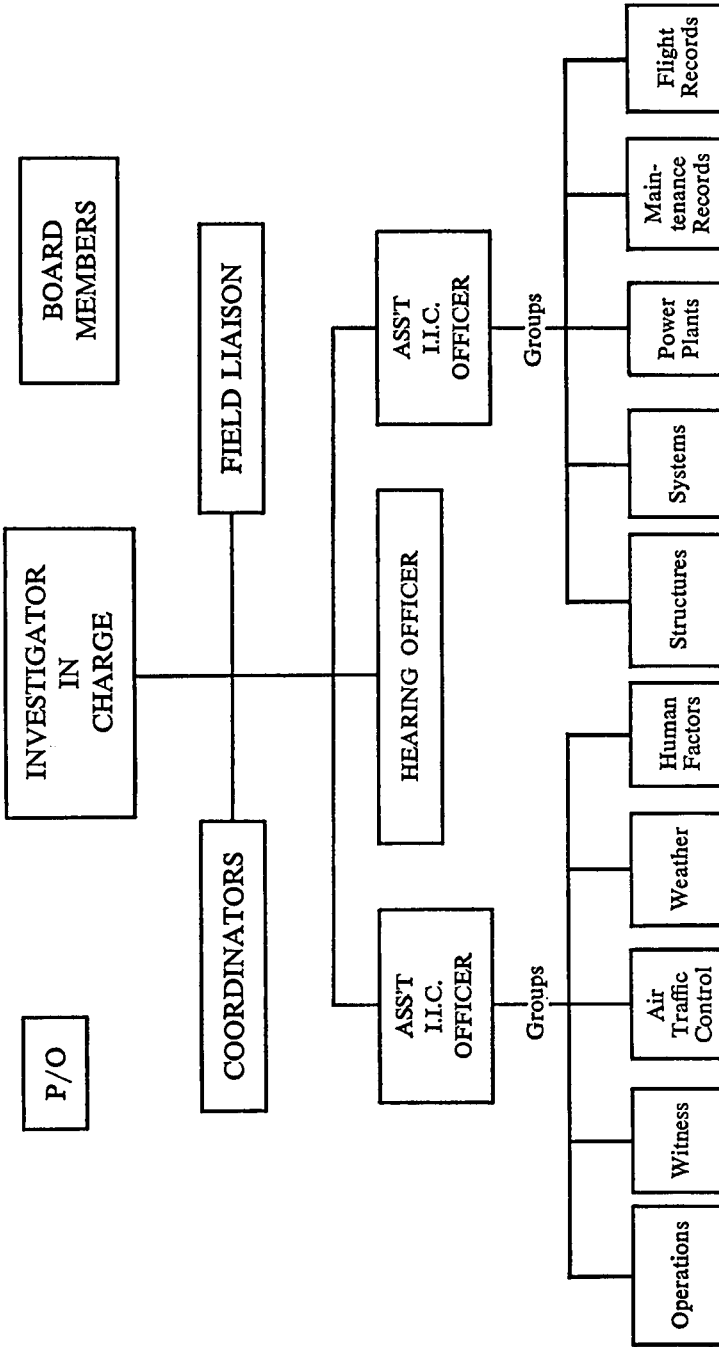


FIGURE 1—Accident Investigation Team Composition

dent and the make-up of the NTSB or FAA membership which sets out on the initial investigation.

There are other considerations which warrant consideration in advance of that chilly morning. One such consideration is economics, which is important. Analysis and discussion between the attorney and his investigator in advance of an accident are highly desirable.

First let's talk about a team of which an engineer will be the team leader, with the advocate's responsibility of best representing the client's interest. This team, initially, will consist of a principal technical investigator, a representative of your client, and yourself. It will be the responsibility of the three members of this team, not only to determine the technical fact, but to assess cause and responsibility and to mine all the resources available to them through the actions of others and through other investigations. Pre-planning in advance of the accident and the assignment of broad areas of responsibility for gathering of information will save not only time and energy, but dollars as well.

Considering the economic aspects of an aircraft accident investigation, the potential size of the loss, the number of deaths, the size of the aircraft, the amount of property damage, limits of coverage, and potential liabilities, all dictate the kind of investigation which can and should be conducted. Whether we like it or not, the ultimate investigative approach adopted must be based on the economics of the over-all situation. This approach is not foreign to the NTSB or the FAA. Their assignment of numbers of investigators, the size and depth of the investigating team and level of effort is based on a pre-programmed basis related to the category of aircraft, incidence of fatalities, and size of the loss encountered. Different philosophies are applied by various parties or team members and the principal investigator must allow for these different philosophies and operating procedures.

Following the writings of the various Government agencies and the training of many of the investigative personnel available, it is a relatively easy task to outline a complete accident investigation program, covering the entire flight sequence, weather, etc. In short, all of the factors which are enumerated in Figure 1. But the real test of an investigator and of a group, such as the three man group described above, is their ability to cut through the many unneces-

sary investigative steps that are superfluous to their assigned objective. An innovative approach is required to arrive at the most direct path for a cost effective solution to satisfy the objective of the investigation as it was preliminarily outlined. The decisions made at this stage in the investigation will shape and determine the suitability of the end product. Time and money expended at this time will maximize results and minimize inefficiency and total expenditure. As in most other areas of investigation, the selection of highly qualified, innovative persons to participate in the initial team planning is of utmost importance!

Based on the preliminary innovative discussions on the part of the lead team, the actual investigative team is then selected and assigned to the job. This investigative team may include psychologists, physiologists, aerodynamicists, power plant specialists, metallurgists, operations specialists, system safety engineers, professional safety specialists, pilots, mechanics, weather experts, cartographers, hydraulics experts, fuel experts, aviation pathologists and others. It can be seen at this point that pre-planning and pre-knowledge of the availability of these persons is of extreme importance. Again, the time to start searching for these persons is not at 4 a.m. on a cold, rainy morning.

Systemization of the procedures and analysis is an essential ingredient. One tool which is sometimes useful as an aid to this systemization is the accident investigation matrix shown in Figure 2. Subdivide the investigative problems into human inputs, environmental inputs and mechanism inputs. Further subdivided down into considerations of power plant, air frame, instrument and guidance system and other categories such as weather, air traffic control, etc. is oft times desirable. From a study of the matrix presented in Figure 2, you can see that the problem you are attempting to solve most often is a relatively simple one. You are attempting to determine from a post-accident investigation of the human factors, environmental inputs, and the mechanism, as it exists after the crash, what the first cause and effect relationships were which led to the accident being investigated. Further, you are attempting, through a study of these three principal factors and your knowledge of the law, to assign the responsibilities to the appropriate parties. The potential involvements of the many parties may be studied or brought into focus by studying the pre-accident items shown in

	PRE-CRASH (Years to Seconds)	DURING CRASH (First Problem to Impact)	POST CRASH (First Inspection to Present)
ENVIRONMENTAL FACTORS (Weather, Runway Condition, Trees, Etc.)			
HUMAN FACTORS (Disorientation, Carelessness, Alcohol, Mental, Experience, Etc.)			
MECHANICAL FACTORS (Airframe, Power Plant, Control Systems, Electrical, Oxygen System, Deicing System, Etc.)			

FIGURE 2—Accident Matrix Grid for Organizing Investigative Information.

Column 1: human factors, environmental inputs, and the mechanism.

At this point in the discussion, I would like to warn against one of the most common faults found in the investigation of accidents and the assignment of responsibilities through an attorney-led lead team—"early-blur blindness." This is the urgent desire to arrive at a decision making stage in the early investigation and to blur the final decision by so doing. There is a requirement, based soundly on human learning behavior, for conducting an investigation into an aircraft accident without the formation of fixed notions which, in effect, deny to the investigator the objectivity and the ability to see other potential solutions to the same problem which ultimately may be of infinitely greater value to the principal or lead investigator. The risk of loss of this objectivity and the potential consequences are so great, that the attorney, in the initial stages of the investigation, must guard against the stultifying effects of early-blur decision making at all costs.

There are other facets to the investigation of aircraft accidents which put an unusual demand on the lead team and each of the investigators selected for each particular task. There is no rational basis to know at the outset the full course which will be followed. It is not possible to know what the responsibilities are, what might be involved, and whether or not the investigation will ultimately lead to litigation and presentation in the courtroom. Accordingly, you must plan your investigation to gather all of the available facts and to document them in a satisfactory manner. One must be prepared to tell the story of the investigation and the logic of the fact determining process and be prepared to defend the logic of the conclusions drawn before those facts and those conclusions are drawn. This requires that the lead team investigator be thoroughly versed in documentation, photography, and in courtroom presentation. It also takes something unusual by way of investigative and photographic capability. One must be able to document and photograph the various artifacts with the knowledge that they may or may not be important parts of the total cause-origin-result sequence and that ultimately the photographs and documents will form an important part of the telling or selling of the story once the results have been formulated. That is, you must prepare to tell the story in court, if necessary, from the start of the investigation by the manner in which the information is documented and, in particular, with the photographs as they are taken. It is important to have a continuing discourse between your team members relative to potential causes, origins, and results, so that you can cover each of the important items and that you formulate a systemized check-off list, such as those outlined in the bibliography, so that the chance of overlooking an important bit of factual information is minimized.

At this juncture, let us review our objective and briefly outline the procedure to be followed by this investigative team. Our primary objective is to find the initiator, that is the first cause-and-effect relationship with the ultimate goal of assigning responsibility. In order to do this, one needs to reconstruct the sequence flown by the aircraft immediately prior to the accident, map the scene, analyze the failure modes and their potential effect, and then reduce these potential failure modes to reasonably fit into the matrix. Data must be gathered to fill in the matrix as expeditiously as possible. The goal is to gather the data on all of the potential failure

modes, analyze them, then re-evaluate each to see if these, or other, modes that are suggested fit the sequence of the accident. This procedure must be repeated with the gathering of new data, continuing analysis and reformulation of the original hypotheses, all within the bounds of the cost effective requirements previously outlined. The demands placed upon the personnel selected at this point in time are sizeable, and a high degree of familiarity in all of the areas, including the past performance of the specific aircraft in question, the behavior of pilots in general, the air traffic control network, the effects of weather and, in short, all of the fields of aviation, including structures, materials and power plants are required in order to map out and properly follow the program. These must be put together with a person or persons who are keen observers, having the ability to observe and to fit those observations into their proper place in the problem solving matrix. Ultimately, these same people must be able to sell the logic of this approach and the correctness of the solution in the courtroom.

We will now attempt to further demonstrate the various points which have been postulated in the preceding introductory material by examining a series of accident case histories.

Case Study No. 1

While operating near the ground, a turbine powered helicopter crashed, impacting in a near inverted attitude. A law suit was initiated against the manufacturer of the craft, alleging a design or manufacturing defect in a flight control system component. Preliminary investigation ruled out the influence of weather and engine malfunction. The causal factors were postulated as being either improper operation by the pilot or a sudden mechanical failure in the control or drive systems of one or both rotors. Most of the fractures in these systems could be easily related to ground impact damage with the exception of the pitch link clevis failures. Two prominent metallurgical groups examined these failures and employed strictly fracture mode analysis which resulted in conflicting fracture modes. One report concluded that the failure was a result of progressive damage (fatigue) and hence, an in-flight mechanical failure. The other report concluded that the failure was typical of a static, one-time overload fracture (ground impact).

The solution to the problem involved a combination of fracto-

graphic analysis, plus the determination of the overall deformation patterns of the upper pitch link control showed the tube and clevis to be noticeably bent. The origin of the fracture could be related directly to the direction of maximum stress introduced by the loads which deformed these components. Detailed fracture mode analysis showed the fracture to be primarily of a static type overload with a coarse striated appearance. Striations in the fracture surface often suggest a progressive failure. However, in this case, the striated fracture areas resulted from post-fracture damage to the surfaces. Laboratory tests were performed to determine the fracture morphology resulting from: (1) tension plus bending overload, and (2) fatigue (cyclic) loading to failure. These tests confirmed the subject failure mode to be of the static type and, hence, a result of ground impact.

This case study points out the need to understand the relationship between the microscopic fracture mode and the gross deformation patterns and ultimate confirmation by laboratory testing. Preservation of sufficient evidence is important when metallurgical examination of fracture surfaces alone is not definitive.

Case Study No. 2

A single engine light aircraft experienced an engine failure resulting in a crash killing two people. The objective of the laboratory investigation was to determine what, if any, defects were present in the engine to cause the failure. The engine was disassembled and the examination pointed to either a failure of one piston or the end cap bolt on its connecting rod. Failure of either component would lead to failure of the other. Aluminum alloy chips of the piston material were carried throughout the oil system and trapped at various locations, showing engine rotation at the time of failure. While the exact sequence of failure could not be determined, the most likely cause of failure was failure of the end cap bolt, since previous accidents of a similar nature were traced to improper tightening and subsequent loosening of such bolts. Proximate cause was established and an award was rendered against the manufacturer in this case.

Case Study No. 3

An accident of a heavy commercial aircraft resulted in extensive property damage and loss of life. The initial failure was determined

to be in an upper splice plate, which is a structural part connecting the outer wing to the inner wing. The splice plate was a high strength 7075 aluminum alloy plate 0.175 inches thick, 3.96 inches wide and 8 feet long. Visual examination of the fractures showed that the failure initiated at a hole on the bottom surface of the splice plate. Scanning electron microscopy revealed that a fatigue crack propagated from the hole and across the plate until the remaining section could not support the load. The fatigue crack occurred because the taperlock fasteners were not beveled. Beveling the fastener holes and applying an inhibitive paint in the joint crevices has prevented recurrence of this type of failure.

Recent Advances In Investigative Hardware

Great advances have been made in the last ten years in developing equipment and techniques to understand material behavior. A complete description of each system, or its particular operation, is beyond the scope of this paper. Two important systems worthy of note are the Scanning Electron Microscope coupled with chemical analyzing capabilities (electron microprobe chemical analyzer) and the infrared thermal imager. These techniques, when combined with standard investigative tools (visual, radiographs, mechanical properties tests, photography, measurement, etc.) can often confirm or deny the validity of a hypothesis. Before the advent of such sophisticated equipment, a hypothesis was often supportable only by opinion. Unfortunately, the interpretation of such data is not the forte of some materials experts and still necessitates the jury to ultimately settle the question of fact. The judicious use of such equipment must be based on the expert's knowledge of interpretation of results and the necessity of such results to arrive at the correct solution of the problem.

The Scanning Electron Microscope

The Scanning Electron Microscope is a high resolution (250°) imaging device used to study the topography of materials. Photographs of the surface of a part can be easily obtained with magnifications ranging from 20X to 100,000X. Subject parts may be directly examined at these magnifications. If, however, suspected parts are too large to be placed in the chamber, and cannot be sectioned, replication techniques can provide the necessary sample to be examined. Briefly, an acetate film is softened with acetone

and firmly pressed against the surface of interest. After drying, the replica is stripped off and a vapor deposited film of pure gold is applied to provide an electrically conducting sample. This replica can then be examined in the same manner as the actual part. Scanning electron microscopy is particularly useful in determining the mode of fracture (ductile overload, brittle, excessive bending, fatigue, stress corrosion cracking, shear, torsion, etc.) or the mode of surface attack or contamination. Furthermore, the results (photographs) are recognizable by the jury, since they appear to be three dimensional, and are simply high resolution, high magnification photographs of the surface.

The Electron Microprobe Chemical Analyzer

The Electron Microprobe is a sophisticated tool for non-destructively analyzing the composition of surfaces of materials. This technique is particularly useful when the type and concentration of surface contamination is important. Particles as small as 0.00004 inches in diameter can be analyzed without in any way destroying the sample. A useful technique, often employed, is to first obtain a scanning electron micrograph of the area in question to provide an easily recognizable reference photograph. The same area can then be scanned to show the distribution of the various elements present on that surface. This method was used to determine whether a copper wire short circuited to a steel distribution box. By combining (a) ordinary metallography with (b) a scanning electron micrograph, and (c) elemental distributions, and (d) x-ray spectra, it was possible to show that the copper bead contained iron and a mating burn on the box contained copper. Furthermore, the wire adjacent to the bead contained no iron nor did the steel box contain copper away from the local burn area. By using these and other techniques, it was possible to prove that the fire was of an electrical origin. It was also established that beads on wire exposed only to the heat of a fire could be differentiated from wire beads produced by electrical arcing.

Infrared Thermal Imaging

The infrared thermal imaging analysis technique is used to study design-related thermal problems in confined and/or hidden areas. This technique has found use in detecting hot spots within an engine nacelle from super-charger operation and exhaust routing

problems. Bright spots on cathode ray tube (CRT, TV screen) are calibrated with temperature to determine maximum temperatures and thermal gradients. The CRT can be photographed to provide a hard copy of the data or the signal can be recorded on magnetic tape. The tape may be played back on a monitor in the courtroom to show the jury how the hot spots develop during operation. This technique led to the determination of the origin of an in-flight fire in a business light twin aircraft.

It is possible to display a typical result for an electrical wire being heated by current while hidden under a section of carpet; (a) normal mode operation, (b) temperature profile across the wire, and (c) y-modulation display mode. Figure 3 presents a useful guide in determining the maximum temperature to which various materials have been subjected.

These new techniques and sophisticated hardware play an important role in aircraft accident causality. However, these are just a small sampling from a large group of tools used by a properly organized and experienced accident reconstruction team.

Heat Pattern Characteristics

1. Glass cloth fuses at 1200° F.
2. Cadmium plating starts to discolor at 500° F.
3. Titanium melts at 3100° F.
Stainless steel melts at 2700° F.
Copper melts at 2000° F.
Brass bearings melt at 1600°-2000° F.
Aluminum alloys melt at 1250° F.
Magnesium alloys melt at 1250° F.
4. Neoprene rubber blisters at 500° F.
5. Silicone rubber blisters at 700° F.
6. Zinc Chromate paint primers start to tan at 450° F.; are brown at 500° F.; are dark brown at 600° F.; and are black at 700° F.
7. Stainless steel discolors starting at 800° F. to 900° F. from tan to light blue, to bright blue, to black with increasing temperature.
8. Titanium discolors from tan, to light blue, to dark blue, to gray with increasing temperature.
9. Titanium metal has a high affinity for gases when heated and a scale will begin to form at 1100° F. This scale increases thickness with time at temperature.
10. Soot will not adhere to surfaces which are over approximately 700° F.

FIGURE 3—Guide to determine local heating patterns for typical aircraft materials.