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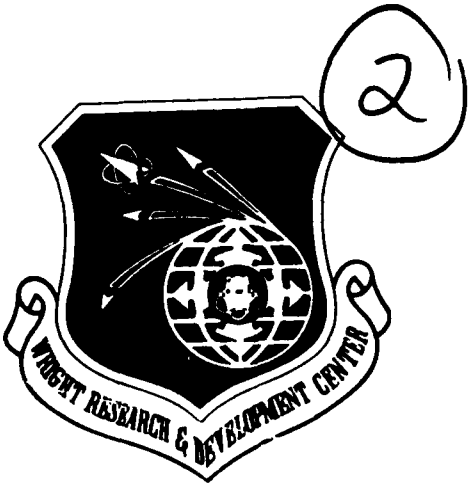

FAILURE ANALYSIS TECHNIQUES FOR THE EVALUATION OF ELECTRICAL AND ELECTRONIC COMPONENTS IN AIRCRAFT ACCIDENT INVESTIGATIONS

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Failure analysis techniques for the evaluation of electrical and electronic components are summarized for: lamps, wiring, connectors, switches, magnetic materials, printed wiring boards and microelectronic devices. Techniques using optical and scanning electron microscopy (SEM) for the analysis of these components are described. Energy Dispersive X-ray analysis (EDAX) of elemental constituents, X-ray radiography, and specialized electrical measurements are also described. The potential for the techniques to distinguish pre-accident conditions from post-impact damage was assessed. Data on the failure rates of aircraft electrical components was reviewed. Data from the Air Force Mishap database indicates that 36 percent of electrical failures on aircraft are caused by interconnections: wiring and connectors. Corrosion is identified as a major cause of connector problems.

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EXECUTIVE SUMMARY

Failure analysis techniques for the evaluation of electrical and electronic components during aircraft accident investigation have been identified and examined. Failure analysis techniques are summarized for: lamps, wiring, connectors, switches, magnetic materials, printed wiring boards and microelectronic devices. Optical and scanning electron microscopy (SEM) are fundamental tools for the analysis of these components. Energy Dispersive X-ray analysis (EDAX) of elemental constituents, X-ray radiography, and specialized electrical measurements are also described. The potential for the techniques to distinguish pre-accident conditions from post-impact damage was assessed.

To establish priorities for further development of failure analysis techniques, data on the failures of aircraft electrical components was reviewed. A review of data from the Air Force Mishap database indicates that 36 percent of electrical failures on aircraft are caused by interconnections: wiring and connectors. Corrosion is identified as a major cause of connector problems. The priority for the further development of failure analysis techniques was assessed by considering the component failures, the ability of the failure analysis techniques to distinguish pre-accident conditions from post-impact damage and the existing documentation on the techniques. Additional testing is recommended to provide documentation to support failure analysis of microelectronic devices, switches, wiring, connectors and printed wiring boards. The development of computer-assisted methods for improving the reliability of analyzed data and for physical modeling of components to support failure analysis are also recommended.

This report summarizes the efforts of a Phase I SBIR contract. The intended Phase II work will result in a handbook of failure analysis techniques for use in aircraft accident investigation.

CHAPTER I
INTRODUCTION

1.0 INTRODUCTION

This report was prepared by Failure Analysis Associates®, Inc. (FaAA) for the U.S. Air Force under contract number F33615-89-C-5647 for the Materials Laboratory, Wright Research and Development Center, Wright-Patterson Air Force Base. The purpose of the work was to collect information on failure analysis techniques that can be used for the evaluation of electrical and electronic components during aircraft accident investigations. A further goal of the work was to identify potential accident investigation techniques that might be developed from failure analysis methods used in industrial applications or ongoing research. Fundamental material properties were also considered as sources of new accident investigation methods. Particular attention was paid to those techniques which can distinguish pre-accident conditions from post-impact damage. Funding for the work was provided by a Phase I contract under the Small Business Innovation Research (SBIR) program.

2.0 PURPOSE OF THIS REPORT

The purpose of this report is to identify and describe failure analysis techniques that can be used for the evaluation of electrical and electronic components as part of the overall process of aircraft accident investigation. Aircraft accident investigation is generally conducted by a team of people because of the number of engineering disciplines involved and the amount of evidence that must be examined. In the U.S. Air Force this team is the Safety Investigation Board, which is responsible for determining the cause of the accident for the purposes of mishap prevention. The investigating officer is the principal coordinator for the technical investigation and relies on laboratory analysts to provide detailed chemical, mechanical, metallurgical and electrical failure analysis of equipment and components. This report is the first step in the process of developing a handbook of failure analysis techniques for the laboratory analyst and other members of the investigating team to use in the examination of electrical equipment as part of an aircraft accident investigation.

As a typical aircraft accident investigation proceeds, attention becomes focused on specific components because of their potential role in the accident. At that point a failure analysis of those

components may be performed either because they are suspected of having played a causal role in the accident, or because they may provide information about the operating condition of the aircraft prior to, or during, the accident. The purpose of the analysis is to answer fundamental questions about the components. For example, it would be useful to know that damage to a particular conductor was caused by an overcurrent condition rather than post-impact fire damage. The laboratory analysts, in their role as accident investigators, use highly specialized failure analysis techniques to obtain the most useful information during this analysis. The fundamental failure analysis techniques which are used during this part of aircraft accident investigation are the subject of this report. Included in this report are existing techniques, techniques being used in other areas that may not be in common use in aircraft accident investigation, and potential techniques identified by FaAA.

The Phase II work, if funded, will result in a handbook of failure analysis techniques that can be used by accident investigators in the analysis of aircraft electrical and electronic components. This handbook will include the failure analysis techniques described in this report, together with examples, procedures and guidelines for the application of the techniques.

3.0 PHASE I TASKS

In carrying out the Phase I work, FaAA performed the following tasks:

1. Reviewed and Analyzed data on the failure rates of electronic components in aircraft.

2. Identified technical literature on accident investigation and failure analysis techniques as related to electrical and electronic components.

3. Reviewed technical reports, text books and other sources to identify techniques that can be used in aircraft accident investigation as related to electrical and electronic components.

4. Reviewed and summarized accident investigation methods for selected electrical and electronic components.

5. Identified areas where further work is needed to develop accident investigation techniques.

4.0 REPORT ORGANIZATION

Failure statistics for electrical and electronic components on aircraft are covered in Chapter II. Chapter III summarizes failure analysis techniques for accident investigation of seven types of electrical components. This chapter is the body of this report and is an example of the kind of material which would be part of a Phase II handbook. The summary, conclusions and recommendations for further work are presented in Chapter IV. Appendix A contains a list of definitions and abbreviations for failure analysis terms used in this report.

CHAPTER II

FAILURE STATISTICS OF ELECTRICAL EQUIPMENT ON AIRCRAFT

1.0 INTRODUCTION

As part of the work performed under this contract, FaAA collected data to identify the contribution of various types of electrical and electronic components to aircraft failures. This chapter summarizes the results of that effort. Data was obtained from three sources:

1. The Air Force mishap database which is maintained by the Directorate of Aerospace Safety at Norton Air Force Base, San Bernardino, California [1].
2. A technical paper on the Avionics Integrity Program [2].
3. A technical paper summarizing a study of printed wiring board failures at Hughes Aircraft [3].

2.0 AIR FORCE MISHAP DATABASE

The Air Force mishap database is a collection of aircraft mishap reports for all aircraft in service in the U.S. Air Force. Mishap reports are filed by pilots for any conditions which affect the safety of the aircraft. In almost all cases some repair activity is performed to address the mishap.

There are four classes of mishaps in the Norton database. Classes A, B and C generally represent in-flight conditions that result in some damage to the aircraft. The designations refer to the dollar value and extent of the damage. The fourth class includes potential mishaps. These may be the result of unusual conditions observed during maintenance or pre-flight checks. Individual reports indicate which system of the aircraft was involved and, in some cases, a component that was repaired or replaced.

Data was requested from Norton Air Force Base on all mishaps related to the electrical system or wiring of the aircraft. The report was generated Nov. 9, 1989 and included all mishap classes, for all aircraft from 1986 to the date of request. A summary report [1] was provided by Norton Air Force Base and reviewed by FaAA. A total of 652 mishaps were included in the summary report, organized by type of aircraft. A sample of the reports was selected and a total of 326 reports were evaluated in detail.

The results of the review are presented in Tables 1 and 2 by aircraft and type of component. The totals for each component are combined in Table 3. Adjusted totals in Table 3 exclude any reports that: (1) could be attributed to operator error; (2) did not identify the component or; (3) listed the constant speed drive as the source of the problem. Although the constant speed drive is generally viewed as part of the electric power system, its operation is primarily mechanical. Percentages based on the adjusted totals by component are listed in the right hand column of Table 3 and shown in Fig. 1.

The data of Table 3 have been grouped according to basic system functions and combined percentages for each of the basic functions have been computed as shown in Table 4. The results are represented in Fig. 2. It is apparent from this figure that interconnections (i.e. connectors and conductors (wiring)) are the largest single contributor to electrical failures on aircraft as recorded in the database. The absence of electronic components from the data shown in Figs. 1 and 2 may be due to the level of detail used in the repair or the accident investigation. It is expected that more active and passive electronic components are actually failure causes than are indicated in Figs. 1 and 2. One reason for this is that the materials used in printed wiring boards and electronic components are not likely to survive post-impact damage. This damage may prevent the components from being identified as failure causes even if they did play a causal role in the mishap. As the complexity of installed electronic equipment continues to grow and fly-by-wire aircraft become more common, accident investigation analysis will be driven to identify electronic devices despite the difficulties caused by post-impact damage.

3.0 AVIONICS INTEGRITY PROGRAM DATA

FaAA reviewed other reports on the failures of electrical equipment on aircraft to support the results shown in Figs. 1 and 2. A paper describing the Avionics Integrity Program (AVIP) [2] includes a summary of electrical failure causes on aircraft. The data is shown in Fig. 3. The paper suggests that connectors account for about 40% of maintenance repairs on aircraft electrical equipment. The formation of surface films that cause connectors to be non-conductive is identified as a major problem. Interconnections on circuit boards (the traces, plated through holes, sockets) and electronic components on circuit boards are also identified as major contributors to failure.

Table 1. Mishap Data from Norton AFB - Group 1
(by Aircraft)

AIRCRAFT

COMPONENT	A-7	A-10	A-37	B-1	B-52	FB-111	C-5	C-10	C-12	C-21	C-23	C-130	C-131	C-135	C-141	F-4	TOTAL
BATTERY					1				1	1							3
CAPACITOR				1													1
CKT BREAKER					2				1			1			1	5	10
CONDUCTOR		5	1	1	1			1	1			3		1	2	10	26
CONNECTOR	1	2	1		1	1			1	3				3	1	10	24
CS DRIVE		2														2	4
EM. POW. UNIT		1															1
GENERATOR-AC	1			1					1			10			1	3	17
GENERATOR-DC	2	1											1				4
INSTRUMENTS												1				3	4
LIGHTS				1								2		2	1		6
MOTOR		1										4		1			6
RELAY		1					1		3						1		6
RESISTOR						1											1
SWITCHES		2	1		2		1				1			1	1	7	16
TRANSFORMER																	0
UNDET (ELEC)												5				1	6
OTHER										1		4	1	2		3	11
TOTALS	4	13	3	6	7	2	2	1	8	5	1	30	2	10	8	44	146

Table 2. Mishap Data from Norton AFB - Group 2
(by Aircraft)

AIRCRAFT

COMPONENT	F-5	F-15	F-16	F-111	H-1	H-3	H-53	O-2	T-33	T-37	T-38	T-39	T-41	OV-10	TOTAL
BATTERY			8								1				9
CAPACITOR			1												1
CKT BREAKER		2									1				3
CONDUCTOR	1	3	11	1		1				1	2		1	2	23
CONNECTOR		1	12	1	1		3		1	2	4			2	27
CS DRIVE			1	1											2
EM. POW. UNIT			7												7
GENERATOR-AC		1	6	1							2				10
GENERATOR-DC							1		2	1	1				5
INSTRUMENTS		1		1		1									3
LIGHTS			3								1				4
MOTOR				1											1
RELAY	1	3	6	1		3					1				15
RESISTOR			1												1
SWITCHES	1	8	9	3	1					2	26				50
TRANSFORMER				2						1	2				5
UNDET (ELEC)			7								1	1			9
OTHER			2	1	1			1							5
TOTALS	3	19	74	13	3	5	4	1	3	7	42	1	1	4	180

Table 3. Summary of Mishap Data from Norton AFB
(by Component)

COMPONENT	GROUP I	GROUP II	TOTALS	ADJUSTED TOTALS	PERCENTAGES
** SWITCHES	16	50	66	56	20
CONNECTORS	24	27	51	51	18
CONDUCTORS	26	23	49	49	17
GENERATOR-AC	17	10	27	27	10
RELAYS	6	15	21	21	8
* OTHER	11	5	16		
* UNDET (ELEC)	6	9	15		
CKT BREAKERS	10	3	13	13	5
BATTERIES	3	9	12	12	4
LIGHTS	6	4	10	10	4
GENERATOR-DC	4	5	9	9	3
EM. POW. UNIT	1	7	8	8	3
INSTRUMENTS	4	3	7	7	2
MOTORS	6	1	7	7	2
* CS DRIVE	4	2	6		
TRANSFORMERS	0	5	5	5	2
CAPACITORS	1	1	2	2	1
RESISTORS	1	1	2	2	1
TOTAL	146	180	326	279	100

* excluded from percentages
** operator errors excluded from percentages

Fig. 1 Summary of Electrically-Related Aircraft Incidents
Approximate Composition by Component
(Based on Data Supplied by Norton Air Force Base [1])
1986-1989

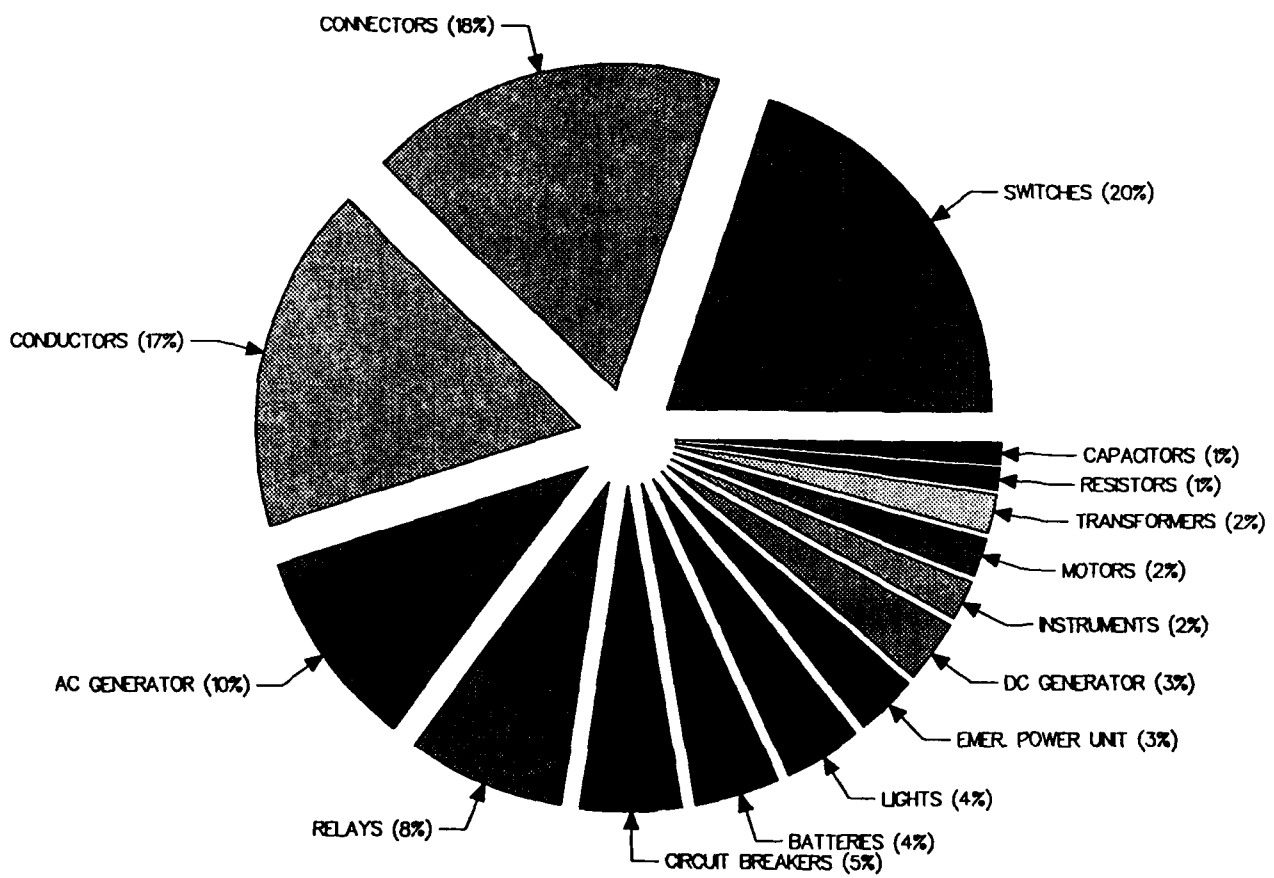


Table 4. Summary of Mishap Data from Norton AFB
(by Function Category)

FUNCTION CATEGORY	# OF INCIDENTS	CATEGORY TOTALS	CATEGORY PERCENTAGES
INTERCONNECTIONS			
CONNECTORS	51	100	36
CONDUCTORS	49		
INSTRUMENTS			
SWITCHES	56		
INSTRUMENTS	7		
LIGHTS	10	73	26
POWER SYSTEM			
GENERATOR-AC	27		
GENERATOR-DC	9		
EM. POW. UNIT	8		
BATTERIES	12		
CKT BREAKERS	13	69	25
ELECTROMECH. DEVICES			
RELAYS	21		
MOTORS	7	28	10
PASSIVE COMPONENTS			
RESISTORS	2		
CAPACITORS	2		
TRANSFORMERS	5	9	3
TOTAL	279	279	100

Fig. 2 Summary of Electrically–Related Aircraft Incidents
Approximate Composition by Basic Function
(Based on Data Supplied by Norton Air Force Base [1])
1986–1989

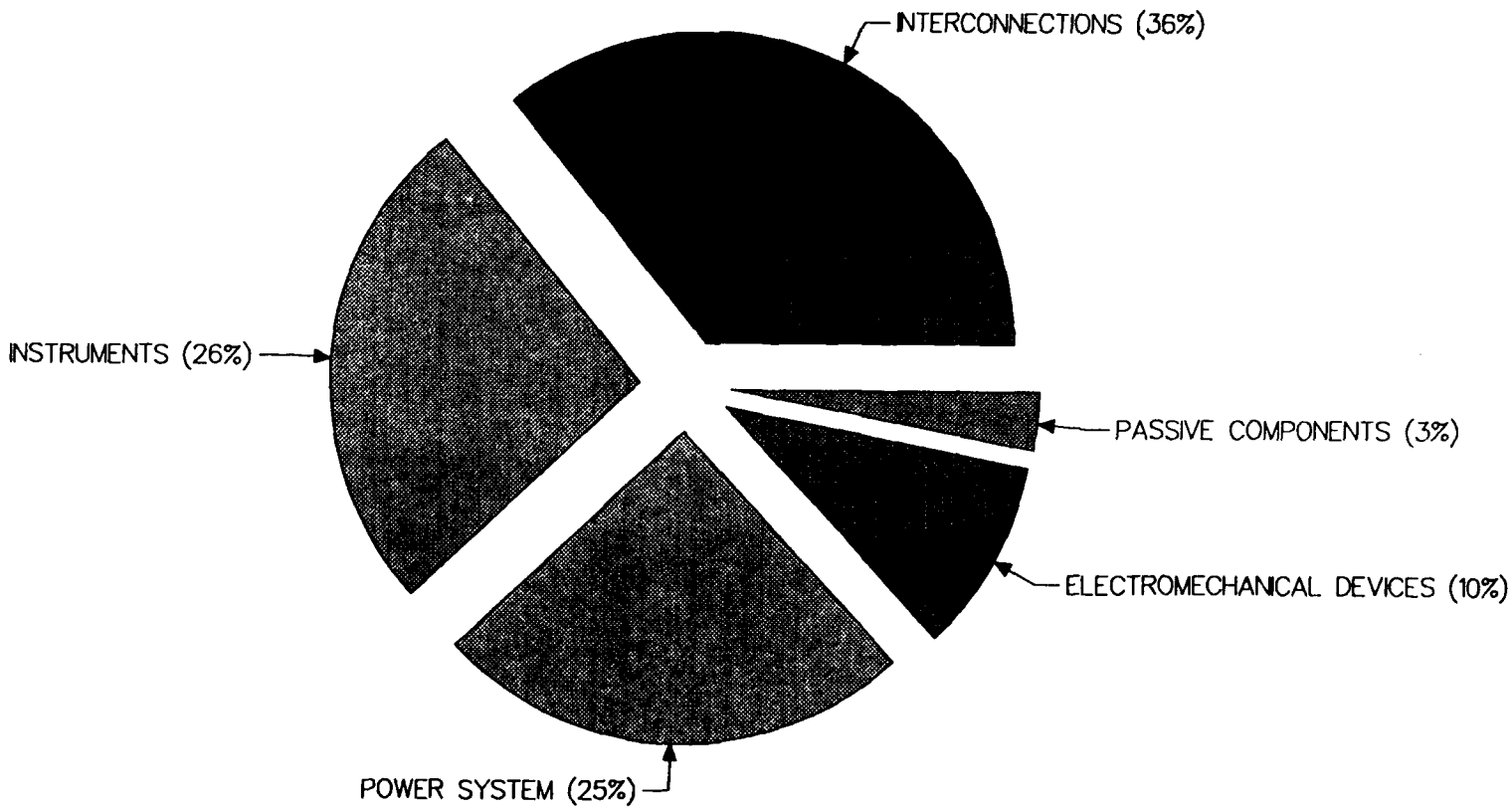
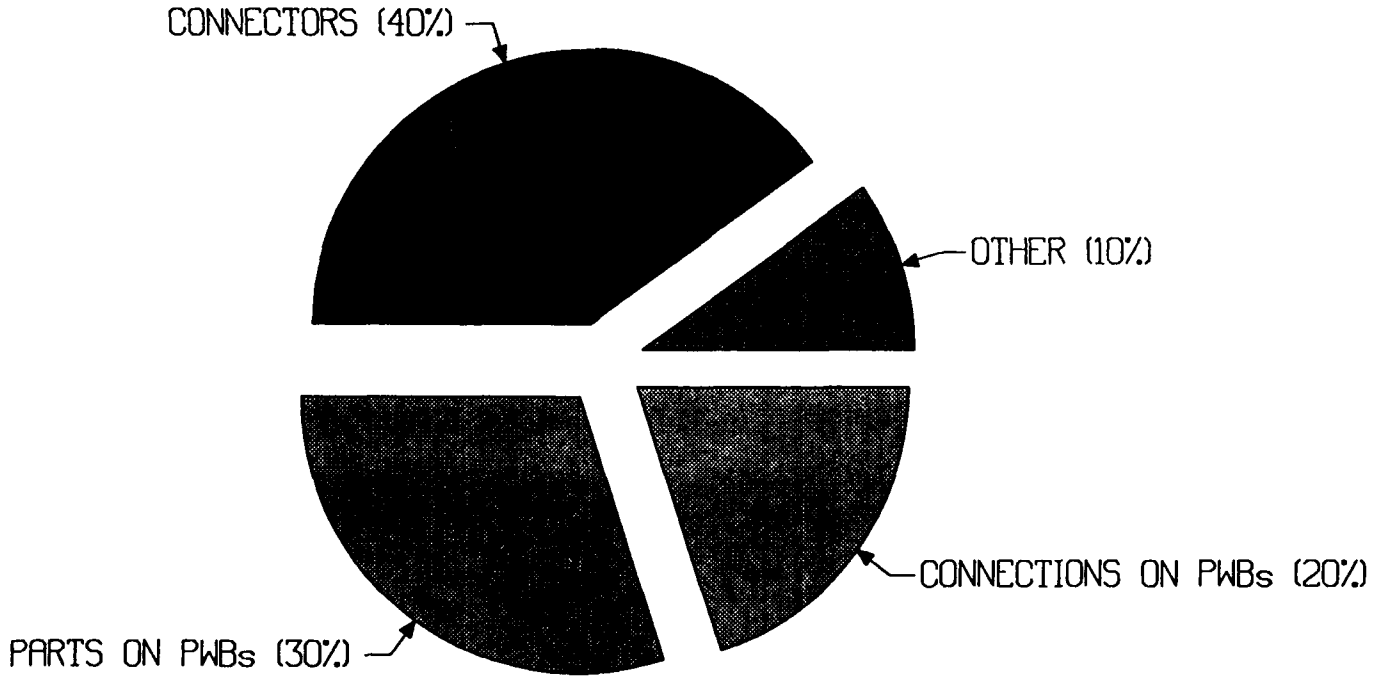


Fig. 3 Causes of Aircraft Electronic Equipment Failures

(Aeronautical Systems Division, Wright-Patterson AFB [2])



4.0 HUGHES AIRCRAFT FACTORY DATA

A study based on repair records for printed wiring boards (PWBs) at Hughes Aircraft [3] presented data which is depicted in Fig. 4. The data is accumulated from four types of PWBs of different ages and complexity levels. The study was based on part replacement data from factory test and quality control activities, not field failures. Over 58,000 repair records were used as the initial source of data for the study. The goal of the study was to rank components in terms of their replacement frequency rather than their failure rate. The reported composite replacement frequency ranking (from highest to lowest) was: ICs; transistors; hybrid circuits, capacitors and resistors; diodes.

5.0 SUMMARY

General conclusions that can be drawn from the data reviewed by FaAA are:

1. Problems with interconnections between equipment are a large contributor to the overall failure rate of electrical equipment on aircraft.

2. Environmental factors, especially corrosion, are significant causes of connector problems.

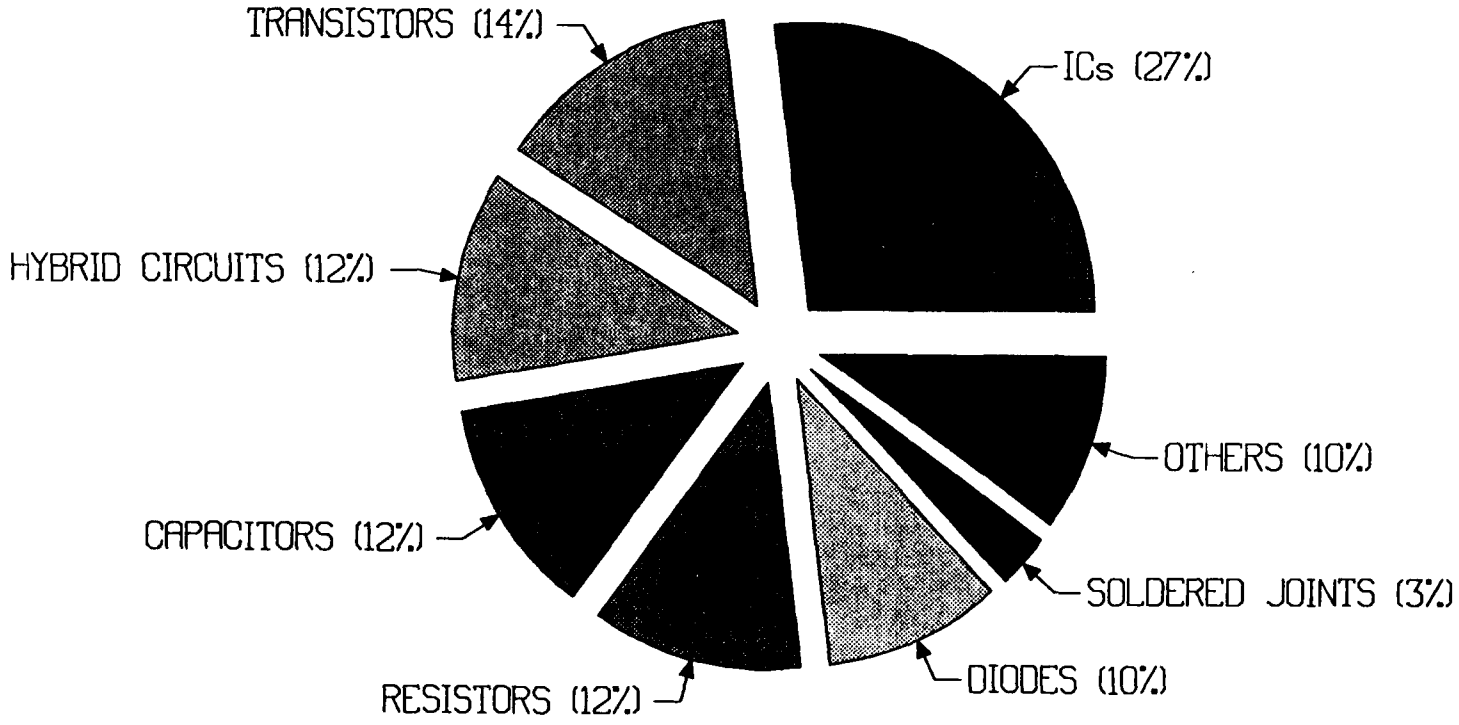
3. Components that have a significant contribution to printed wiring board failures are: integrated circuits; transistors and hybrid circuits.

6.0 REFERENCES

1. Report from Norton Air Force Mishap Database. 1986 to Nov. 9, 1989. Report No. 11041.

Fig. 4 Part Replacement Data for Printed Wiring Boards

(Based on Data from Hughes Aircraft [3])



2. AVIP Air Force Thrust for Reliability. J.C. Halpin. Aeronautical Systems Division, Wright-Patterson Air Force Base. 1985 Proceedings of the Annual Technical Meeting, Institute of Environmental Sciences.

3. Culprits Causing Avionic Equipment Failures. K.L. Wong, et al. 1987 Proceedings of the Annual Reliability and Maintainability Symposium. Summary of work done under F33615-84-C-3410.

CHAPTER III

FAILURE ANALYSIS TECHNIQUES FOR AIRCRAFT ACCIDENT INVESTIGATION

1.0 INTRODUCTION

This chapter describes failure analysis techniques for electrical and electronic components which can be used during aircraft accident investigation. The material is presented in seven sections which deal with specific topics as follows:

2.0 Incandescent Lamps
3.0 Wiring
4.0 Connectors
5.0 Switches
6.0 Permanent Magnet Materials
7.0 Printed Wiring Boards
8.0 Microelectronics

Each section briefly describes the construction and materials used in the components. Failure modes are discussed and the failure analysis techniques are described. Each section discusses the opportunity for the techniques to distinguish pre-accident conditions from post-impact damage. Where possible a preliminary procedure for the application of the techniques for each component has been outlined. Much of the material presented in this chapter is a synopsis of reported techniques. Reference documents are cited in each section.

2.0 INCANDESCENT LAMPS

The analysis of filaments in incandescent indicator lamps has been used in aircraft for a number of years. The condition of the filament and the surrounding envelope provides the accident investigator with information which can be used to determine the ON or OFF condition of the lamp at the time of impact. The majority of the investigation techniques presented in this section are based on a 1985 study funded by Transport Canada [2.1, 2.2]. The basis for the Canadian study was extensive testing of type 327 lamps which are 28 V lamps used as indicators in commercial and military aircraft. A 1966 study by the Royal Canadian Air Force [2.3] used type 313 and 327 lamps and obtained similar results.

2.1 Construction

A typical lamp and its components are shown in Fig. 2.1. The lamp consists of an evacuated glass envelope, a tungsten filament structure and a base. Depending on the specific lamp, the filament may be supported only at its ends by the contact posts or may have additional support at intermediate points from support posts. The filament of a new lamp is shown in Fig. 2.2. Several filament geometries are used in small incandescent lamps. Some of these are shown in Fig. 2.3 [2.4]. The type 327 lamp uses the C-2F configuration. The C designation indicates that a coiled filament is used; 2F is the designation for the support structure. Several filament structures are used in aircraft indicator lamps. Table 2.1 [2.5] lists the filament structures and other data on aircraft indicator lamps.

The material used for the filament is tungsten wire, which is typically made by a powder metallurgy process. A nearly pure form of tungsten is used for lamp filaments. The filament for a 327 lamp is about 300 microinches in diameter, has a total (uncoiled) length of about 2.1 inches, and has a mass of about 40 micrograms. Mechanical properties of Tungsten wire include tensile strengths from 250,000 to 600,000 psi at room temperature, depending on the diameter [2.6]. The tensile strength at the operating temperature of 1500 to 2000°C can be as much 20 times lower than at room temperature. Other data on the 327 lamp is presented in Table 2.2. Military standard MS 25237 [2.7] describes the mechanical and performance requirements of the 327 lamp.

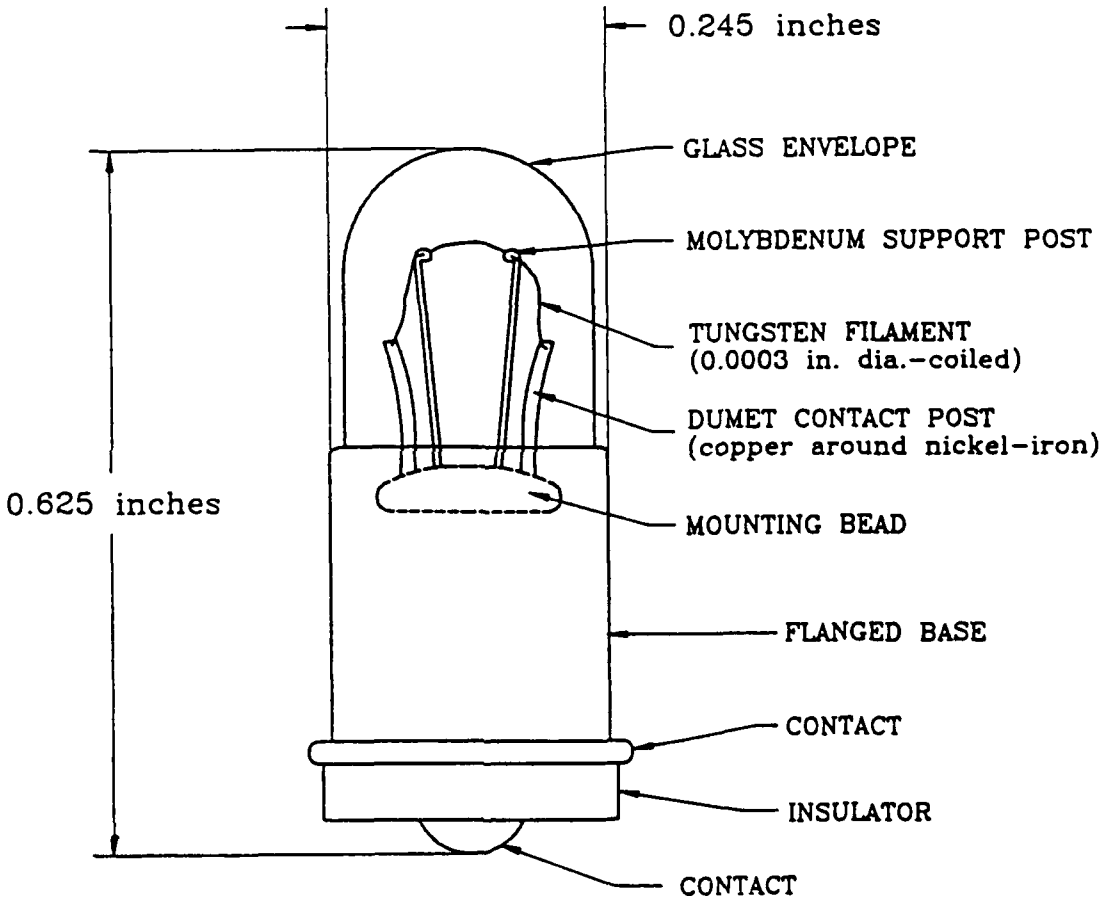
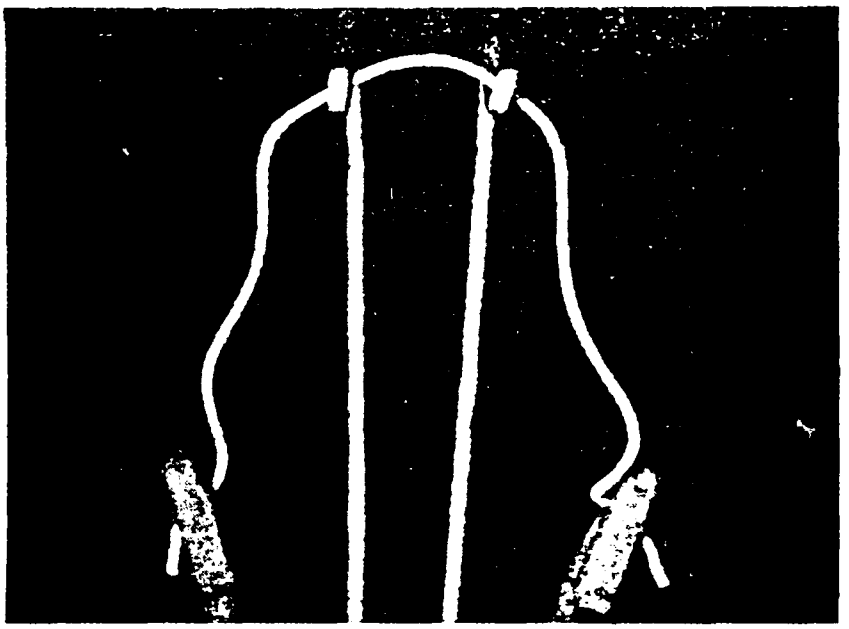


Fig. 2.1 General Construction of Type 327 Lamp

a.



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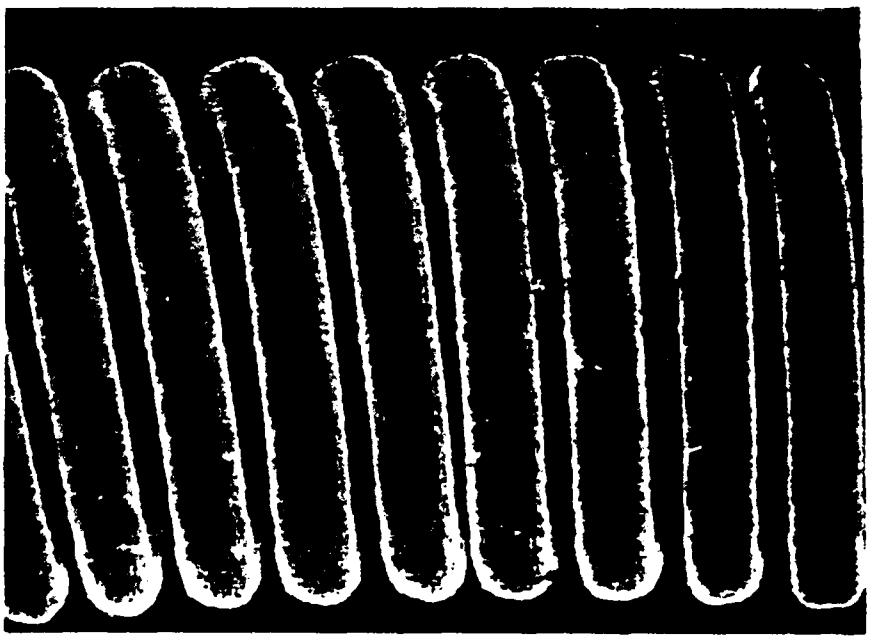
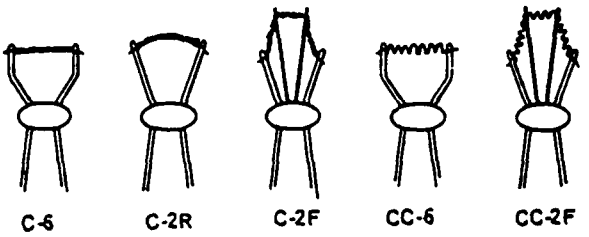
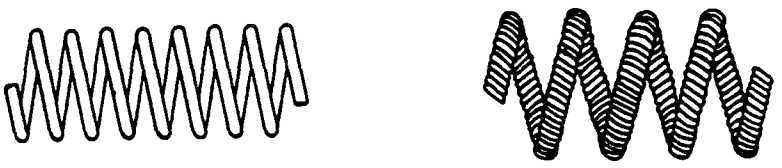


Fig. 2.2 New filament of Type 327 lamp [2.1]. a - 20X, b - 1000X.



Filament Structures



Coiled Filament

Coiled Coiled Filament

Fig. 2.3 Filament Structures used in small incandescent lamps [2.4].

Table 2.1 Aircraft Indicator Lamps (Data adapted from [2.5])

Design Volts	Trade Number	Amperes or Watts	Mean Spherical Candelas	Bulb	Base	Fila-ment	Rated Average Lab Life (hours)	Approx. Weight	Military Standard	Notes
5.0	680	.06A	0.03	T-1	Wire Term.	C-2R		0.2	MS24367-680	1
5.0	682	.06A	0.03	T-1	Sub-mid. Flange	C-2R		0.3	MS24515-682	1
5.0	683	.06A	0.05	T-1	Wire Term.	C-2R		0.2	MS24367-683	2
5.0	685	.06A	0.05	T-1	Sub-mid. Flange	C-2R		0.3	MS24515-685	2
5.0	715	.115A	0.15	T-1	Wire Term.	C-2R		0.2	MS24367-715	2
5.0	718	.115A	0.15	T-1	Sub-mid. Flange	C-2R		0.3	MS24515-718	2
6.0	316	.7A	3.40	T-3-1/4	Min. Bay.	C-2R	500	3.0	MS25231-316	-
6.0	328	.2A	0.34	T-1-3/4	Mid. Flange	C-6	1000	0.5	MS25237-328	3
13.0	89	.58A	6.00	G-6	S.C. Bay.	C-2R	750	5.0		
13.0	1816	.33A	3.00	T-3-1/4	Min. Bay.	C-2V	1000	3.0		
14.0	330	.08A	0.50	T-1-3/4	Mid. Flange	C-2F	750	0.5		
28.0	301	.17A	3.00	G-5	S.C. Bay.	C-2F	500	5.0	MS25238-301	
28.0	303	.30A	6.00	G-6	S.C. Bay.	C-2F	500	5.0	MS15570-303	
28.0	313	.17A	3.50	T-3-1/4	Min. Bay.	C-2F	500	3.0	MS25231-313	
28.0	1864	.17A	3.00	T-3-1/4	Min. Bay.	C-2F	1500	3.0		
28.0	387	.04A	0.30	T-1-3/4	Mid. Flange	C-2F	7000	0.5	MS25237-387	
28.0	327	.04A	0.34	T-1-3/4	Mid. Flange	C-2F	4000	0.5	MS25237-327	
28.0	1495	.30A	6.00	T-4-1/2	Min. Bay.	C-2F	500	3.0	MS25069-1495	

Notes

1. Theoretical life is 100,000+ hours
2. Theoretical life is 40,000+ hours
3. A+ 5V, average life will be about 8,000 hours

Table 2.2 Data on 327 Lamp Filament

Voltage	28 V
Current	40 ma
MSCP	0.34
Filament Configuration	C-2F
Average Life	4000 hours
Hot Resistance	700 Ω
Operating Temperature	2150° K (1877° C)
Diameter	300 microinches
Length	2.1 inches
Mass	48.3 micrograms
Cold resistance	66 Ω
Power	1.12 watts

2.2 Failure Analysis Techniques

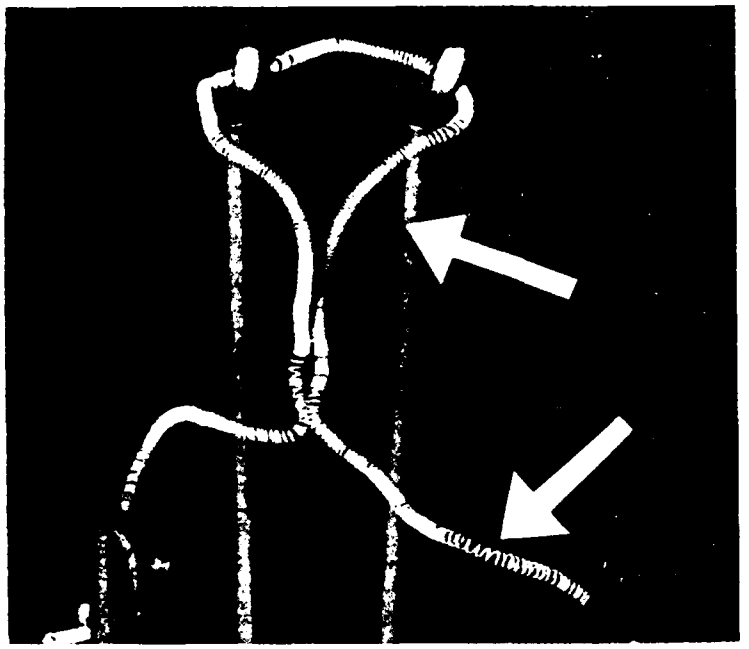
Failure Analysis techniques for accident investigation focus on examination of the deformation of the filament after impact. In general, the deformation is more severe in hot filaments (lamp ON) due to increased ductility at the operating temperature. There are, however, several additional characteristics that need to be considered in order for deformation to provide a reliable indication of the ON or OFF state of the lamp. The deformation and additional characteristics are covered in the following discussions.

2.2.1 Filament Deformation

An examination of the entire filament reveals two common types of deformation that can occur upon impact. General (global) deformation results from most impacts when the filament is hot and when the direction of impact is perpendicular to the axis of the filament. When the impact is along the filament axis, local deformation can occur and usually appears as a stretching or uncoiling of the filament. Local and global deformation are shown in Fig. 2.4a. An undamaged filament is shown in Fig. 2.2a. Deformation is noticeably more severe on lamps with hot filaments than those with cold filaments. Global and local deformation can be observed in small lamps like the 327 with accelerations in the range of 1000 to 4000 g's.

Impacts containing high frequency components produce other distinct deformation characteristics. In high-g, short duration impacts the support posts can resonate and cause severe deformation, tangling, and multiple filament fractures. This type of resonance deformation is shown in Fig. 2.4b. The loading on the filament was a peak acceleration of about 4000 g's occurring over a period of about 0.9 msec [2.1]. Violent resonance of the support posts and filament of the 327 lamp can occur when excited between 1300 and 1550 Hz [2.1]. For very short duration impacts that excite this resonance lower g values of acceleration can cause failure. Hot filaments tend to show extreme amounts of local and global deformation. Cold filaments typically fracture with little or no deformation. A half sinusoidal deceleration corresponding to 1300 Hz would last about 385 microseconds.

a.



b.

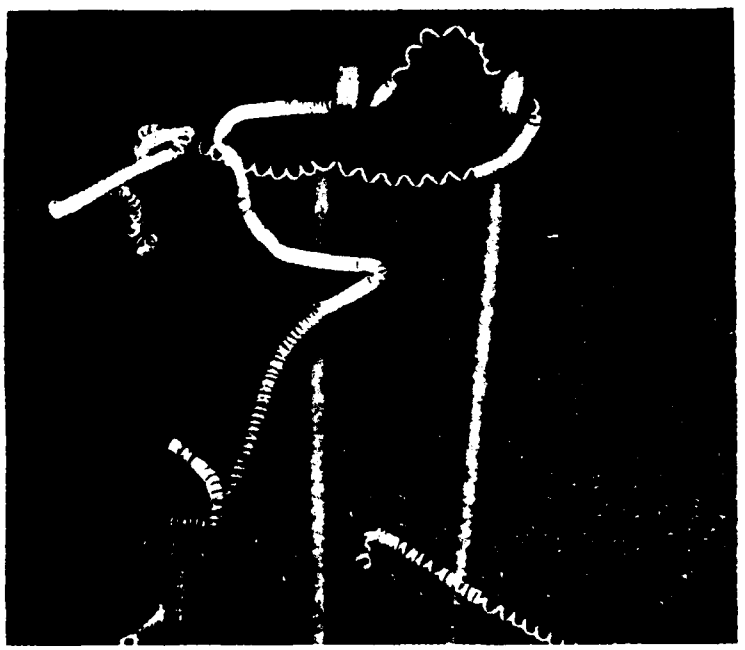


Fig. 2.4 Deformation of filament impacted at 4006 G for 0.9 millisec. Filament ON. (a) Global and local deformation (b) Resonance and multiple fractures (Ref. 2.1).

2.2.2 Filament Fracture Surfaces

Microscopic examination of the fracture surfaces can provide some information about whether the lamp was ON or OFF at the time of impact. Fractures from impacts with the filament ON will sometimes be characterized by more rounded edges. In general, however, examination of the fracture surface alone is not sufficient to reliably determine whether the lamp was ON or OFF at the time of impact. This examination is not reliable because of several factors. First, the high strain rates associated with aircraft impacts can result in fracture morphologies that appear traditionally "brittle" even though the lamp is ON. Second, multiple fractures of the filament can occur and, unless the primary fracture can be identified, incorrect conclusions about the ON or OFF state of the filament can be made. For example, fractures can occur after an initial fracture in cases where multiple impacts occur even if the lamp was initially ON. This is possible because the filaments of small lamps can cool off in 10 to 100 milliseconds for small lamps.

2.2.3 Notching

Lamp filaments operated on dc develop a characteristic sawtooth shaped pattern when examined microscopically. This characteristic, called notching, provides an indication of the relative age of the lamp. As lamp age increases the size and extent of the notching increases. An illustration of notching is shown in Fig. 2.5. The phenomenon has been attributed to migration of the tungsten ions over time in a preferred direction resulting from the fixed magnetic field from the dc current in the filament. Notching is one of the factors that reduces the life of lamps when operated on dc rather than ac. As the filament ages, notching progresses and the filament becomes more brittle and susceptible to fracture at lower impact energies. Fig. 2.6 [2.1] shows the relationship between lamp age and the impact needed to fracture the filament.

2.2.4 Evaporation

Most miniature lamp envelopes are evacuated during manufacture. As a result of the manufacturing process a small amount of water vapor remains trapped in the envelope. The water increases evaporation of the tungsten in a process called the water cycle. The water decomposes when heated by the filament and the free oxygen combines with the tungsten to form

Fig. 2.5 Notching of lamp aged 77 hours at 28 Volts DC. 2000X. (Reference 2.1)

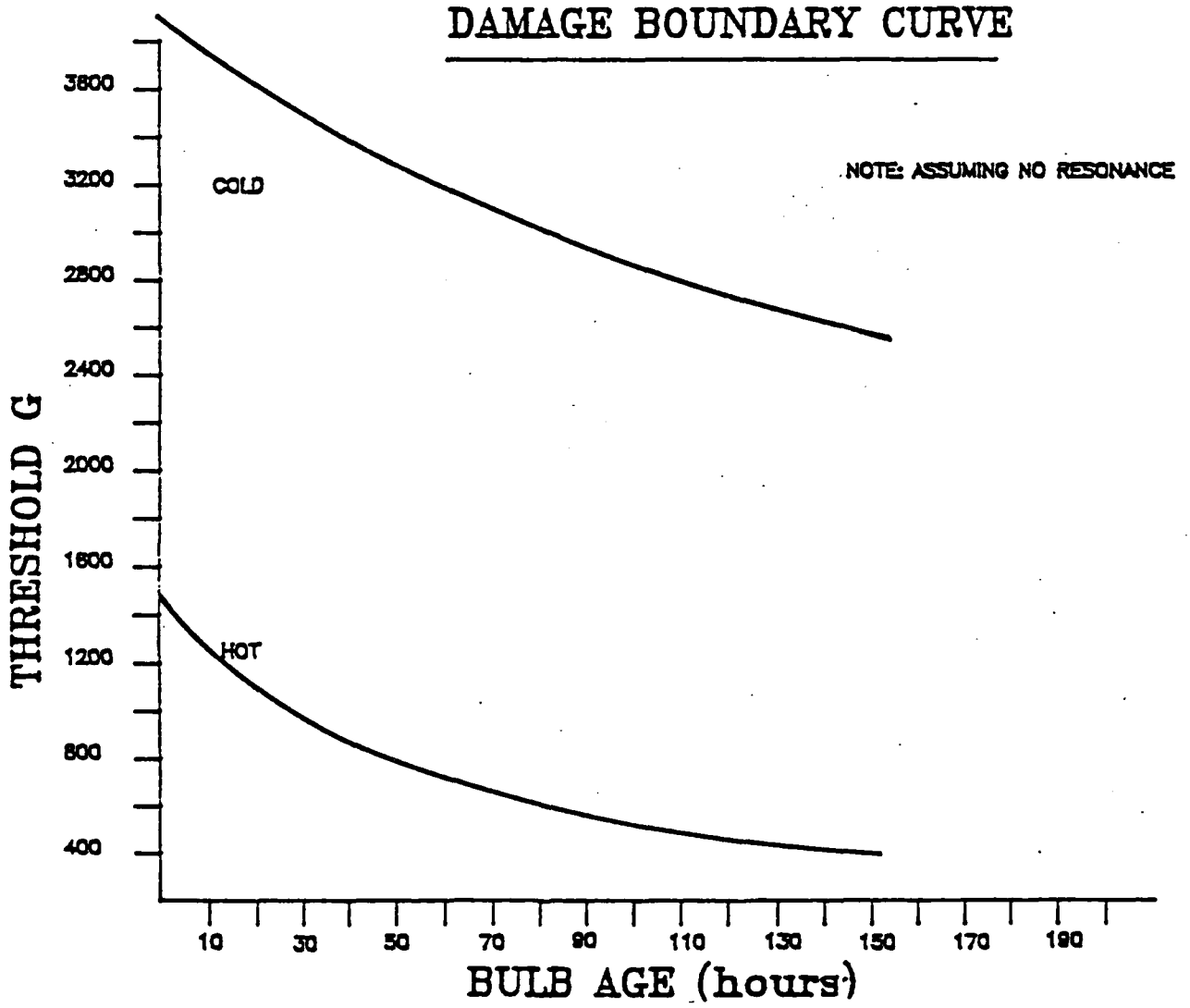


Fig. 2.6 Relationship between g levels for filament damage and lamp age for hot and cold Type 327 lamp [2.1].

tungsten oxide which deposits on the wall of the envelope. The free hydrogen recombines with the oxide to form water vapor, leaving tungsten deposited on the wall of the envelope. The water molecules return to the filament continuing the cycle. The deposited tungsten is an indication of lamp age.

2.2.5 Envelope Damage

If the envelope of a lamp breaks during impact with the filament energized, the tungsten filament will oxidize rapidly and fail. This condition can be identified by the presence of an oxide layer on the filament. Additionally, broken glass may come in contact with and fuse to the filament while it is still hot. These conditions are both indicative of impacts with the lamp ON.

2.2.6 Additional Considerations

Applied Voltage. Operating voltage affects lamp life and filament temperature and must be considered in accident investigation. As a result of damage to the aircraft's electrical system upon impact, the applied voltage may exceed the lamp's rating and cause rapid burn-out. This is usually accompanied by spherical blobs of molten tungsten at the filament ends, especially at very high voltages. An additional consideration is the use of dimming circuits which can reduce the filament temperature by reducing applied voltage. Reduced filament temperature prior to impact can alter the g levels needed for filament damage.

Accident Scenario. It is important to consider the possibility of multiple impacts during the evaluation of lamp condition. It is possible for an initial impact to cause electrical damage which changes the state of the lamps prior to final impact. In order for this to occur practically, the time between impacts must be at least long enough for the filament to reach its hot or cold temperature. The 327 lamp requires about 50 milliseconds to change from hot to cold or cold to hot [2.1].

Data Collection. To improve the reliability of the examination of filaments, data from the examination of more than one lamp should be used. This can be data from other lamps in a

multi-lamp indicator, or data from other lamps whose conditions were known at the time of impact.

2.3 Failure Analysis Guidelines

A simplified method for examination, based on a single impact situation, might be outlined as follows:

First, examine the envelope. If it is broken, the presence of an oxide layer on the filament and glass fused to the filament suggest that it was ON at the time of impact. If the envelope is not broken, examine the filament for global deformation. Examine notching and envelope deposits to estimate the age of the filament. Global deformation usually suggests that the filament was ON at the time of impact.

If the filament has contacted itself and welded together, this is further indication that the lamp was ON. If the lamp is old and the filament is fractured, it will be necessary to examine the fracture surface using SEM.

The accident investigator should be cautioned that conclusions can be drawn only after considering the following:

1. condition of other lamps subjected to the same impact
2. accident scenario
3. estimated g levels
4. applied voltage
5. fracture surface

2.4 Supplemental Methods

A computational model of the filament and support structures would be useful to supplement the basic examination method. Although not trivial, such a model could be developed using three dimensional finite element techniques. The model could include: nonlinear spring characteristics

representing deformation; the resonant characteristics of the support structure; the temperature dependence of material properties. Correlating results with existing test data on lamps would be done during the development and testing of such a model. Tabulated results from the model would be prepared by introducing accelerations for various accident scenarios.

Such an analytical model could be used in two ways. First, the accident investigator could use the results of typical scenarios which have been tabulated and compare those results with field evidence. This would aid in establishing the condition of lamps at the time of impact. Second, modeling of this type could be used to reduce the scope of experimental data required for example, to establish failure characteristics of a new type of lamp.

2.5 Additional Work

The following is a brief listing of the work required to make the method generally practical for accident investigations:

1. Additional testing with other types of lamps.
2. Testing at higher g levels.
3. Logical organization of the examination technique to reduce it to procedural form.
4. Develop a computational model of the filament and support structure.

2.6 References

2.1 Transport Canada Report No. TP-6254E. Light Bulb Filament Impact Dynamics Study in Support of Aircraft Accident Investigation. M.R. Poole, M. Vermij. Aviation Safety Engineering Branch, Canadian Aviation Safety Board. May 1985, reprinted May 1988.

2.2 Transport Canada Report No. TP-6255E. A Guide to Light Bulb Analysis in Support of Aircraft Accident Investigation. Communications Gillies Inc., Quebec, March 1985.

2.3 Light Bulb Analysis as an Aid in Accident Investigation. M.R. Landgren. The Royal Canadian Air Force Material Laboratory, 1966. Laboratory Technical Report N68-14043.

2.4 VCH International - Chicago Miniature Brand. Catalog 8700. VCH Incorporated, Buffalo Grove, Il. 1987.

2.5 IES Lighting Handbook. 1981 Reference Volume. Illuminating Society of North America, NY.

2.6 Metals Handbook 8th Edition. Vol. 1 Properties and Selection of Metals. American Society for Metals. 1961.

2.7 Military Standard MS 25237 Lamp, Incandescent, Single Contact Midget Flanged Base (T-1 3/4 Bulb).

3.0 WIRING

The physical and metallurgical examination of wiring has been used in investigating accidents in conventional ground-based electrical apparatus, in building fire investigations, and in aircraft accident investigations. Little of the published literature deals with wire of the specific types used in aircraft, but the basic techniques have been reported. The investigation techniques are intended to determine the extent to which damage to the conductor and its insulation were caused electrically. Although electrical damage frequently occurs after impact, the distinction between electrical and fire damage gives the accident investigator clues about when the damage may have occurred.

The material presented here deals predominantly with the type of wire classified as "hookup" wire. This is the largest class of wire used in aircraft. Hookup wire is used for interconnect cabling between pieces of equipment, harnesses attached to the airframe, and for interconnect wiring inside larger equipment. This section deals specifically with copper hookup wire, since little aluminum is used. Other types of wiring include: multi-conductor cabling; high voltage cables; special purpose data cables; shielded coaxial or multiaxial cables. The investigation methods discussed here may be applied to these as well, depending on the specific circumstances.

3.1 Construction

The properties of finished copper wire are the result of a number of processing steps which begin with the final steps of processing copper ore itself. The last step in processing the ore results in a product which is at least 99.5% copper. It is cast into anodes and electrolytically refined to produce cathodes which are at least 99.95% pure copper. Copper cathodes are the end product of the copper producer companies and are an item of commerce.

Traditionally, the cathodes have been melted and cast into wire bars, followed by hot-rolling into wire rod. More recently, continuous casting has been used to produce wire rod directly from the cathodes. In either case, the wire rod is cold drawn through a series of dies until it is reduced to the proper diameter. As a result of the cold working of the metal during the drawing process,

an elongation of the crystal grain structure occurs. This characteristic is the basis for one of the investigative methods that will be discussed later in this section.

Most airframe wires are made from one of two types of copper: (1) oxygen free high conductivity copper (OFHC) copper; (2) high strength copper alloy. OFHC is made by induction melting prime quality copper cathodes. The heating is done in a non-oxidizing environment produced by using a covering bath of granulated graphite and a protective reducing atmosphere that is low in hydrogen. The resulting alloy is at least 99.99% pure copper.

The high strength copper is usually a cadmium-copper or cadmium- chromium-copper alloy. The alloy has improved mechanical properties including increased tensile strength and resistance to annealing at elevated temperatures. The annealing temperature of OFHC copper is in the range of 700-1200°F, whereas that of typical high strength alloys is in the range of 1000-1400°F. Additional data on the fabrication and the properties of copper wire can be found in [3.1].

Either of the two copper alloys used in aircraft wire may be coated with silver, nickel or tin. Typical coating thicknesses are 40 microinches for silver, 50 microinches for nickel and 30 microinches for tin. Silver is widely used because it has high conductivity and good solderability. The coatings are applied to the individual strands of the conductor, usually by electroplating. The composition of silver coated wire may be roughly 0.5 to 2 percent silver by volume or about 0.6 to 1.7 percent silver by weight, depending on the diameter of the strands.

Copper wire for aircraft use is stranded to provide flexibility. The stranding arrangements are similar to those used for general purpose electronic hookup wire. "Concentric lay" stranding is used for the smaller wire sizes, usually below AWG 10. In this arrangement, a central strand is surrounded by one or more layers of helically wound strands. Larger wire sizes use rope lay stranding, in which a central wire is surrounded by one or more layers of helically wound wires. Stranding configurations and other mechanical data are shown in Table 3.1.

Table 3.1 Data on Standard Conductors from MIL-W-81381

Size Designation	Nominal Conductor Area (Cir.Mils) 1/	Stranding (No. of Strands x AWG Gage of Strands)	Allowable No. of Missing Strands (Max)	Nominal Dia of Individual Strands (inch) 1/	Diameter of Stranded Conductor							Maximum Resistance of Finished Wire (Ohms/1,000 Ft. at 20°C)				Breaking Strength, Alloy Conductor (lbs)(min)
					Min. (inch)	Max (inch)						Soft or Annealed Copper		High Str Cu Alloy		
						General Purpose		Small Dia(Cu)		Small Dia(Alloy)						
						Silver Coated	Nickel Coated	Silver Coated	Nickel Coated	Silver Coated	Nickel Coated	Silver Coated	Nickel Coated	Silver Coated	Nickel Coated	
30	112	7 x 38	0	0.0040	0.011	0.012	0.013	0.012	0.013	0.012	0.013	100.7	110.7	117.4	129.6	5.17
28	175	7 x 36	0	0.0050	0.014	0.015	0.016	0.015	0.016	0.015	0.016	63.8	67.9	74.4	79.0	8.16
26	304	19 x 38	0	0.0040	0.018	0.020	0.021	0.019	0.020	0.020	0.020	38.4	[illegible]	44.8	49.4	14.2
24	475	19 x 36	0	0.0050	0.023	0.025	0.026	0.024	0.024	0.024	0.025	24.3	25.9	28.4	30.1	22.4
22	754	19 x 34	0	0.0063	0.029	0.032	0.033	0.030	0.031	0.031	0.031	15.1	16.0	17.5	18.6	35.8
20	1,216	19 x 32	0	0.0080	0.037	0.040	0.041	0.038	0.039	0.039	0.040	9.19	9.77	10.7	11.4	58.1
18	1,900	19 x 30	0	0.0100	0.046	0.050	0.051	0.048	0.049	-	-	5.79	6.10			
16	2,426	19 x 29	0	0.0113	0.052	0.057	0.058	0.054	0.055	-	-	4.52	4.76			
14	3,831	19 x 27	0	0.0142	0.065	0.072	0.073	0.068	0.069	-	-	2.88	3.00			
12	5,874	37 x 28	0	0.0126	0.084	0.089	0.090	0.087	0.089	-	-	1.90	1.98			
10	9,354	37 x 26	0	0.0159	0.106	0.112	0.114	0.110	0.112	-	-	1.19	1.24			
8	16,983	133 x 29	0	0.0113	0.158	0.169	0.173	0.166	0.169	-	-	0.658	0.694			
6	2[illegible],818	133 x 27	0	0.0142	0.198	0.213	0.217	0.208	0.212	-	-	0.418	0.436			
4	42,615	133 x 25	0	0.0179	0.250	0.268	0.274	0.263	0.268	-	-	0.264	0.275			
2	66,500	665 x 30	2	0.0100	0.320	0.340	0.340	-	-	-	-	0.170	0.177			
1	81,700	817 x 30	2	0.0100	0.360	0.380	0.380	-	-	-	-	0.139	0.144			
0	104,500	1,045 x 30	3	0.0100	0.405	0.425	0.425	-	-	-	-	0.108	0.113			
00	133,000	1,330 x 30	3	0.0100	0.450	0.475	0.475	-	-	-	-	0.085	0.089			
000	166,500	1,665 x 30	4	0.0100	0.515	0.540	0.540	-	-	-	-	0.068	0.071			
0000	210,900	2,109 x 30	5	0.0100	0.5[illegible]	[illegible].605	0.605	-	-	-	-	0.054	0.056			

Almost all aircraft wire uses polymeric insulation materials. In traditional wire manufacture, the plastic insulation material is heated to melting and extruded over the finished conductor. Another type of insulation uses a tape wound around the conductor and is commonly used for wires insulated with Kapton* tape. Kapton film is made from an aromatic polyimide resin. It is made only in sheet and tape form, and cannot be extruded. Two layers of the tape are spiral wound around the bare conductor. An FEP resin is used with each layer to seal the insulation. The direction of the spiral is reversed between the two layers. Finally, an outer coating of resin is applied to provide wire color and a base for marking. The resin is a modified aromatic polyimide. One of the trade names for the resin is "Liquid-H". Kapton insulated wire for aircraft use is covered by MIL-W-81381.

Information on other insulating materials, their electrical properties and other data on wire properties can be found in [3.2]. Guidelines on the application of wire are covered in MIL-W-5088 [3.3]. The properties of Kapton can be found in [3.4].

3.2 Failure Analysis Techniques

The accident investigator examines the wire, conductor and insulation, as a single unit. When a particular wire has been singled out, the following questions are of interest.

1. Is the wire damaged?
2. Is the damage due only to post impact fire?
3. Is there electrical damage due to insulation failure which resulted in arcing?
4. Is there electrical damage due to overcurrent heating resulting in melting or fusing (opening)?

* Trademark of Dupont Chemical Co.

Techniques presented in the following discussions may be applied individually or collectively to address these questions. The examination of conductors to distinguish fire damage from electrical damage is covered in [3.5], [3.6] and [3.7]. Corrosion of conductors is covered in [3.8].

3.2.1 Examination for Arcing

When a conductor fails electrically and arcing occurs, extreme local heating results. The heating is a result of the arc current and the voltage drop that occurs at the point the arc is established. The voltage-current product in watts represents the thermal power available to cause conductor melting. A 20 A fault on a 28 V system will result in 560 Watts, most of which will be dissipated in a relatively small area near the arc. Arc welding experience suggests that voltages at the arc will be between 10 and 35 V for currents up to several hundred amperes. The remaining voltage is dropped across the conductor resistance and the source impedance of the power system.

Damage from maintained arcing is less likely on ac than on dc systems because of the opportunity for the arc to extinguish during the zero crossings of the ac waveform. Experience with commercial apparatus operated at 208 Vac suggests that sustained arcing below the trip level of overcurrent protection devices is unlikely.

Arcing in dc systems will be associated with localized melting and loss of conductor material. Recrystallization will tend to occur near the point of arcing and along the current carrying portion of the conductor. The amount of recrystallization will depend on the temperature and time of exposure, resulting from the current level and duration of the fault.

3.2.2 Fused (opened) Conductors

Wire breaks due to arcing are usually accompanied by spherical wire ends. Arcing without breaks in the wire can occur at points of abrasion or other types of damage to the conductor insulation. This is usually accompanied with a loss of material, or gouging caused by the arc. Arcing is also accompanied by a migration of the metallic constituents from both sides of the arc.

SEM/EDAX analysis of the composition can be useful in examining an isolated wire that has been damaged by arcing. For example, the presence of aluminum in the conductor material is an indication that arcing to the aircraft frame has occurred.

3.2.3 Examination of Grain Shape

The process of cold drawing copper wire results in a grain structure which exhibits obvious elongation even if the wire has undergone some annealing. This elongation can be seen easily with microscopic examination as shown in Fig. 3.1 [3.5]. The longitudinal cross section shows the sides of the long, stretched out grains while the transverse cross section shows the small, uniform end view of the grains.

When the wire is subsequently heated, it goes through a process of recrystallization. The recrystallization process consists of three activities: recovery, recrystallization and growth. The properties and grain growth characteristics for the three activities are shown in Fig. 3.2 [3.9]. The change in size of the grains is accompanied by a reorientation. As recrystallization proceeds, new grains appear which are equiaxed rather than elongated. The appearance of equiaxed grains is the basis for one of the traditional procedures for metallurgical examination of conductors that have been involved in fires. The amount of recrystallization depends on the temperature and the time the conductor is exposed. Once the grains become equiaxed, further crystallization takes place and the size of the recrystallized grains continues to increase. The rate of recrystallization is governed by the same principals as a chemical reaction. As a general rule, a 10 °C increase in temperature will be accompanied by a halving of the exposure time to achieve the same level of recrystallization.

It is apparent from Fig. 3.2 that, in general, the strength of the material decreases rapidly during the recrystallization procedure. No research has been found on how the strength of copper strands could be analyzed as part of an accident investigation method. It is conceivable that tests such as tensile strength or microhardness could be done on individual strands of copper wire to identify the extent of the time-temperature exposure of the wire. This data might be useful in conjunction with an examination of the microstructure. It is not clear that practical tests could

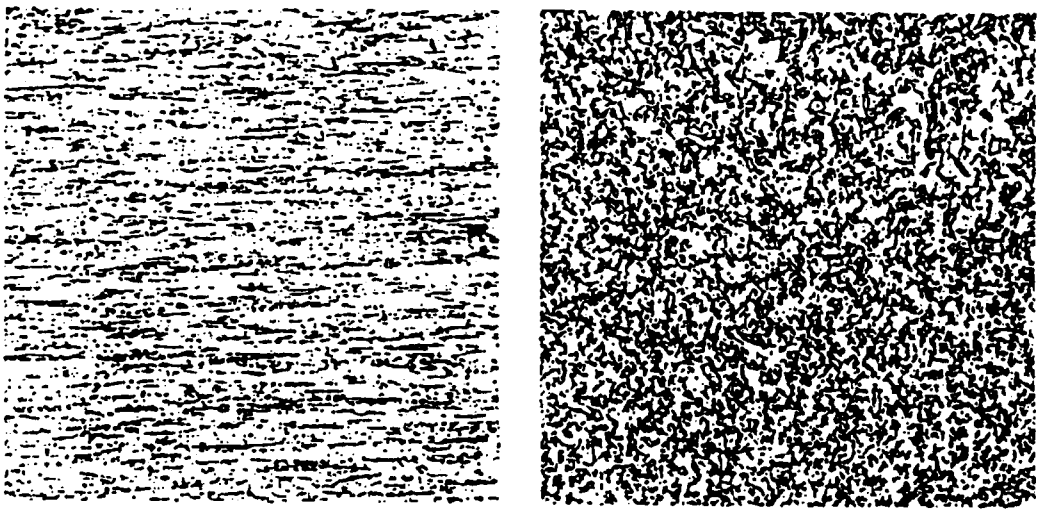


Fig. 3.1 Longitudinal (left) and transverse (right) sections of copper wire showing grain size and orientation. 100x [3.5].

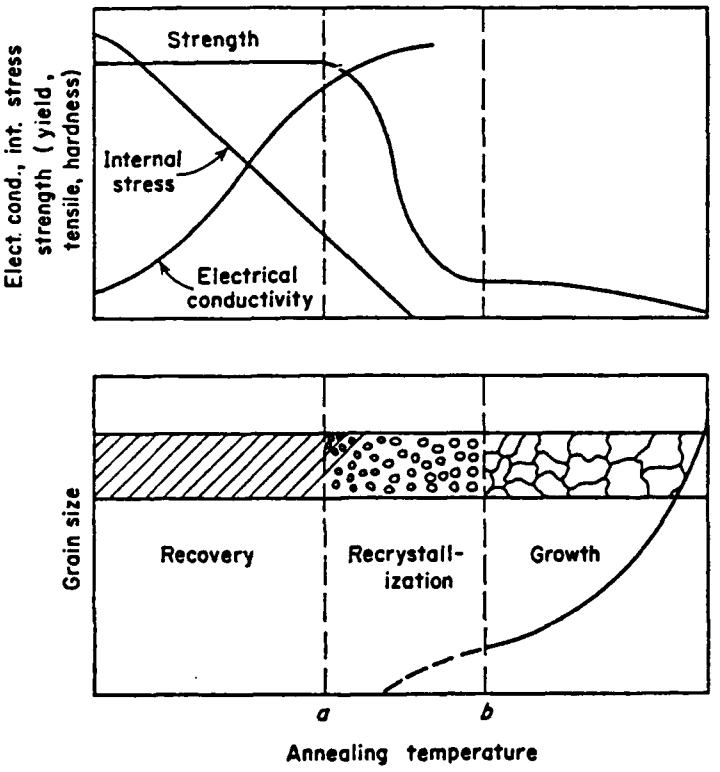


Fig. 3.2 Effect of heating a plastically deformed metal on grain size and properties [3.9].

be devised in view of the small diameter of the strands, and the low forces that would be required to implement a tensile strength test. Nonetheless, materials property tests such as tensile testing or micro-hardness testing may be useful if practical test procedures could be developed.

The discussion above is based on recrystallization of copper conductors. The basic principal has been used in the field on the silver- and nickel-plated conductors used in aircraft, although the specific effects of these platings on recrystallization and other properties have not been developed in the literature on failure analysis methods.

3.2.4 Flashover Failures

Flashover in wire is the sudden catastrophic electrical breakdown of the insulation. It is usually attributed to poor track resistance characteristics and is caused by carbonization of the insulation surface under conditions of relatively low current prior to breakdown. Poor track resistance has been reported to be a property of highly phenylated polymers such as aromatic epoxies, phenolics, and polymers with the para-phenylene group in the polymer chain. Kapton* is a polyimide film with this structure, and has been reported to be susceptible to flashover [3.10]. The underlying mechanism is a chain scission reaction, one that breaks down the polymer chain. The reaction causes embrittlement and fraying of the polyimide in both the top coating and the tape wrapping of the insulation on MIL-W-81381 style conductors. At bends in the wire, radial cracks form which propagate completely through the insulation material to the conductor. The bare conductor is thereby exposed rather quickly, catastrophically accelerating the breakdown. The problem is especially severe in moist environments. Initially the conduction occurs in small, localized areas which become carbonized quickly. Other materials such as polyethylene and polytetrafluorethylene degrade into gaseous products rather than solid carbonized products. These materials apparently do not exhibit flashover in wet environments.

The products of combustion are essentially the same as those of the flashover failure, and as yet no method has been reported to make a post-accident distinction between the two effects.

* Trademark of Dupont

However, where a significant amount of undamaged wire remains, it may be possible to analyze the surface condition of Kapton-insulated wire to determine whether tracking is a general problem in the electrical system of the aircraft. The carbonized surface of the insulation, being moderately conductive, should be suitable for SEM examination.

The carbonized material on the surface of the wire may have metal constituents due to the ionic nature of the current prior to breakdown. In this case EDAX analysis could be used to examine for metals on the outside of the wire. Results presented briefly in [3.11] suggest that SEM can be used on polymeric insulations that have sufficient metal contamination. If the insulation is not sufficiently conductive, carbon sputtering may be used instead of gold. Since many EDAX systems cannot detect carbon, it is a convenient way to perform SEM imaging on plastics without disturbing the EDAX results. Patterns of metallic elements would indicate tracking and should be quite distinct from the ordinary patterns of metallic contamination due to handling, abrasion and corrosion.

3.2.5 Chaffing

Discussions with the US Air Force indicate that chaffing is a significant cause of wiring failures. The likelihood of chaffing relates to design of the wire bundles, the arrangement of the cable clamps and the type of wire. Some fighter aircraft are susceptible to chaffing caused by movement of the wires during high g maneuvers. Kapton-insulated wire is susceptible to chaffing because of its stiffness. Unfortunately, no method of distinguishing post-impact damage related to chaffing was found in the technical literature. The accident investigator may rely on examination of cable clamping, cable type and signs of chaffing in undamaged areas of the aircraft, or on similar aircraft.

3.2.6 Temperature Exposure of Silver-Plated Wire

Aging tests on silver-plated copper wire show the formation of silver globules on the surface of the individual strands of the conductor [3.12]. The data was developed for uninsulated and Kapton insulated wire aged at 200 and 230° C for up to 1000 hours. The result shows that the globules form after about 100 hours at these temperatures. The globules are plainly visible with SEM. The data may have some use in determining the time-temperature exposure of wires involved in accidents.

3.3 Failure Analysis Guidelines

An example of the approach used to assess a damaged wire is presented below. The intent of the example is to illustrate how the techniques might be applied and is not intended to be a general purpose procedure. The example is based on a particular case where the wire of interest is several feet in length, and a portion of the wire is apparently damaged from post-impact fire.

1. If there is a visible break in the insulation, use SEM/EDAX to evaluate the constituents in the vicinity of the damage.

    - If aluminum is present in the solidified copper, then arcing probably occurred between the wire and an aluminum member of the aircraft.
    - If material is lost near the break in the insulation, then arcing occurred, probably to another conductor.

2. If there is no visible break in the insulation, examine the microstructure for recrystallization in several locations along the length of the conductor.

    - If the wire is recrystallized along its entire length, then it was probably heated electrically.
    - If the wire is recrystallized only in the area where the insulation is damaged, then the wire was probably damaged by post-impact fire only.

3.4 Supplemental Methods

In arcing between conductors, there is a general spreading of metal ions along the conducting path. In cases where the damage is not too severe, it may be possible to detect the presence of metals deposited on polymeric insulations. SEM/EDAX may be used to make the analysis. The examination may provide information which merely supplements other analysis methods. This would be true where the materials in the damaged wire have already been analyzed. However, additional information may be obtained, such as the physical direction of the current path prior to the onset of heavy current.

3.5 Additional Work

No literature was found which characterizes the microstructure of the specific types of wires used on aircraft. The OFHC and high strength alloys are processed differently, and will have different features with respect to recrystallization. Further, the literature available does not deal with coated wires, or wires stranded with the specific arrangements known to be used in aircraft. Significant work must be performed to assure that failure analysis methods presented in this section are applicable to all aircraft situations. A brief list of that work is presented below:

1. Tests to identify microstructure vs. time-temperature exposure for OFHC and high strength copper wire under external heat only.

2. Tests similar to 1 above, but electrically heated.

3. Tests to characterize appearance of wires electrically heated to the point of opening, where arcing is established at the break.

4. Arcing tests conducted before and after fire damage to characterize the materials found in the melted wire.

5. Tests to characterize materials deposited onto polymeric wire insulation due to arcing.

3.6 References

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3.7 Scanning Electron Microscopy of Burnt Electric Wires. R.P. Singh. Scanning Microscopy, Vol. 1, No. 4 December 1987.

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3.11 SEM Examination of an Overheated Aluminum Wired Electrical Receptacle. Proceedings of the 34th Annual Electron Microscopy Society of America. 1976. pp. 454-455.

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4.0 CONNECTORS

Connectors are used in aircraft electronic equipment to connect harness wiring to equipment, to connect electronic panels to rack mounted wiring, for interconnections between circuit boards and for specific types of replaceable components. The construction of MIL style connectors is covered in [4.1] along with a summary of data on failures in commercial aircraft. The materials used in the mating electrical contacts of connectors are protected by the connector shell (housing). Depending on the type of connector, the shell may also provide some protection from corrosion damage during fire fighting and handling after an accident. This protection may serve as a means of preserving the pre-accident condition of the connector. The range of materials used in the construction may also help to provide the accident investigator with additional data with which to judge pre-accident conditions.

4.1 Construction

Contacts in connectors are fabricated primarily from some base metal, with a relatively thin plating of a special contact material. The base metal provides strength, current carrying capacity and the spring characteristic necessary for proper retention. The contact plating is normally required to prevent deterioration of the mating surfaces of the contacts from mechanical or chemical factors. Typical base materials are beryllium-copper, phosphor-bronze, spring brass and low-leaded brass. Silver and gold are used for contact plating in most military applications. An overplating of gold with an underplating of a less precious metal, usually silver, is used to provide added protection against corrosion in the event that the gold overplating wears through. The typical total plating thickness is 100 microinches.

Insulating materials are used in the body of the connector to support the individual contacts and to insulate them from each other and from the metal housing or shell of the connector. The choice of insulating material is crucial to the effectiveness of the connector in a particular application because it provides both mechanical strength and electrical insulation. Typical properties of connector insulating materials are shown in Table 4.1. Resistance to heat, dielectric

Table 4.1 Properties of Insulating Materials used in Connectors [4.2].

Property	Diallyl phthalate		Silicone		Epoxy	
	Mineral-filled	Glass-filled	Mineral-filled	Glass-filled	Mineral-filled	Glass-filled
Mold shrinkage, in./in	0.004–0.006	0 002	0.006–0.007	0-0.005	0.001–0.008	0.001–0.002
Specific gravity	1.50–1.60	1.55–1.70	1.81–2.82	1.68–2.0	1.6–2.06	1.8–2.0
Tensile strength, psi	3,000–8,000	5,000–10,000	3,000–3,500	4,000–5,000	5,000–7,000	.....
Compressive strength, psi	18,000–25,000	20,000–30,000	15,000–18,000	10,000–15,000	18,000–25,000	.....
Flexural strength, psi	6,000–10,000	10,000–20,000	7,000–8,000	10,000–14,000	10,000–15,000	.....
Impact strength (ft-lb/in. of notch) (½ by ½-in. notched-bar Izod test)	0.30–0.50	1.0–10.0	0.26–0.35	3–15	0.25–0.40	.....
Water absorption (24 hr, ¼-in. thickness), %	0.2–0.3	0.1–0.3	0.13	0.1–0.2	0.1	0.5–0.095
Thermal conductivity, 10^{-4} cal/(s)(cm²)(°C)(cm)	7.0–10.0	7.0–10.0	.....	7.51–7.54	7–18	7–10
Thermal expansion, 10^{-5} per °C	2.0–3.0	2.0–3.0	.....	0.8	2.5–5.0	1.1–3
Resistance to heat, °F (continuous)	350–450	350–500	600	600	300–500	330–500
Volume resistivity, 50% RH, (Ω-cm	10^{13} +	10^{12}–10^{16}	10^{14}	10^{16}–10^{14}	10^{14}	10^{14}
Dielectric strength, V/mil:						
Short time, ¼-in	395–420	395–450	200–400	200–400	300–400	300–400
Step-by-step, ¼-in	390–400	395–400	380	125–300	300–400	300–400
Dielectric constant:						
60 Hz	5.2	4.3	3.5–3.6	3.3–6.2	3.5–5.0	3.5–5.0
1 kHz	4.8–5.3	4.1–4.4	.....	3.2–5.0	3.5–5.0	3.5–5.0
1 MHz	3.9–4.0	3.4–4.5	3.4–6.3	3.2–4.7	3.5–5.0	3.5–5.0
Dissipation factor:						
60 Hz	0.03–0.06	0.01–0.05	0.004–0.005	0.004–0.03	0.01	0.01
1 kHz	0.03–0.10	0.004–0.009	.....	0 0035–0.02	0.01	0.01
1 MHz	0.02–0.04	0.009–0.014	0.002–0.005	0.002–0.02	0.01	0.01
Arc resistance, s	140–190	125–180	250–420	150–250	150–190	120–180

Property	Alkyd and polyester		Phenolic		Melamine		Polyethylene oxide, unfilled	Polysulfone	Polycarbonate, unfilled
	Mineral-filled	Glass-filled	Flock-filled	Glass-filled	Flock-filled	Glass-filled			
Mold shrinkage, in./in	0.004–0.010	0.002–0.006	0.004–0.009	0.006–0.009	0 006 0.007	0.001-0 004	0.006	0.007	0 005–0 007
Specific gravity	1.60–2.30	1.8–2.30	1.32–1.45	1.75–1.95	1.50–1.55	1.8–2.0	1.06–1.10	1.24–1 25	1 2
Tensile strength, psi	3,000–8,000	4,000–10,000	6,500–9,000	5,000–10,000	7,000–9,000	5,000–10,000	7,800–9,600	10.200 (at yield)	8,000–9,500
Compressive strength, psi	18,000–25,000	20,000–30,000	22,000–38,000	17,000–26,000	30,000–35,000	20,000–35,000	16,000–16,400	13,900 (at yield)	10,300–10,800
Flexural strength, psi	6,000–10,000	12,000–20,000	8,500–12,000	10,000–16,000	13,000	15,000–23,000	12,800–13,500	15,400 (at yield)	12,200–12,700
Impact strength (ft-lb/in. of notch) (½ by ½-in. notched-bar Izod test)	0.30–0.50	1.5–16.0	0.24–0.60	10–50	0.4–0.45	4.0–6.0	1.7–1.8	1.3 (¼-in. bar), 1.2 (⅛-in. bar)	12.0–18.0
Water absorption (24 hr, ¼-in. thickness), %	0.5–0.05	0.06–0.28	0.3–1.0	0.1–1.2	0.16–0.3	0.09–0.21	0.06	0.22	0 15
Thermal conductivity, 10^{-4} cal/(s)(cm²)(°C)(cm)	7.0–15.0	7.0–10.0	4–7	.....	.....	11.5	.....	1.8 Btu/(hr)(ft²)(°F)(in.)	4 6
Thermal expansion, 10^{-5} per °C	3.5–5.0	2.5–3.3	3.0–4.5	1.6	.....	1.5	5.2	3.1 × 10^{-5} in./(in)(°F)	6.7–7
Resistance to heat, °F (continuous)	300–350	300–350	360–500	350–500	250	300–400	250	300	250
Volume resistivity, 50% RH, (Ω-cm	10^{12}–10^{15}	10^{15}	10^{8}–10^{13}	7 × 10^{12}	.....	2.0 × 10^{11}	10^{16}–10^{17}	5.0 >, 10^{16}	2.1 × 10^{16}
Dielectric strength, V/mil:									
Short time, ¼-in	350–450	350	200–400	140–400	350–400	170–300	400–550	425	400
Step-by-step, ¼-in	300–350	300	100–375	120–270	250–350	170–240	400–550	400	364
Dielectric constant:									
60 Hz	5.1–7.5	5.7	5.0–13.0	7.1	6.2–7.6	9.7–11.1	2.64	3 14	2 97–3.14
1 kHz	5.0–6.2	5.4	4.4–9.0	6.9	6 0–7.5	.....	2.64	3.13	3 02
1 MHz	4.6–5.5	5.2	4.0–6.0	4.6–6.6	4.7–7.0	6.6–7.5	2.64	3.10	2.92–2.98
Dissipation factor:									
60 Hz	0.009–0.06	0.010	0 05–0 30	0 05	0.019–0.035	0.14–0.23	0 0004	0.0003	0.0009
1 kHz	0.007–0.03	0.007	0 04–0.20	0.02	0.013–0.034	.....	0.0004	0.0010	0.0021
1 MHz	0.006–0.04	0.008	0.03–0.07	0.012–0.026	0.032–0.060	0.013–0.015	0.0009	0.0034	0.010
Arc resistance, s	75–190	180	Tracks	T-190	95–135	180	75	75–122	10–120

strength and track resistance are the properties most important to the accident investigator. One of the most common types of material is a thermosetting plastic of the Diallyl-phthalate family. This family of materials has high insulation resistance and low dielectric loss and maintains these properties up to 400°F even in high humidity environments [4.2].

The cylindrical connector is by far the most common mechanical configuration used for interconnection of equipment. One of the most common styles of cylindrical connectors is covered by MIL-C-38999 [4.3]. The basic connector is available in a variety of mounting arrangements. Fig. 4.1 illustrates the basic mechanical structure of the connector. The mating contacts use a pin and socket configuration. Two of the possible arrangements are shown in Fig. 4.2. Wires are connected to the contact either by crimping or soldering. The contactor may be molded into the insulator, or may be insertable after the wires are connected. In this case a retention mechanism is provided in the insulator.

4.2 Failure Analysis Techniques

Failure Modes

Some of the possible failure modes for connectors are:

1. contacts achieve high resistance in operation
2. electrical breakdown of insulator
3. loose or intermittent solder or crimp
4. contacts or solder joints contacting adjacent contacts
5. structural failure of the connector shell
6. contacts unmating or vibrating
7. contacts welding together
8. connector mating halves separate

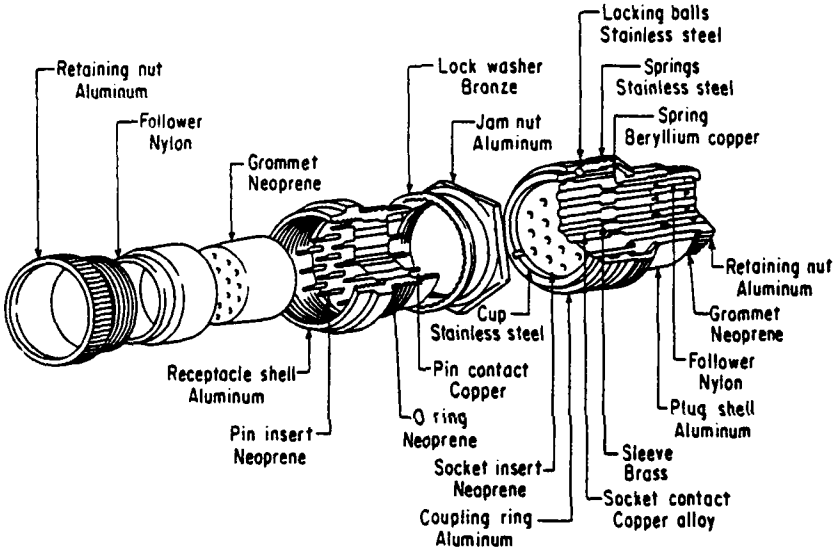

Fig. 4.1 Component Parts of a typical Cylindrical Connector [4.2].

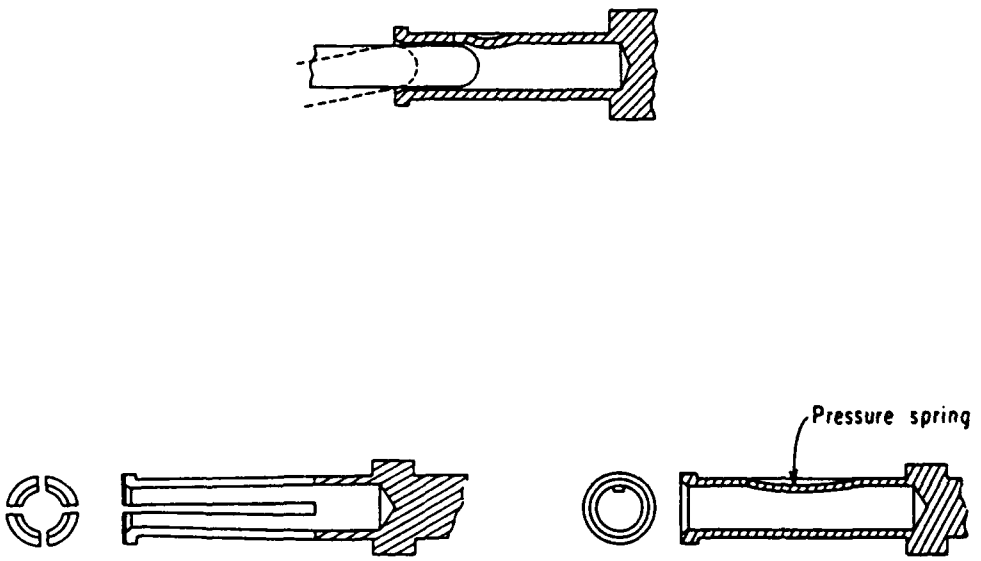

Fig. 4.2 Two Styles of Pin and Socket Contact Construction [4.2].

Corrosion

One of the fundamental problems which affects connectors on all military aircraft is corrosion [4.4]. Water intrusion or fluid contamination can cause corrosion and insulation damage and ultimately result in many of the failure modes listed above. Connector shell corrosion occurs when protective finishes are damaged and expose the base metal. Visual inspection of mated connectors is not always a good indication of their condition because of possible internal damage.

The use of MIL-C-81309 Type III water displacing corrosion inhibitor for Naval Aircraft applications was reported in [4.4]. The material can be sprayed onto connectors and forms a thin soft film that is designed to be displaced by the wiping action of sliding electrical contacts. The effect of the chemistry of this product on chemical or electrical analysis during accident investigation was not considered here. Based on the results of [4.4] water displacing corrosion inhibitors which also prevent air and gases from interacting with plated contact surfaces should be effective in reducing corrosion.

Vibration and shock can lead to cracking and other structural failures of the connector shell. This in turn leads to corrosion, EMI, chaffing of wire bundles, and other problems. Structural failure can also be the result of corrosion. Connector shells made of aluminum with tin or nickel plating are susceptible to corrosion.

4.2.1 Corrosion examination

Although it will generally not be necessary to use SEM analysis to determine that corrosion of a connector was a contributing cause, it may be useful in determining the type of contaminants that caused the corrosion. One study carried out on gold plated connectors used SEM, EDAX and electron probe microanalysis (EPMA) to study the onset of corrosion [4.5]. Pores in the gold plating were identified as an important factor in the corrosion process. Gold plated onto copper (Au/Cu) and silver base (Au/Ag) materials and gold plated onto copper with a silver undercoat (Au/Ag/Cu) were examined in the study. The condition of some of the contacts was such that it could have caused operational failure in the equipment. A summary of the results is as follows:

1. Contacts with gold over silver showed signs of silver migration in SEM analysis.

2. Migration of silver from the underplate to the surface and its reaction with sulphur or chlorine from air pollutants or contamination can be a catastrophic process.

3. Development of contamination begins in the active contact areas even though no pores in the plating can be observed.

4. Corrosion progresses faster in operating contacts than in non-operating contacts due to the acceleration of ion migration caused by the electric current.

Fig. 4.3 shows an example of corrosion observed in the study using optical microscopy, SEM and EDAX. Silver Sulfide (Ag_2S) is shown on the outside surface of the gold outer plating in contacts with the gold-silver-copper alloy structure.

The corrosion process may be organized into these steps:

1. Some initial pores are created in the gold plating during the manufacturing process.
2. Contaminants and handling increase the number of pores in the plating.
3. Base metals, copper or silver, migrate through the gold plating surface.
4. Base metals react with surface contaminants.

Additional testing of gold plated contacts for corrosion related problems using SEM, EDAX, electron microprobe, Auger electron spectroscopy and laser microprobe examinations is described in [4.6]. In this report EDAX X-ray maps showed chlorine and sodium present in the nickel underplate of gold plated contacts. The cause was identified as improper washing before the nickel plating.

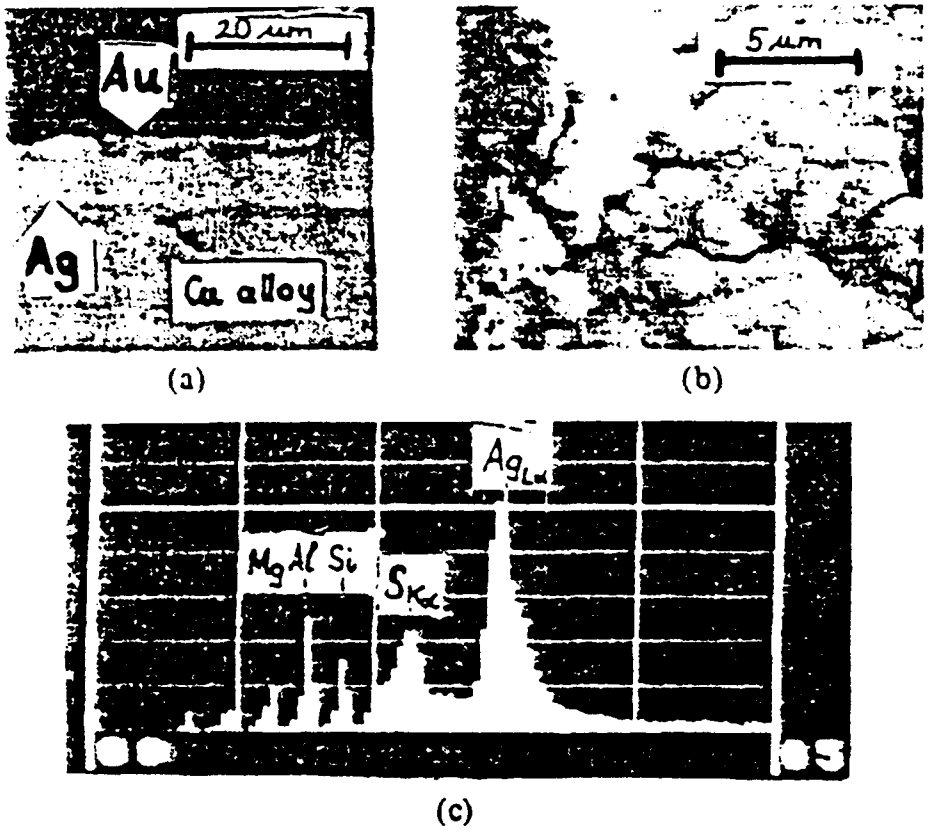

Fig. 4.3 Surface analysis of contaminated contact. (a) Light microscopic cross section shows silver islands growing through the gold electroplate. (b) Secondary electron image represents characteristic view of silver sulfide and its morphology (15 kV). (c) EDAX spectrum of the area shows that it was really silver-sulfide [4.5].

No reports could be found on work done to study the effects of impact or fire damage on connectors. However, it is clear that these types of rapid damage could contrast corrosion damage which is typically a slow mechanism. Most studies are conducted on connectors that have had at least a year of service, or the equivalent of much greater lengths of time in accelerated aging tests. The effects of pre-existing corrosion should be distinguishable from post-impact damage. If a suspect connector is hosed down at the scene of an accident, it may become contaminated but will probably not be corroded if examined quickly. With careful handling and storage, and an understanding of the post-impact scenario, it may be possible to identify progressive corrosion that existed prior to impact.

4.2.2 Corrosion Testing of Connectors

As in other areas of accident investigation, the researcher may be interested in verifying the susceptibility of a particular connector to corrosion by testing samples from the manufacturer. Porosity of gold plating is likely to be of interest in experimentation of this type. Three procedures that may be applicable are published in ASTM B583-80 [4.7]. There are two gas tests using either Nitric acid vapor or sulphur dioxide vapor at high humidity levels. The third test uses an electrographic technique referred to as a type of "gel-bulk electrography". The tests are suitable for coatings containing 75% or more of gold on substrates of silver, copper, nickel, and their alloys. The tests are all destructive in nature, and can only give qualitative results. The procedures may be useful in comparative testing.

4.2.3 Solder Joints

Solder connection of wires to connectors are generally made using a solder-cup terminal which is an integral part of the connector. Examination of these terminals using optical microscopy can reveal a number of the defects related to poor solder joint formation. Two examples of poor solder joints are shown in Fig. 4.4 [4.8]. In Fig. 4.4a insufficient solder was used and the wire is not bonded to the solder cup. Excess solder was used in the case shown in Fig. 4.4b.

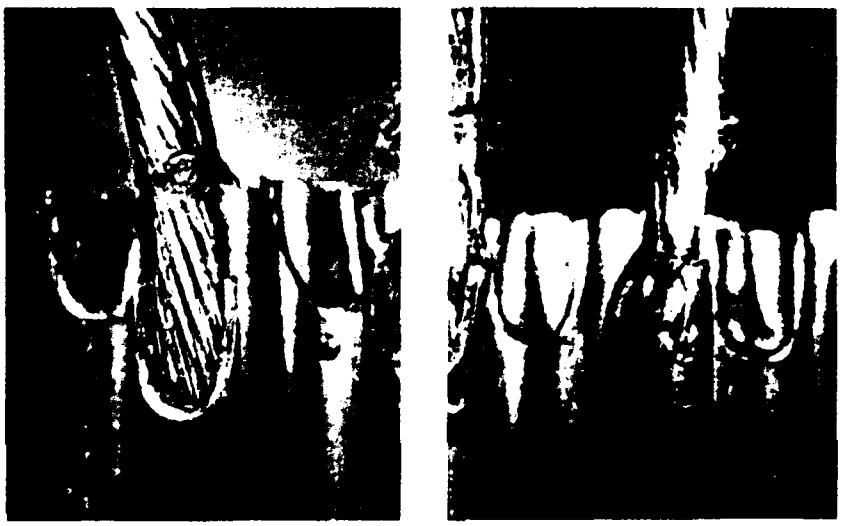

Fig. 4.4 Poor solder joints on connector solder cup terminals.
(a) Insufficient Solder. (b) Excess Solder [4.8].

Due to the low melting point of solder, approximately 361°F for 63 Sn - 37 Pb, visual examination of solder joints will be useful only when little or no post-impact fire exposure has occurred. In this case solder splashes, solder slivers, and solder cracking can be examined by sectioning and optical microscopy.

Solder failures can be caused by contamination of the solder by other metals such as gold, copper and aluminum. SEM/EDAX analysis of the solder joint after moderate exposure to post-impact fire will be able to identify these contaminants. In sufficient quantities, these metals can cause changes in the flow, wetting and mechanical properties of the solder. The resulting joints may be brittle and could result in intermittent or open connections. Fig. 4.5 shows the grain structure of a connection made using 60-40 solder with 15 percent gold. The large white crystals are $AuSn_4$.

4.2.4 Insulation Failure

Insulation breakdown can be caused by any one of several factors. Water penetration, ionizing radiation and thermal aging all have a degrading effect on the mechanical and electrical properties of insulating materials, especially polymeric insulators. [4.9] Ionizing radiation can cause polymer chain scission in some plastics resulting in cracking and increased conductivity. The aging process in organic solid insulators is a continuous chemical process whose rate increases with temperature. A general rule for the effect is that every 10 degree C increase in the continuous operating temperature will reduce the life expectancy of the material by one-half.

Contamination from corrosion can cause insulation failure in two ways. First, by providing ionic compounds in water-based solutions which are absorbed into the bulk of the insulating material. Second, by providing a layer of moisture, with or without the ionic compounds, that degrades the surface resistance. In either case, corona or tracking will occur generally on the surface of the material prior to complete breakdown. In the presence of an incomplete water film, small arc discharges occur between interrupted parts of the film. Conducting tracks grow progressively across the surface, eventually bridging between conductors and causing complete breakdown.

Fig. 4.5 Grain structure of solder joint (60-40) contaminated with 15% Gold. Large white crystals are $AuSn_4$ [4.8].

Insulators made of silicone rubber are not likely to cause tracking problems. Epoxy and Neoprene insulators are more likely to cause flashover due to carbon tracking. If the insulating material of a connector has become sufficiently conductive then the most useful diagnostic tool will probably be SEM/EDAX analysis. This will provide a means of inspecting for erosion of the insulator due to tracking and the presence of surface contaminants.

4.2.5 Electrical Measurements

Under certain circumstances, it may be meaningful to make electrical resistance measurements on a connector to determine its pre-impact condition. In order for such measurements to be useful the connector must be relatively undamaged by impact and post-impact handling. It will be very important that the connector not be unmated after impact because the effect of contact wiping due to unmating and mating will render electrical measurements meaningless. Resistance measurements can be made on both the contacts and the insulator. These will be covered in the following discussions.

In most types of military connectors the contact resistance is specified by measuring the millivolt drop across the mated connector. Generally the resistances are on the order of 0.001 Ω. Resistances in this range can be made with a micro-ohmmeter. If a thin film has developed between contacts by corrosion or other insulating contamination, then the contacts will appear to have a high resistance, on the order of 1 MΩ, at low voltages. The resistance decreases slowly as the voltage is increased and then drops sharply. The voltage at the point when the resistance drops is called the fritting voltage. Fritting voltages have been used to characterize moderately corroded connector contacts [4.5].

Another method for examining the effect of low level corrosion on connector performance was reported by Lockheed [4.10]. Lockheed developed a technique called the discontinuity detector function which detects low-level conduction problems in connections that would result in data errors in logic circuits. The report also discusses Low-Level Contact Resistance (LLCR) measurements which are used to diagnose "dry-circuit" conditions.

Military specifications provide guidelines on how to measure the insulation resistance between contacts and from contacts to the shell. Some of these are MIL-C-8384, MIL-C-21097, MIL-C-26500, and MIL-C-26518. High resistance values beyond 1 GΩ can be measured with digital meters but these generally do not apply more than a few volts to the unknown resistance. In higher voltage circuits, a megger may be used. These apply 500 V or 1000 Vac to the circuit under test. The investigator must remember that the most likely conditions that existed at the time of failure are the prevailing operating voltages and currents for the connector. Both contact and insulation resistance can be nonlinear functions of applied voltage and these measurements should be made at the prevailing operating conditions.

4.2.6 Problem with Glycol/Water Mixtures

The analysis of a potential problem related to the use of glycol/water solutions is reported in [4.11]. The problem may occur when these solutions come in contact with energized silver plated conductors or contacts. Although connector contacts are primarily gold plated, the exposure of silver-plated wire at connectors has resulted in failures in these areas. DC voltage on the connector causes a current which passes through the solution and results in a chemical breakdown. A violent exothermic reaction occurs near the connector, usually resulting in fire. No literature describing an accident investigation technique for identifying this problem in post-impact investigation was found. A detailed description of the chemical reaction involved is covered in [4.11].

4.3 Failure Analysis Guidelines

No single procedure for the failure analysis of connectors will be appropriate for all the different connectors used on aircraft. However, some steps may be outlined as follows:

1. Visual examination of the outside of the connector and wiring
2. Prepare access to wiring for electrical tests on the connector

3. Make resistance measurements for contact resistance and insulator
4. Visually examine solder joints or crimps
5. Separate connector and visually examine contact pins and insulator surface
6. SEM/EDAX analysis of contacts and insulator

The steps above assume that the connector has not previously been separated, and is still in its post-accident state. Access to wiring is needed to make meaningful resistance measurements.

4.4 Supplemental Methods

No method of analyzing connectors specifically for accident investigation was found in the technical literature reviewed and no supplemental methods can be recommended at present.

4.5 Additional work

A broader consideration of connector types and their failure modes is warranted because of the high apparent involvement of connectors in aircraft incidents. Some of the problems to which connectors are subject, such as corrosion, have been reported. No literature was found which addresses accident investigation using the characteristics of corrosion, or any other connector problem. Significant work needs to be done to address this area of aircraft accident investigation. A brief list of that work is presented below:

1. Review and supplement the methods presented here with additional illustrations from test data.
2. Identify additional examination methods.

3. Classify all connectors into classes such as: circuit board, rack-and-panel, circular, RF.

4. Consider the mechanics of applying the methods to each class of connectors.

5. Verify above by testing samples of each.

6. Define best sequence of tests for each class.

The following effects would need to be demonstrated in developing examples for illustrating failure analysis methods:

1. Contact corrosion
2. Insulation breakdown
3. Solder joint failure
4. Crimp joint failure

4.6 References

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4.3 MIL-C-38999H. Connectors, Electrical, Circular, Miniature, High Density . . . General Specification for. February 27, 1981.

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4.9 The Standard Handbook for Electrical Engineers, Ed. by D.G. Fink, H.W. Beatty. 12th edition. McGraw-Hill, 1987, New York. Section 4. Properties of Materials.

4.10 Modern Avionics Connector Unreliability. R. Morrison and J. Simmons. 1989 AIAA, AHS and ASEE Aircraft Design, Systems and Operations Conference.

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5.0 SWITCHES

Switches, like light bulbs, are of particular interest to the accident investigator, not because they are the cause of a large number of failures, but because of the information they provide on the condition of the aircraft's circuitry prior to impact. Nonetheless, switches do fail for a variety of mechanical and electrical reasons and the failures are an important consideration when the mechanical position of the switch is examined. This section addresses switches of the manually operated type, such as the toggle, push-button and rotary switches. The dual function of circuit breaker and switch is provided by a commonly used device in military aircraft and will be covered in this section as a representative device.

5.1 Construction

A switching device widely used in aircraft is the circuit breaker meeting the requirements of MIL-C-5809 G [5.1]. The construction of a typical unit is shown in Fig. 5.1 [5.2]. Internally, the device uses a bi-metal creep mechanism to provide the overcurrent trip function. Although not intended to be used as a switch, the device is switchable. The position of the handle indicates whether the switch is in the closed (in) or opened (out) position. If an overcurrent trip condition occurs when the device is in the closed position, the contacts open and the handle pops out. The device must be manually reset after tripping. Ratings for the breakers covered by MIL-C-5809 G include the voltage range from 28 Vdc to 208 Vac. The current range is 0.5 to 100 A. The performance criteria for different environmental conditions are in the standard as well.

The condition and operation of the main electric contacts are of fundamental concern, and the remainder of this section will deal with that issue. The contacts in switches of the type described here are almost all made of a Silver-Cadmium Oxide (Ag-CdO) alloy. The alloys used are usually 10 to 15 percent CdO by weight and are made by sintering. The contacts are made separately and then welded or brazed onto the contact arms. Common materials for the moveable arms or the body of a stationary contact base are copper, brass and phosphor-bronze.

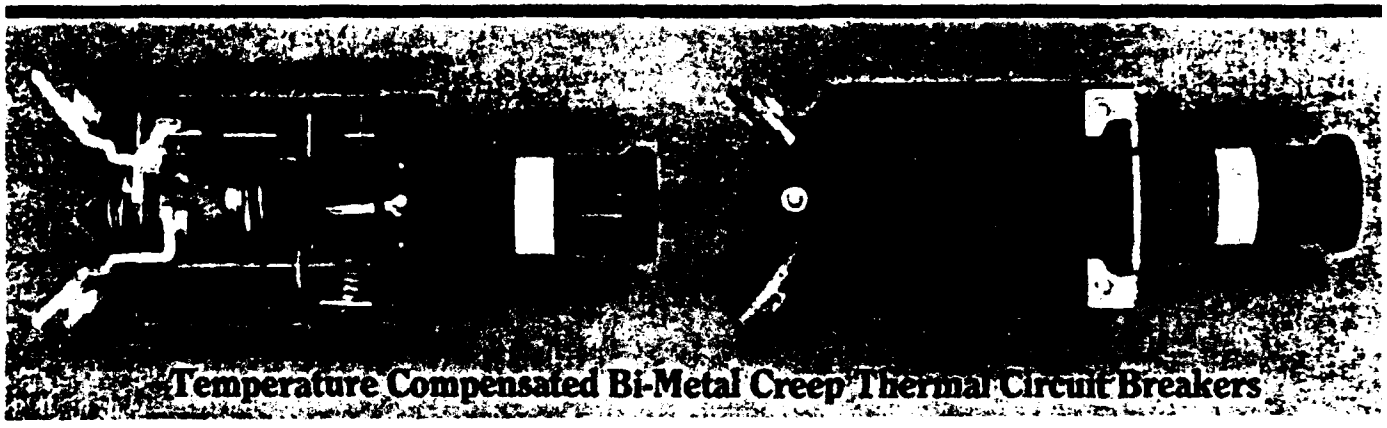

Fig. 5.1 Aircraft Style Circuit Breaker [5.2].

The powdered contact material can be made using cadmium oxide - in which case it is referred to as pre-oxidized. It can also be made using cadmium and then oxidized after the sintering process. These post-oxidized contacts may have some unoxidized cadmium inside the body of the contact.

Experimental analysis of the beneficial characteristics of Ag-CdO as compared to other materials was reported by Holm [5.3]. The improvement over pure silver contacts are: (1) reduced susceptibility to contact welding; (2) reduced erosion of the contacts and; (3) increased current handling capability.

5.2 Failure Analysis Techniques

Some of the possible failure modes for switches are:

1. Switch opened but contacts stay closed.
2. Switch closed but contacts stay opened.
3. Excessive contact drop in closed condition.
4. Excessive leakage to ground.

5.2.1 Electrical Measurements

Measurement of the electrical state of switch contacts can, of course, be made in the field or laboratory by using a conventional ohmmeter. In many cases this will give the field investigator a confirmation that the mechanical and electrical states of the switch, are consistent. If the contacts appear to be closed then it may be appropriate to measure contact drop, which should be done at rated current or conditions specified by the manufacturers' ratings.

If the contacts appear to have a high resistance, caution should be taken in handling the switch. This would be especially true in a case where the switch appears to have failed in the open condition. The concern here is to prevent any accidental movement of the contacts, or any electrical disturbance which may overcome film-type contamination.

5.2.2 X-ray Examination

X-ray examination of switches can be a valuable procedure for determining the internal condition of the switch prior to opening the case. Many switches are made with plastic cases which are transparent to X-rays and the internal metal components will be clearly visible in X-ray photographs. Microfocus X-ray equipment will be the best choice for this type of examination because of the ability to view the small internal components of the switch [5.4, 5.5]. The ideal procedure for examining switches might be to have an X-ray photograph taken very early in the investigation, possibly as the switches are being removed from a panel and being tagged for identification. This would verify the position of all the internal components before further handling.

5.2.3 Fritting

Fritting is a mechanism which involves a thin film of contamination between electrical contacts [5.3]. When low voltages are applied to the contacts, a high resistance, on the order of 1 MΩ, is measured. As the voltage is increased, the electrons between the contacts are able to tunnel through the film and the apparent resistance lowers. At some voltage, called the fritting voltage, a marked decrease in the resistance occurs. It is not clear if the fritting voltage, once overcome, permanently renders the contacts more conductive. Because of this, it is important that initial field measurements on switches be made with meters that do not apply more than a few volts to the circuit. The mechanism of fritting is complex and it is not clear from the literature whether AgCdO is particularly susceptible to the problem. It is common with gold plated contacts.

5.2.4 Contact Erosion

Electrical contacts tend to wear away in normal use, mainly due to arcing. An example of contact wear on larger contacts is shown in Fig. 5.2 [5.6]. As the contacts part, the current is confined to flow in a reduced area at the mating surface between the contacts. The resistance of the contact material and the high current density cause local heating which melts the contact material at the surface of the contacts as they begin to separate. In dc circuits, some of the melted material is transferred in the direction of (conventional) current flow. This causes

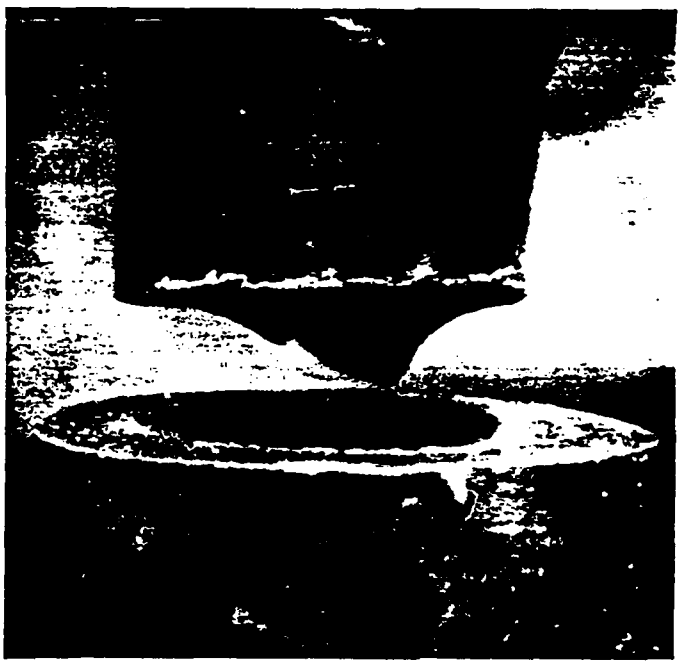

Fig. 5.2 Worn Contacts showing Pip and Crater form of erosion due to metal transfer [5.6].

mounds, called pips, to form on the cathode, while depleted areas, called craters, develop on the anode.

Erosion under normal conditions takes place over thousands of switching operations. The craters formed on the anode connect to form ravines with deep cracks in the contact. The properties of CdO cause an eventual "healing" of the ravines. The cross section of such a ravine was taken by SEM [5.7]. The work using SEM and EDAX analysis also showed that the eroded anodes had surfaces which were CdO rich, while the cathodes were Ag rich. The effects of erosion can be observed after a small number of arcing operations. In fact, the damage of one arcing operation on gold plated contacts was examined in [5.8] and is shown in Fig. 5.3.

5.2.5 Examination Using Ultraviolet Light

A general examination of the switch or circuit breaker using Short Wave Ultraviolet (UV) light can reveal evidence of the contact material spattering. Cadmium-Oxide fluoresces under UV and CdO particles that have been displaced onto nearby surfaces can easily be seen [5.9].

5.2.6 Contact Erosion

Contact erosion can be examined with optical microscopy or SEM. In dc circuits, the anode will be marked with craters, while pips will appear on the cathode. The direction of current under normal conditions will be known and the erosion will not be severe for normally operated switches. However, the abnormal condition that occurs during failure may be investigated by examining the apparent severity and polarity of the contacts based on erosion examination. Since the melting point of silver is 1760° F and cadmium oxide decomposes at 1850° F, the contact condition will survive moderate exposure to fire damage. No literature was found which characterized the appearance of worn contacts versus the number of switch operations.

5.2.7 Contact Welding

Under severe overload conditions contacts can weld shut. Since this is a condition of particular interest in accident investigation, some method of measuring the welded surface should be developed. No such method was found in our survey of the technical literature on the subject.

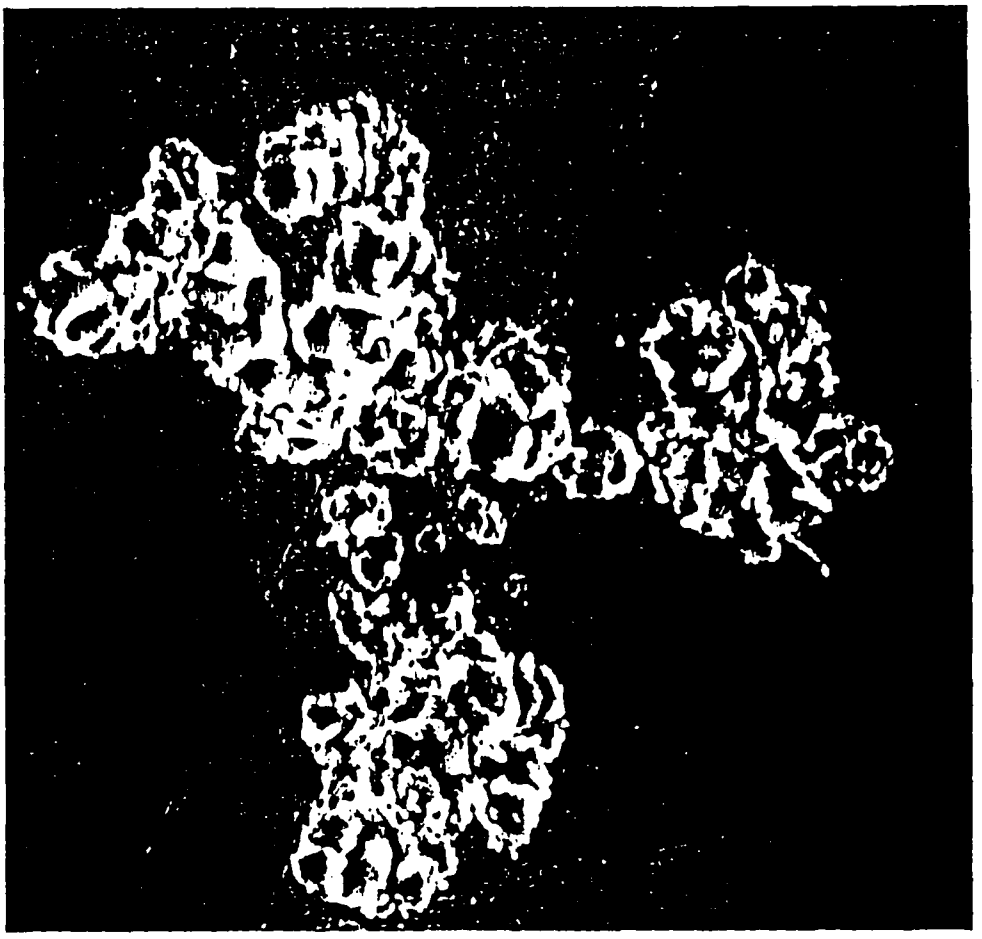

Fig. 5.3 SEM photograph of contact damage on gold electrodes sustained during one gas breakdown discharge. 20,000 x. [5.8].

Since the weld may be quite brittle and relatively small in cross sectional area, ordinary metallographic specimen preparation may break the weld in the sectioning operation. However, it may be possible to chemically stain the sample and then break the weld. The unstained area would then show the cross section of the weld.

5.2.8 Contamination from Polymeric Materials

In [5.9], off-center striking of the switch contacts with an inductive load caused the contacts to burn the phenolic case of the switch. The case material became volatile and condensed on the switch contacts. The surface contaminant was chemically analyzed by Infrared spectrographic analysis and found to be a phenol-formaldehyde polymer.

5.3 Failure Analysis Guidelines

Analysis of the literature identified during the research, and consideration of the techniques listed above, suggests the following investigation procedure:

1. Observe mechanical position of the outside mechanism
2. Measure contact resistance with low voltage ohmmeter circuit
3. Disassemble and examine contacts
4. Examine for contact spatter with UV light
5. SEM examination, determine polarity of current flow
6. IR spectral analysis of contaminants

Under any given set of circumstances, only selected steps would need to be undertaken.

5.4 Supplemental Methods

In addition to these techniques it is recommended that X-ray photographs of the switch be taken at an early stage in the investigation process. The measurement of fritting voltages may also be of use in testing high resistance contacts.

5.5 Additional Work Needed

The following is a brief list of additional work needed to make the methods presented here generally practical for accident investigation.

1. Identify specific equipment for some of the tests.
   a. low resistance measurements
   b. IR spectral analysis
   c. measurement of fritting voltage

2. Characterize contact wear as a function of switch life (number of operations).

3. Prepare photographs of typical switches and document procedures.

4. Organize the methods into a logical procedure.

5.6 References

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5.7 Developments of the Arc-Induced Erosion Surface in Silver-cadmium Oxide. P.C. Wingert, et al. (GTE products, Reidsville NC). IEEE Transactions on Components, Hybrids and Manufacturing Technology. Vol. CHMT-8, No. 1. March 1985.

5.8 Using Scanning Electron Microscopes to Uncover Contact problems. N.H. Winquist. Bell Laboratories Record, Volume 49, No. 5, May 1971.

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6.0 PERMANENT MAGNET MATERIALS

Permanent magnets are used in a variety of aircraft applications. Some of these applications include motors for control surface and gear actuators, alternators for on-board power generation, magnets in avionic instruments and focusing magnets in CRT displays. Highly specialized materials are used to make permanent magnets which are not used in other aircraft applications. This is particularly true of the rare earth permanent magnets which are widely used in high performance aircraft applications. Because of their unusual properties, especially their sensitivity to temperature and shock, magnets may provide some data about the circumstances leading up to an accident. Unfortunately, no literature could be found which described specific accident investigation techniques related to permanent magnet materials.

6.1 Fabrication of Magnets

Two magnet materials which are widely used in high performance applications are: (1) Alnico and (2) Rare-Earth magnets. A brief description of the fabrication processes is presented below.

Alnico

A common method of producing Alnico-type alloys starts with preparation of the alloy in an induction furnace. Small batches of the alloy are melted rapidly in a furnace and poured into baked sand molds. These steps are performed quickly to prevent excessive oxidation and metal segregation. The subsequent heat treatment process involves three steps: a high temperature solution treatment; a controlled quench; low temperature aging. A magnetic field is used in conjunction with the controlled quench for some alloys to impart anisotropic magnetic properties [6.1].

Another method of making these alloys uses a powder metallurgy technique. A mixture of the constituent metal powders and a lubricant are compacted to shape in a forming die. The compacts are sintered in a hydrogen atmosphere at a temperature slightly below the melting point of the alloy. A subsequent heat treatment is used to develop the desired magnetic properties. Properties of Alnico materials are shown in Table 6.1 [6.1].

Table 6.1 Properties of Alnico Magnetic Materials [6.1].

	Alnico 1	Alnico 2	Alnico 3	Alnico 4	Alnico 5	Alnico 6	Alnico 7	Alnico 8
Chemical Composition								
Nickel	20	17	25	28	14	15	18	14.5
Aluminum	12	10	12	12	8	8	8.5	7
Cobalt	5	12.5	...	5	24	24	24	35
Titanium	...	...	...	...	...	1.2	5	5
Copper	...	6	...	...	3.2	3	3.2	5
Mechanical Properties								
Tensile strength, psi	4,100	3,000	12,000	9,000	5,400	23,000	...	39,500
Transverse modulus of rupture, psi	13,900	7,200	22,500	24,000	10,500	45,000	2,000	30,000
Rockwell hardness	C45	C45	C45	C45	C50	C56	C60	C58
Electrical Properties								
Resistivity (microhm/cm/sq cm) temp. 25°C	75	65	60	75	47	50	58	62
Magnetic Properties								
Peak H, oersteds	2,000	2,000	2,000	3,000	3,000	3,000	5,000	5,000
Peak induction, B, gausses	12,350	12,500	12,000	11,850	16,500	15,700	14,700	13,500
Residual induction, B_r, gausses	7,300	7,250	6,950	5,300	12,600	10,650	7,400	8,000
Coercive force, H_c, oersteds	440	560	480	730	600	790	1,065	1,400
Maximum energy product, (B_dH_d) m.g.o.	1.4	1.66	1.38	11.3	5.0	3.95	3.0	4.0
Loss (W-sec/cyc) lb	7.4	9.5	7.1	10.8	15.3	17.8	17.4	16.6
Coefficient of linear expansion								
(20–120°C)	11.9×10^6	11.5×10^6	13.2×10^6	12.3×10^6	11.5×10^6	10.7×10^6	...	10.3×10^6
(20–220°C)	12.1×10^6	12.1×10^6	13.2×10^6	12.7×10^6	11.5×10^6	11.1×10^6	...	10.7×10^6
(20–300°C)	12.6×10^6	12.4×10^6	13.0×10^6	13.1×10^6	11.6×10^6	11.4×10^6	11.4×10^6	11.0×10^6
Curie Point, deg C (+10°C)	780	815	760	800	890	860	840	845
Specific heat (30–400°C) calorie per gm/per deg C.	...	0.11	...	...	0.11	0.11	...	...
Additional Properties								
Weight, lb/cu in.	0.249	0.266	0.249	0.253	0.264	0.262	0.259	0.263
Density, gm/cu cm	6.9	7.1	6.9	7.0	7.3	7.2	7.17	7.25

Rare Earth Magnets

Many of the rare earth materials are cobalt-rare earth alloys designated Co_5R. One of the widely used alloys is Samarium Cobalt. The ingots are prepared by standard melting techniques and ground to powder by a number of methods [6.2]. These materials oxidize easily when in fine powder form and are protected during grinding by an inert gaseous atmosphere or a protective organic liquid, such as toluene or isopropyl alcohol. One method stabilizes the powder against oxidation by electrolytic plating of Nickel in an acid bath. The powder is oriented by an applied magnetic field and hydrostatically compressed. The density of the resulting compact is about 80%. Final density and magnetic properties are the result of further compaction, and heat treating processes. Properties of Samarium Cobalt Magnets are shown in Table 6.2 [6.2].

Finishing/Magnetization

The magnets produced by the above processes are finished to size by machining or abrasive operations prior to magnetization. Magnetization is accomplished by placing the magnet in specially designed coils which expose the magnet to a strong field in the direction of the desired final field of the magnet. A pulse type dc power supply energizes the coil. The fields created cause an immediate alignment of the magnetic domains in the material resulting in permanent magnetization [6.3].

6.2 Failure Analysis Techniques

6.2.1 Temperature Effects

Although there is no literature which describes an accident investigation technique that utilizes the irreversible loss of magnetization due to exposure to high temperature, the fundamental effect is well known. Fig. 6.1 illustrates the theoretical relationship between temperature and magnetization [6.1]. All magnetic materials exhibit reasonably good agreement with this law. The basis for the property is the increasing thermal agitation of the elementary electron spin alignment. Virtually all magnetization will be lost when the magnet is returned to room temperature after prolonged exposure at the Curie temperature. The irreversible loss of a permanent magnet's field strength is a more complicated phenomenon than shown in Fig. 6.1 because of the simultaneous loss of coercive strength. Coercive strength is the externally applied magnetomotive force required to force the flux to zero.

Table 6.2 Properties of Samarium Cobalt Magnetic Materials [6.2].

PROPERTY	UNITS	LOW	AVERAGE	HIGH
Density	g/cm^3	7.3	8.2	8.5
Porosity	%	0	0	0
Flexural Strength	$10^3 lbf/in^2$	9.8	13.5	17.1
Compressive Strength	$10^3 lbf/in^2$	---	42.7	---
Tensile Strength	$10^3 lbf/in^2$	---	5	---
Elastic Modulus	$10^6 lbf/in^2$	22.5	23.9	25.3
Rockwell Hardness	R_c	50	52.9	55
Vickers Hardness	kg/mm^2	460	510	580
Specific Heat	(cal/g °C)		0.089	
Thermal Conductivity	cal/cm · sec · °C			
Direction not given		0.020	0.023	0.025
Parallel to c-axis			0.027	
Perpendicular to c-axis			0.024	
Coefficient of Thermal Expansion	10^{-6}/°C			
Direction not given		5	8.43	10
Parallel to c-axis		5	5.6	6.1
Perpendicular to c-axis		12.5	12.8	13.0
Electrical Resistivity	$10^{-6}\Omega$ cm			
No orientation given		10	48.8	60
Parallel to c-axis			49	
Perpendicular to c-axis			---	

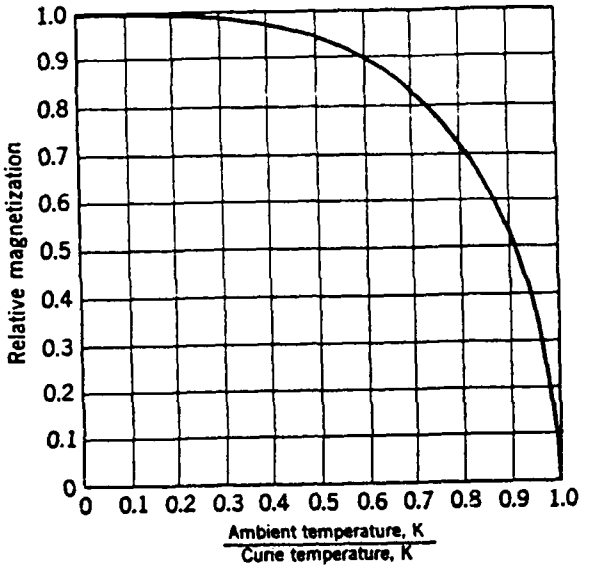


Fig. 6.1 Theoretical curve of magnetization versus temperature [6.1].

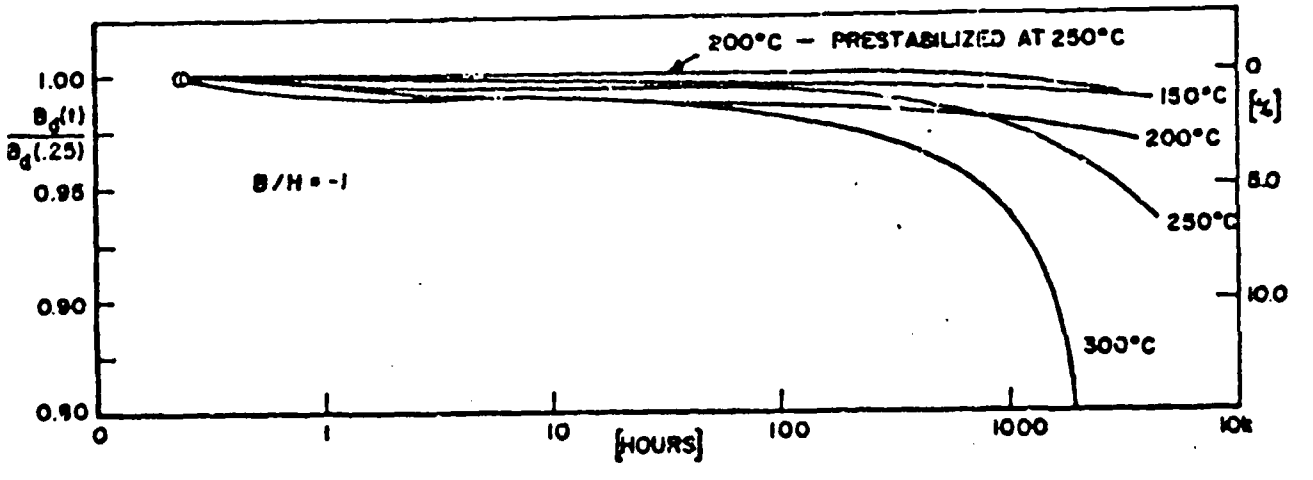


Fig. 6.2 Effect of aging in air at elevated temperatures. Samarium cobalt [6.4].

Temperature excursions above the normal operating temperature, but below the Curie temperature, will result in some irreversible loss of magnetic field strength. In practice, a magnet will stop performing its intended function if the exposure time is too long or temperature is too high. As a result, there is little data to characterize the irreversible loss of magnetization when the loss of magnetic field strength is more than about 20%. Table 6.3 shows the irreversible loss in magnetization for Alnico materials. Notice that the irreversible loss increases with decreasing Curie temperature. Fig. 6.2 shows the effect of aging on $SmCo_5$ permanent magnets at elevated temperature [6.4]. The Curie temperature is 700-750° F.

Opposing magnetic fields will accelerate demagnetization at elevated temperatures just as applied magnetic fields during heating will aid in magnetization during manufacturing. By virtue of this fact, magnets will demagnetize more rapidly in an operating motor or generator than they would if the device were not operating. The specific structure of the magnetic circuit, shock and vibration will also affect the demagnetization phenomenon.

The complexity of the demagnetization process at elevated temperatures introduces questions about whether or not these effects can be reduced to a practical accident investigation procedure. Nonetheless, it is expected that some bounds on the time-temperature history of a permanent magnet motor or alternator can be found from examining the field strength of the magnets and comparing the measurements to a sample motor.

6.2.2 Mechanical Shock

It has long been known that a magnetized bar of steel could be partially demagnetized if subjected to shock or vibration in the absence of an applied magnetic field. In essence this is the reverse of the effect which causes partial magnetization in soft iron when impacted in the presence of a magnetic field. There is an indication in the literature [6.1] that the loss of

Table 6.3 Irreversible loss of magnetization versus temperature for Alnico and other magnets [6.1].

Column I: % irreversible remanence loss at room temperature after heating to indicated temperature.
Column II: % of initial room temperature remanence found stable with magnet at indicated temperature.

Material	Dimension Ratio L/D	Temperature, °C 100 I	100 II	200 I	200 II	300 I	300 II	400 I	400 II	500 I	500 II
Alnico 2	8.00	2.0	98	3.1	94	4.2	90	6.1	86	8.2	80
	3.62	3.1	98	4.0	92	6.9	88	8.6	84	12.0	78
	2.00	3.5	97	4.7	91	7.4	89	10.7	85	13.1	81
Alnico 5	8.00	0.1	99.9	0.2	96	0.4	93.6	0.7	91.2	1.2	88.0
	4.68	0.4	99.6	0.8	96.3	1.1	93.8	1.7	91.1	2.0	88.2
	2.00	0.5	99.4	1.7	96.6	2.1	94.1	2.6	92.2	3.0	88.6
Alnico 6	20.00	0.1	98.2	0.2	95.6	0.4	93.0	0.8	89.7	1.8	86.5
	4.12	0.5	98.7	0.9	95.6	1.2	92.7	2.0	89.4	3.0	85.2
	2.00	0.7	99.1	1.2	97.2	1.5	94.2	2.1	90.5	3.3	86.0
Alnico 7 (Anisotropic)	2.00	0.4	98.0	1.0	95.0	1.7	92	3.0	89	5.1	84
Alnico 7 (Isotropic)	2.00	0.8	98.0	1.8	94.0	3.0	91	4.5	87	6.8	83
Alnico 8	5.62	0.7	98.8								
	2.85	0.7	99.0								
	1.91	0.9	99.4								
	1.01	1.0	99.8								
Barium Ferrite (All Grades)	All	0	85	0	68	0	50				
Cobalt-Platinum	31.67	0	97.9								
	16.02	0	98.5								
	10.63	0	98.8								
	5.56	0	97.9								

magnetization is related to the compression that takes place during impact. Fig. 6.3 shows the effect of impact on magnets. These data were taken on 10 inch long bars, 1/2 inch square in cross section. The impact was generated by dropping the magnet onto a wooden platform from a height of one meter.

6.2.3 Microstructural Inspection

Microstructural inspection of Samarium Cobalt magnets was conducted in [6.4]. In this study the samples were prepared by sectioning the magnets parallel to the direction of magnetization. The samples were then mounted, polished and etched with a 1% Nital solution prior to examination with a light microscope. The study included the examination of magnets that had been aged, and were produced by several different manufacturers. An illustration of the microstructural examination is shown in Fig. 6.4 [6.2]. The effect of cooling during manufacture can be seen in the figure. An electron beam microprobe examination scan was also conducted to verify the composition of surface layers.

Other features detrimental to magnet performance that can be observed are:

1. Sm_2CO_7 precipitate
2. Pores interconnected by cracks
3. Outer oxide layer
4. Surface faults leading to internal cracks
5. Series of connected subsurface cracks

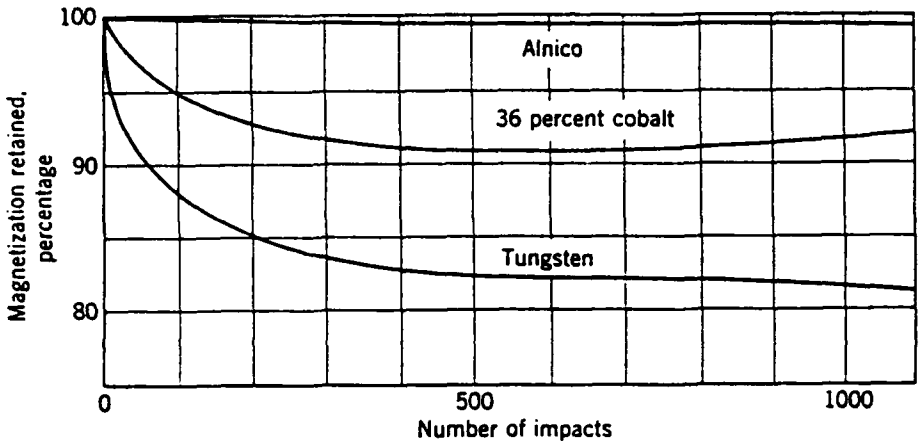


Fig. 6.3 Demagnetization of Permanent Magnets due to Repetitive Impact [6.1].

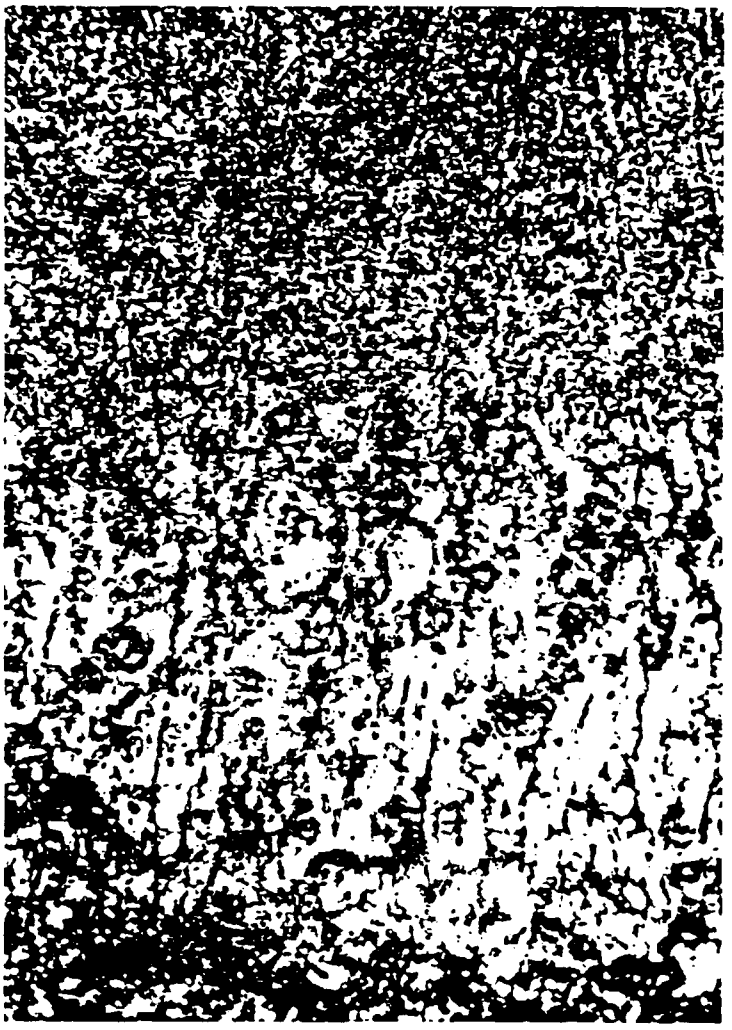


Fig. 6.4 Microstructure of the cross section of a cast 1 in diameter rare-earth magnet. Striations through the thickness of the magnet are due to the temperature gradient during cooling [6.2].

6.2.4 Examination of Magnetic Domains

This technique is mentioned here only for completeness and potential application despite the absence of its application to accident investigation at the present time. It involves the preparation of a colloidal suspension of magnetite (Fe_3O_4) and special preparation of the magnet surfaces. The procedures are explained in some detail in reference 6.2 and provide a method for viewing the magnetic domains with a reflected light microscope. The shape and orientation of the magnetic domains may be used to diagnose manufacturing or application problems.

6.3 Failure Analysis Guidelines

A preliminary procedure for analysis of permanent magnets used in motors and generators should include the following steps:

1. Mark rotor position with respect to stator.
2. Disassemble motor or generator.
3. Measure flux density of all magnets.
4. Obtain sample motor and measure flux density of all magnets.

6.4 Additional Work

The theoretical and limited experimental data presented in this section does not itself constitute a practical accident investigation technique at this time. Based on the reports and literature identified during this work, it is apparent that additional test data on temperature and shock demagnetization would be needed to develop the procedures further. Because of the complexity of these processes, they may ultimately be suitable for comparative analysis only.

The following is a brief list of the work required to make the method generally practical for accident investigation:

1. Temperature testing of magnets to document the change in magnetization versus temperature exposure.

2. Shock testing of magnets to document the change in magnetization at various g levels of shock.

3. Examination of microstructure before and after temperature/shock.

4. Analysis of experimental data to develop a procedure for estimating time-temperature or shock exposure.

6.5 References

6.1 Permanent Magnets and their Applications. R.J. Parker, R.J. Studders. 1962, John Wiley & Sons, New York.

6.2 Rare Earth Permanent Magnets. E.A. Nesbitt, J.H. Wernick. 1973, Academic Press. New York.

6.3 Magnetization, Demagnetization and Measurement of Permanent Magnets. H.A. White, O.V. Gigliotti. 1984, Stackpole Magnet Division, Kane, PA.

6.4 Physical Properties of Rare Earth-Cobalt Magnets (Alternator Service Aging Study). H.F. Mildrum, K.J. Strnat. 1975, University of Dayton, Electrical Engineering Department. Dayton, Ohio, report No. UDRI-TR-75. Air Force Materials Laboratory report AFML-TR-75-90.

7.0 PRINTED WIRING BOARDS

The fabrication of printed wiring boards (PWBs) is a complex process involving a variety of material processing steps. One of the traditional processes, still used widely in military equipment, involves the use of copper clad laminates which are etched to produce circuit traces. The boards are drilled with automatic machinery, loaded with components and soldered by hand or with wave soldering so as to complete the printed board. Although there have been a variety of new chemical processes in board structures that have evolved and pervaded military equipment in recent years, the final result of these new processes is a product similar to the one just described. Even in the more traditional processes there are at least 12 process steps, as many chemical treatments, and a half a dozen special alloys used to prepare a printed wiring board.

Contamination in the composition of the alloys or in any one of the processes can lead to reduced reliability and increase the potential of failure of the printed wiring board under the right conditions. As a result, the accident investigator has a variety of areas to examine when trying to determine the cause of failure of a particular type of printed wiring board. The variety of materials and processes used to fabricate a printed wiring board makes the failure analysis examination procedure quite complex, but at the same time these materials provide an opportunity to differentiate post-impact damage from electrical damage which may have occurred prior to the accident. For example, if an electronic component on a printed wiring board overheats just prior to its failure, there will be some damage to the laminate, the copper cladding and the solder connections. Some of this evidence can be distinguished visually and chemically from the general heating that might result from post-impact fire.

In this section we will review some of the fundamental processes used in printed wiring fabrication, the materials used in those processes, and some of the problem areas related to material contamination which can provide useful information to the accident investigator.

7.1 Construction of Printed Wiring Boards

A variety of printed wiring board construction methods are used in military aircraft. A brief description of the construction and materials used is presented in the following discussions.

7.1.1 Types of Printed Wiring Boards

Traditional construction of printed wiring boards involves the use laminated board materials to construct single-sided, double-sided, or multi-layer boards with copper clad conductor traces. Components are mounted on the boards with their leads passing through holes perpendicular to the board's surface. More recently these boards have been replaced by high density circuits using surface mount devices. The terms "through-hole" and "surface mount" are used to distinguish the two types of construction methods. Fig. 7.1 illustrates the mounting of components on these two types of boards [7.1].

Surface mount components have leads which are soldered onto pads on the exterior surfaces of the board without using holes. Several surface mount integrated circuit (IC) lead styles are shown in Fig. 7.2. Leadless devices are also used and these have plated contacts which are soldered directly to the pads on the board surface. An example of a ceramic leadless device is shown in Fig. 7.3.

In through-hole boards the component leads fasten the components to the board. However, in surface-mount construction the solder joints alone provide the mechanical fastening of the components as well as the electrical connection. Without the compliant lead connection, mismatch between the coefficient of thermal expansion (CTE) of the components and the board material causes considerable stress on the solder joints [7.2]. Metal core boards have been developed to remove heat and help control the CTE of the board material. Fig. 7.4 shows a copper-invar-copper board construction designed to reduce solder joint stress in surface mount applications. Another construction, shown in Fig. 7.5, uses a compliant surface layer to reduce solder joint stress [7.3].

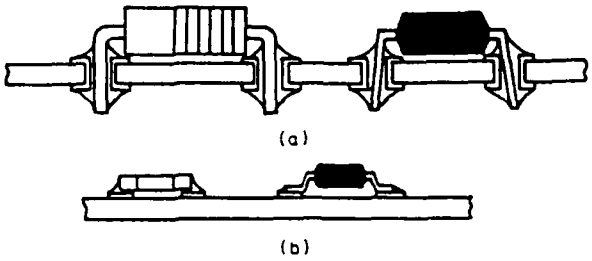


Fig. 7.1 Component mounting on through-hole (a) and surface-mount (b) printed wiring boards [7.1].

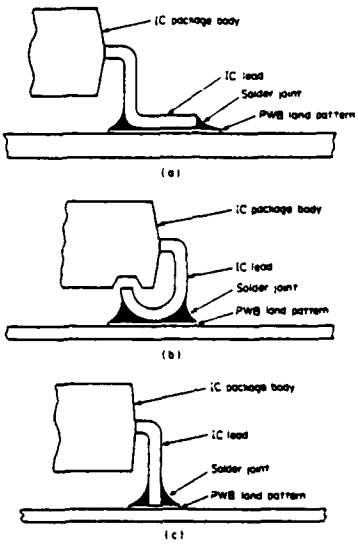


Fig. 7.2 Some examples of surface-mount component leads [7.1].

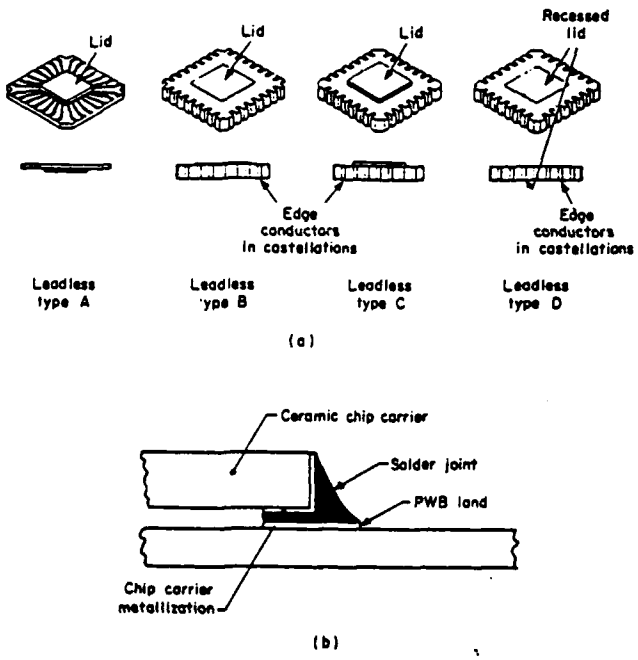


Fig. 7.3 Ceramic leadless devices for surface-mount [7.1].

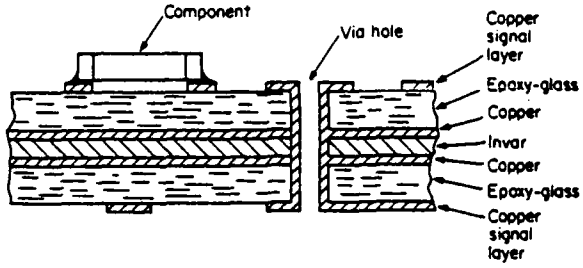


Fig. 7.4 Copper-Invar-Copper printed wiring board structure [7.1].

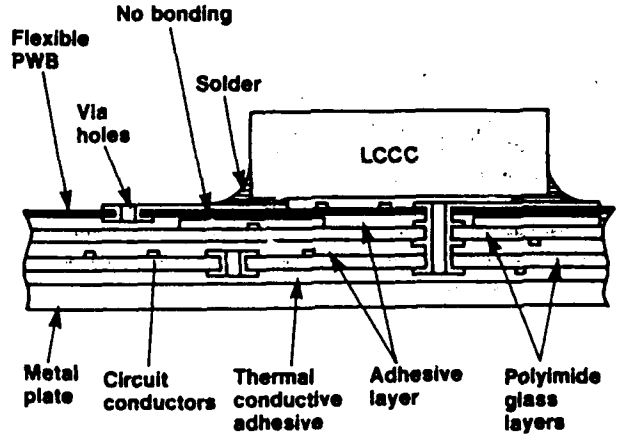


Fig. 7.5 Compliant layer printed wiring board [7.3].

Flexible printed circuit boards are used both for flexible circuit connections and for the construction of circuitry whose geometry would not be possible using conventional methods. In both cases copper circuit traces are laminated between two sheets of a plastic film. Polyimide films like DuPont's Kapton are used almost exclusively in these applications. For circuit traces a flexible sheet is constructed with terminations at the ends allowing the majority of the sheet to flex as needed by the application. In flexible circuit boards, components are mounted on the flexible laminate. The finished "board" is fitted into the housing, using the flexibility of the construction to allow the circuit board to be inserted into an unusual shape. Flexible circuits are used in aerospace applications to reduce the size and weight of circuitry in addition to providing flexibility. An illustration of a "flexible circuit board is shown in Fig. 7.6 [7.4].

7.1.2 Board Materials - Copper Clad

Some of the common board materials are listed in Table 7.1 and 7.2 [7.1]. Only the fabrication of glass epoxy laminates is discussed below because the other materials used to construct copper clad boards are fabricated in a similar manner. During the first step of the fabrication process the base material is impregnated or coated with resin, which is then polymerized to a point suitable for storage. The partially cured material is called "prepreg". Copper foil is made by an electrodeposition process and supplied in rolls for lamination onto the prepreg. The side of the foil to be pressed against the prepreg is treated with an alloy to improve adhesion. The alloys are proprietary coatings, usually of zinc or brass. The foil and prepreg are pressed together in large heated presses at pressures exceeding 1000 psi. The thickness of copper cladding is specified in ounces per square foot. The cladding used for military work [7.5] is 1/2 ounce. Final circuit traces after plating must have minimum thickness equivalent to 1 ounce copper - a nominal thickness of 0.0014 inches.

Specific characteristics that may be examined during failure analysis are discussed below.

Peel Strength

Peel strength is the ability of copper traces to be pulled away from the laminate. It is tested on a standard test pattern with boards before soldering, during soldering, after soldering, and after gold plating.

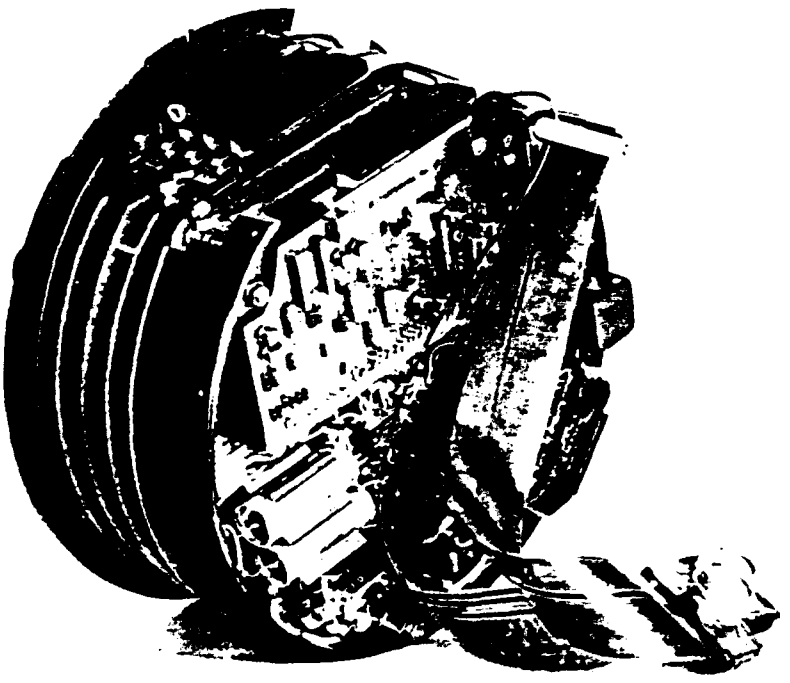


Fig. 7.6 Application of flexible printed wiring [7.4].

Table 7.1 Standard base materials for printed wiring boards [7.1].

NEMA grade	Military designation MIL-P-13949F	Resin system	Base	Color	Description
XXXPC	None	Phenolic	Paper	Opaque brown	Phenolic paper with punchability at or above room temperature
FR-2	None	Phenolic	Paper	Opaque brown	Phenolic paper, punchable, with flame-resistant (self-extinguishing) resin system
FR-3	PX	Epoxy	Paper	Opaque cream	Epoxy resin, paper base with flame-resistant resin system, cold punching, and high insulation resistance
CEM-1	None	Epoxy	Paper-glass composite	Opaque tan	Epoxy resin paper core with glass on the laminate surface, self-extinguishing, economic fabrication of paper base, mechanical characteristics of glass
CEM-3	None	Epoxy	Glass matte	Translucent	Epoxy resin nonwoven glass core with woven glass surfaces, self-extinguishing, punchable with properties similar to FR-4
FR-6	None	Polyester	Glass-matte	Opaque white	Polyester, random glass fiber, flame-resistant, designed for low-capacitance or high-impact applications
G-10	GE	Epoxy	Glass	Translucent	Epoxy-glass, general purpose
FR-4	GF	Epoxy	Glass	Translucent	Epoxy-glass with self-extinguishing resin system
G-11	GP	Epoxy	Glass	Translucent	High-temperature epoxy-glass with strength and electrical retention at elevated temperatures
FR-5	GH	Epoxy	Glass	Translucent	High-temperature epoxy-glass with flame-resistant resin system with strength and electrical retention at elevated temperatures
None	GI	Polyimide	Glass	Translucent dark brown	Polyimide resin, glass laminate with high continuous operating temperature and high property retention at temperature, low-z dimensional expansion

Table 7.2 Board materials for high frequency applications [7.1].

NEMA grade	Military designation MIL-P-13949	Resin system	Base	Color	Description
GT	GT	TFE	Glass	Opaque brown	Glass fabric base, PTFE (Teflon) resin, controlled dielectric constant
GX	GX	TFE	Glass	Opaque brown	Glass fabric base, PTFE (Teflon) resin dielectric constant with closer controlled limits than GT
		Polystyrene	Glass	Opaque white	Polystyrene cast-resin base for low-dissipation-factor applications
		Cross-linked polyethylene	Glass	Opaque white	Polyethylene cast base, radiation cross-linked for low dissipation factor

Solder resistance

Solder resistance is the ability of the laminated board to withstand temperatures from soldering. A test sample is floated on solder at 550° F for 10 seconds. Characteristic problems are:

- Measling - White spots or crosses below surface of the laminate due to separation of weave fibers.
- Weave exposure - Glass cloth not evenly coated with resin.
- Delamination - Caused by trapped moisture. Usually found after soldering.

Other properties include: Bow and twist; dimensional stability; degree of arc; insulation resistance; thickness; coefficient of thermal expansion; water absorption.

The failure analyst may perform tests to determine the properties discussed above as a means of identifying the role that manufacturing processes may have had in field failures.

7.1.3 Fabrication Processes

Printed wiring boards (PWBs) can be made on clad or unclad materials. In the traditional process, copper clad boards are printed with an etch resistant material (resist) in the pattern of the desired circuit traces. Then the board is chemically etched, leaving the desired circuit traces where the resist was printed. The resist is removed, and the traces are plated with solder. This process is typical of those originally used on single-sided wiring boards and is illustrated in Fig. 7.7. In the processing of double-sided and multi-layer boards, plated through holes are developed to make electrical connections between the layers. Two classes of process, called additive and subtractive, are used in plated-through-hole (PTH) processing. The subtractive process is similar to that described above. Steps for the additive and subtractive processes are shown in Fig 7.8.

7.1.4 Plating and Etching

Electroplating of metals is a basic step in most PWB processes. Among the metals that can be electroplated are gold, copper, nickel, tin, tin-lead (solder). Properties of metals that can be deposited onto PWBs by electroplating are contained in [7.1]. Electroplating of copper is a basic

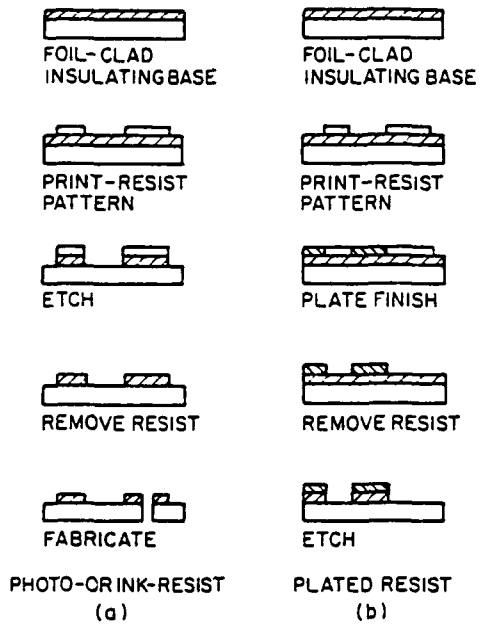


Fig. 7.7 Steps in two processes for single sided printed wiring boards [7.1].

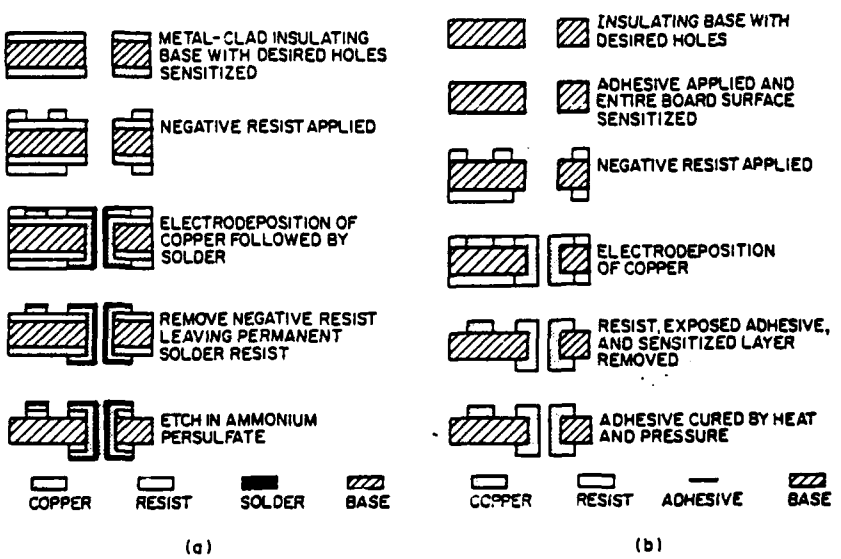


Fig. 7.8 Steps in subtractive (a) and additive (b) process for boards with plated-through-holes [7.1].

step in most of the commercial PWB processes. Copper is plated onto the circuit boards, which are connected to the cathode (negative potential) of the plating power source. The preferred process for electroplating copper uses an acid copper sulfate solution containing copper sulfate, chloride ion and organic additives. If the proper additives are used, the plated copper is fine-grained with tensile strengths of 50,000 psi, a minimum of 10% elongation, and a surface to hole thickness ratio of 1.2 [7.1].

Solution contaminants that can cause problems are: chromium; iron; tin; antimony; nickel; lead; arsenic. Copper deposition is sensitive to chloride ion content which must be carefully controlled in 40-80 ppm range. Plating problems related to the solution chemistry are: corner cracking; nodules; uneven PTH plating thickness; pitting. Problems that show up after plating but are related to previous process steps are: voids; smear; hole-wall pullaway; copper-copper peeling; solder blow holes. Some of these problems are illustrated in Fig. 7.9 which are examined after plating by sectioning and optical microscopy.

Another process, called the pyrocopper process, is an older plating process but is still used in some military applications. It uses copper pyrophosphate as the source of copper metal. Other constituents of the plating solution are: potassium pyrophosphate, ammonium hydroxide, and organic additives.

Tin-lead Plating

Solder is plated onto copper as 60 percent tin - 40 percent lead. MIL-STD-275 requires that tin-lead plate shall be at least 300 microinches thick. A widely used plating solution is a high concentration fluoboric acid-peptone system. Other processes use low-fluoboric, nonpetone and a nonfluoboric organic aryl sulfonic acid process [7.1]. The fluoboric acid processes use lead, tin as Sn^{2+}, fluoboric acid, boric acid and additives. Contaminants that can cause problems are: organics; copper; iron; nickel; chlorides and sulfates (only 2 ppm). Solder, 60/40, bars are used as the anodes in the plating process.

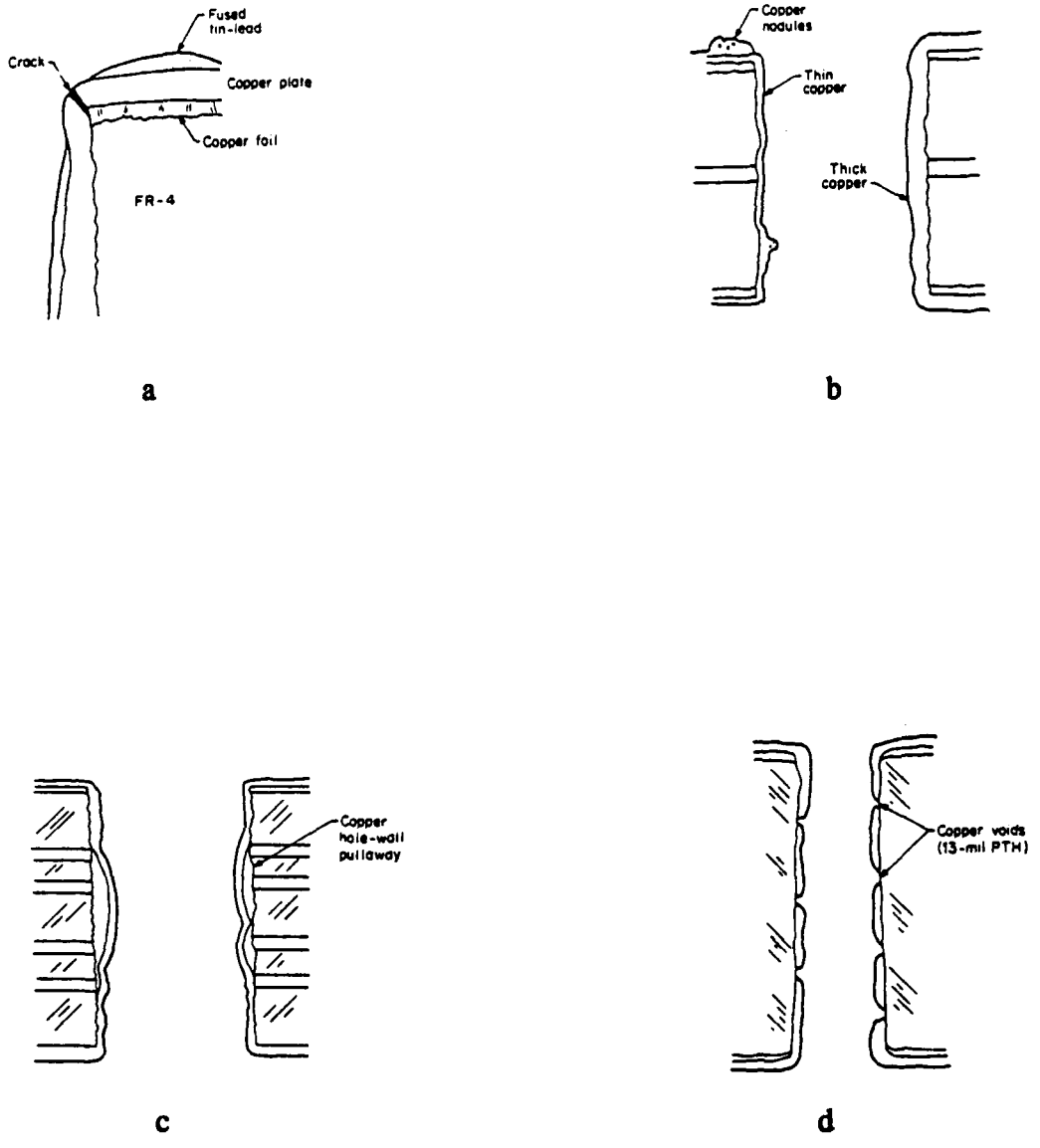


Fig. 7.9 Printed wiring board problems that show up after copper plating: (a) corner cracking; (b) copper nodules; (c) hole-wall pullaway; (d) copper voids [7.1].

Etching

Tin-lead solder, 100 to 300 microinches thick is the most commonly used plated etch resist. This is used in the process shown in Fig. 7.8a. Solder is sometimes plated over tin-nickel. Some of the etchants are alkaline ammonia, sulfuric acid and ammonium persulfate-phosphoric acid. The main chemical constituents of the alkaline ammonia etch are ammonium hydroxide; ammonium chloride; sodium chlorite; ammonium bicarbonate; ammonium phosphate; ammonium citrate. The sulfuric acid-hydrogen peroxide system uses: hydrogen peroxide; sulfuric acid; copper sulfate; molybdenum; aryl sulfonic acids; thiosulfates; phosphoric acid. One of the fundamental problems in all etching systems is that of the etchant attacking the solder plate. Other problems are caused by the etching of exposed copper edges of solder plated traces.

7.1.5 Solder

The tin-lead alloy used for electronic soldering is a eutectic. This alloy melts at 361° F. When the liquid solder is cooled, two distinct crystal phases appear in the solid. The "eutectic point" is the alloy of 63% tin, 37% lead by weight. Solder alloys are usually composed of tin and lead in ratios close to the eutectic point. All other alloys, including pure tin or pure lead, have higher melting points. The phase diagram is shown in Fig. 7.10. The regions labeled as "pasty range" become more pronounced further from the eutectic point. When non-eutectic mixtures cool, the excess base metal solidifies first, leaving a eutectic alloy to cool at the reduced temperature. Operating in the pasty range results in internal stress and cold solder joints. For this reason, compositions near the eutectic point are best for automatic soldering.

Impurities in Solder

Metallic and non-metallic impurities are of concern in solder alloys. Non-metallic impurities such as the sulfides and oxides are formed by the reaction of the solder alloy with sulfur and oxygen. Some of the common metallic contaminants are discussed below. The contamination limits for metallic contaminants can be found in [7.1].

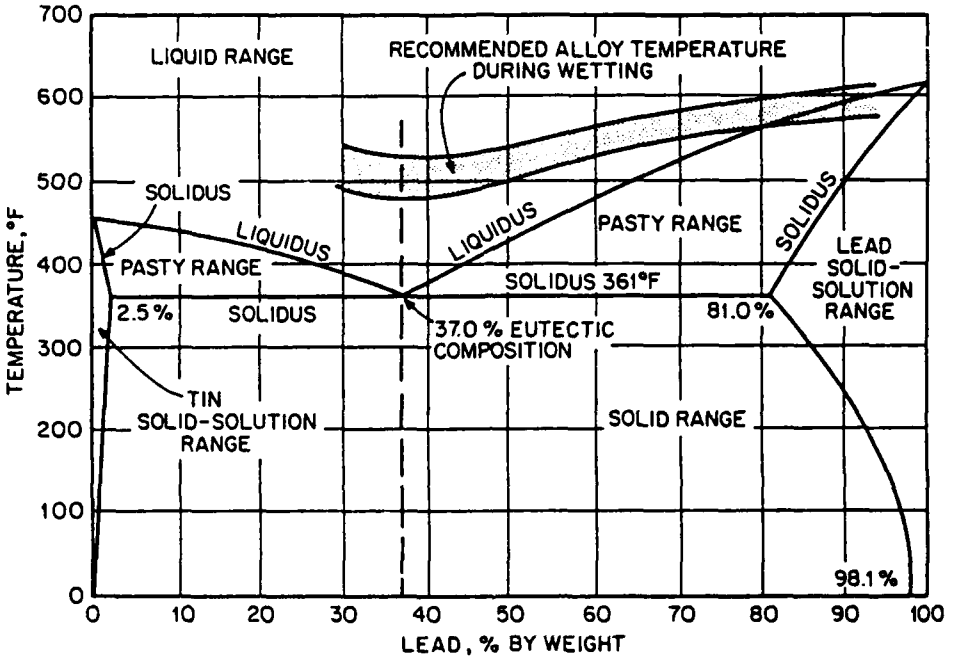


Fig. 7.10 Binary phase diagram for tin-lead solder alloys [7.1].

The effect of some of the metallic contaminants is discussed below:

Copper - Copper forms two intermetallic compounds with tin: Cu_3Sn and Cu_6Sn_5. The compounds weaken the solder joint and cause the solder to become sluggish and gritty.

Gold - Gold is readily soluble in molten solder and small percentages can cause brittle, dull solder joints.

Zinc - One of the most detrimental of solder contaminants. As little as 0.005% zinc will cause grittiness, lack of adhesion and eventual failure of the joint.

Metallic Surfaces and Soldering

Bare Copper - Chemically clean copper is the easiest material to solder. Solderability degrades rapidly because of the development of oxides and tarnish. Sulfur produces a tarnish which is difficult to remove and seriously impairs solderability.

Gold - Highly solderable but rapidly dissolves in molten solder, causing joints to become dull and grainy.

Kovar - Used on many IC leads, Kovar is difficult to solder. Kovar leads are pretinned with organic acid fluxes and proprietary acid cleaners.

Silver - Avoided because of silver migration and problems when exposed to sulfur - bearing materials.

Tin-Lead - Tin-lead coatings are put on printed boards and component leads to preserve solderability.

Wetting and solderability

Solderability is a measure of how well molten solder will wet the surface of the metals being joined. Good wetting is essential to the long term mechanical and electrical performance of solder joints and the circuit board as a whole. Wetting is examined visually on test samples prepared during the manufacturing process.

7.2 Failure Analysis Techniques

Some of the possible failure modes of printed wiring boards include the following:

1. Solder joint failure.
2. Fractures or cracks in circuit traces.
3. Delamination of traces.
4. Mechanical failure of the laminate.
5. Insulation failure between traces.
6. Insulation failure between layers.
7. Failure of PTH connections to layers.
8. Solder fatigue related to thermal coefficient mismatch.
9. Failed circuit traces due to overcurrent.

Many of the problems listed above can be the result of contamination, either in the manufacturing process or by environmental exposure in the application. Contamination during the manufacturing process, as in the case of solder or copper, can degrade the mechanical and electrical properties of the board as a whole and ultimately lead to failure. Environmental contamination can lead to corrosion of copper circuit traces, damage to components and a rapid loss of the laminate's electrical insulating properties. Aging of the board materials can also cause many types of failures.

Some of the techniques for examining these conditions are covered in the following discussions. Unfortunately, no literature was found describing the evaluation of printed wiring boards that had been exposed to post-impact fire damage.

7.2.1 Solder Joint Failure

The electrical failure of a solder joint involves some inherent mechanical weakness of the joint and the cyclic forces which cause cracking or separation of the solder from the board or the component lead. One source for the cyclic forces is the result of the mismatch of the coefficient of thermal expansion (CTE) between the components and the board materials. Although traditionally CTE mismatch has been a problem only in surface mount applications, military equipment is subjected to wide and frequent temperature excursions and the accident investigator should be familiar with this mechanism.

Table 7.3 shows the CTE for typical PWB and component materials. Stress is caused by the CTE mismatch acting over the length of the component package. Stress is caused by the mismatch in the expansion between a component package and the board material when a particular temperature excursion is encountered. Small packages, or small CTE differences will reduce the stress to tolerable levels. A method by which the fatigue life of solder joints can be predicted is covered in [7.2].

Table 7.3 Coefficients of Thermal Expansion for Printed Wiring Board Materials

MATERIAL	CTE (ppm/°C)
Alumina	5-7
Epoxy-glass	12-16
Polyimide-glass	11-14
Copper-Invar-Copper	5-6
Copper-clad Molybdenum	5-6
Epoxy-Kevlar	6-7
Polyimide-Kevlar	5-7
Ceramic	5-7
Aluminum	22.9
Copper	16.5
Epoxy	45-65
Steel	10-13
Gold	14.2
Silver	19.6
Iron	12.2
Kovar	5.86
Solder 50-50	13.1

7.2.2 Solder Joint Examination

Solder joints can be examined non-destructively by real time microfocus X-ray equipment. There are practical limitations to the resolution of this equipment, so cracking and other defects with finer details may not be visible. Sectioning and optical microscopy are used successfully for diagnosing such manufacturing problems, and these techniques will work equally well in failure investigations if it is acceptable to section the board. Contaminants in the solder can be analyzed by SEM/EDAX analysis.

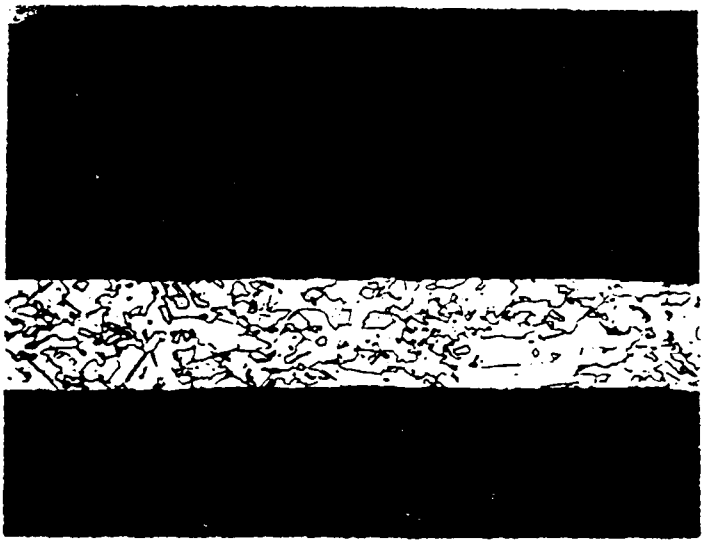
As a consequence of the low melting point of solder, 361° F, cracked or broken solder joints will not survive significant exposure to post-impact fire. However, if the solder reflows during post impact fire, its appearance should be different than that of an undamaged PWB. Reflow of the solder will cause some redistribution of the solder that may be obvious. Broken solder joints that have reflowed due to external heat may have additional voids. SEM/EDAX analysis may reveal contaminants trapped in the voids.

7.2.3 Circuit Trace Examination

The copper portion of circuit traces may be clad copper, electrodeposited copper or a combination of the two. Since the cladding is generally produced by electrodeposition rather than rolling, the whole trace has the grain structure characteristic of electroplated copper. Fig. 7.11 shows the cross section and grain structure of both rolled and electrodeposited copper. The fine vertical grain structure of electrodeposited copper provides a useful point of reference in examining circuit boards. Traces that have been heated enough to begin recrystallization will have distinctly larger grain sizes.

7.2.4 Insulation Failure

Leakage current on PWBs can occur on the surface or in the bulk material of the laminate. Leakage can be the result of moisture, contamination or metal migration. Moisture can reduce the surface and bulk resistance of a PWB dramatically. An increase from 30% RH to 90% RH can decrease surface resistivity from 10^{15} to 10^{11} ohms/square [7.1].



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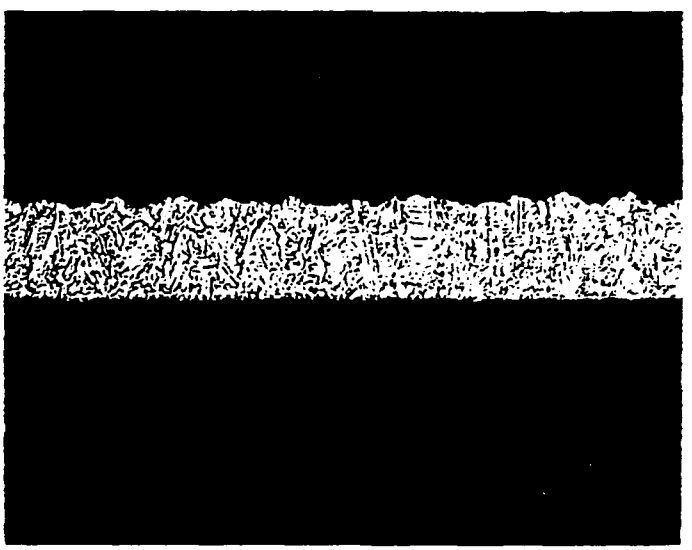

b

Fig. 7.11 Grain structure of (a) rolled copper foil and (b) electrodeposited copper foil [7.1].

Contamination may be metallic, such as metal slivers, solder bridges, contamination from fabrication processes, fingerprints or dust. Ionic contaminants become active in the presence of moisture and may lead to conduction at high humidity.

Metal migration is typically an aging effect. There are several forms of metal migration. One form is known as whisker growth, which is a single crystal growth a few microns in diameter. Another form is the result of corrosion. Chlorides or sulfides, which are by-products of corrosion, migrate across insulating surfaces. This type of migration can be examined by elemental mapping using EDAX analysis. Electromigration occurs when a dc potential electrolytically transfers metallic ions between conductors. A metal dendrite forms on the cathode when the ions are reduced. Transmitted light microscopy can be used to examine dendritic growth. Several types of insulation resistance failure modes including dendritic growth are shown in Fig. 7.12.

Specially designed test patterns are used to verify PWB insulation resistance in production. The test boards are subjected to conditions of temperature and humidity cycling in accordance with military standards.

Test procedures and special board test patterns are covered by the following standards:

MIL-P-55110	Military Specification for Printed Wiring Boards.
MIL-STD-202	Military Standard Test Methods for Electronic and Electrical Component Parts.
IPC-B-25	Test board
IPC-SM-840A	Qualification and Performance of Permanent Polymer Coating (Solder Mask) for Printed Boards.

The standard procedures measure insulation resistance between traces using special trace patterns. Applied voltages are 100 or 500 Vdc and typical minimum resistances are 100 to 500 MΩ. A

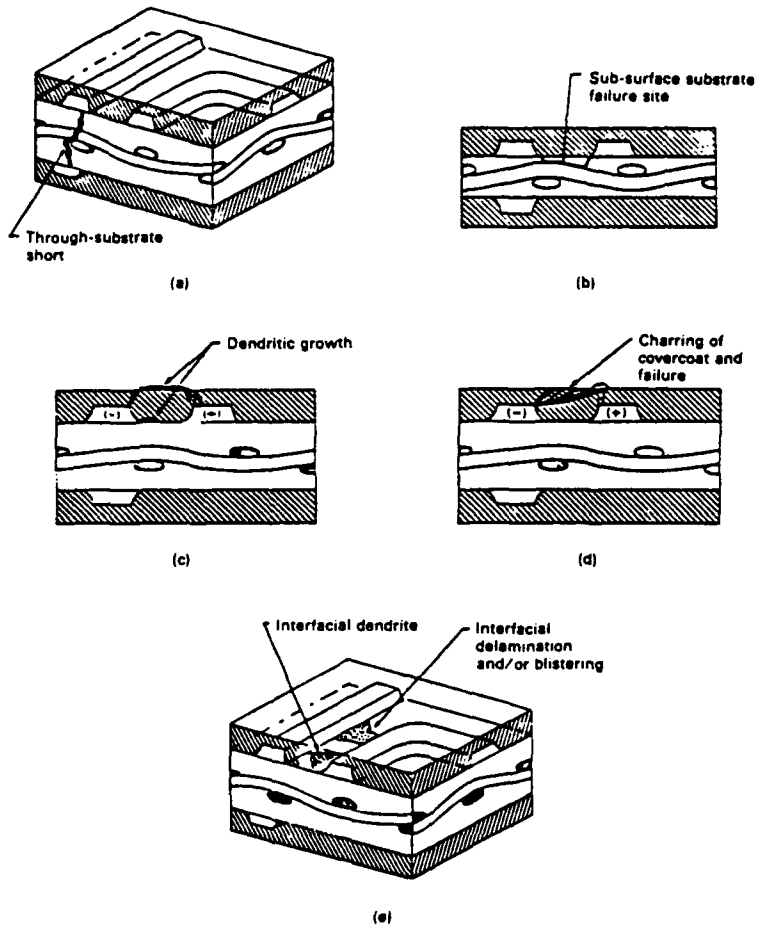

Fig. 7.12 Insulation failures on printed wiring boards [7.1].

test for susceptibility of the solder mask to electromigration is carried out at 10 Vdc with a limiting current of 1 ma. Making these measurements on assembled boards is difficult because of the high resistance, and low voltages that must be used to prevent damage to the components.

High resistance meters, such as the Hewlett Packard 4329A or equivalent, can measure resistances up $10^{16}\Omega$ with proper probes. An alternate method is to use a low voltage power supply and measure the leakage current. Keithley series 600 electrometers can measure currents on the order of 10^{-15} A for these applications. To interpret high resistance tests on PWBs it may be necessary to compare the results to those obtained on undamaged boards.

7.2.5 Coated Boards

The removal of conformal coatings may be a significant problem in accident investigation. There are four methods for removing conformal coatings. Solvents such as xylene, trichlorethane and methylene chloride may be used to remove coatings, but care must be taken not to damage the board or components. Thermal parting is a method using controlled low temperature heating and is best for the removal of thick coatings. Abrasion is used in conjunction with these methods. Abrasive jet equipment, similar to sand blasting, can be used to remove coatings that cannot be removed by solvents. One such coating, parylene, is covered by MIL-I-46058. Plasma etch methods can also be used if solvents are unsuccessful. The entire board is placed in a vacuum chamber and a low temperature plasma removes the coating. The plasma is created by exciting a gas with an RF (radio frequency) field. This method is useful for removing parylene [7.1]. In some cases, contamination introduced during board fabrication may be trapped beneath the conformal coating. Sectioning the board and performing SEM/EDAX mapping can be used to identify the contaminant. The use of this technique to identify chlorides trapped on the board surface is reported in [7.6].

7.3 Failure Analysis Guidelines

Some of the steps for the examination of printed wiring boards are listed below:

1. Visual examination for solder joint, boards trace failures.

2. Sectioning of laminate - elemental map to observe contaminants especially chlorides and sulfides.

3. Cross sectioning of selected solder joints to identify solder failures, voids, or cracks.

4. SEM/EDAX of solder joints and traces for composition analysis.
   - Sulfur, oxygen
   - Copper, gold, zinc

5. Examine grain structure of selected copper traces to identify overheating.

6. Examine traces using SEM/EDAX to identify contaminants in the copper.

7. Transmitted light micrograph for metal migration - dendritic growth.

8. Microfocus X-ray examination of boards.
   - Cracks or voids in solder joints.
   - Broken components.
   - Damaged circuit traces.

7.4 Supplemental Methods

Solder joint stress continues to be a major factor in the failure of PWBs. Some form of tabulated data which describes the propensity of a particular configuration to cause solder fatigue or component stress would be useful. The purpose of the data would be to aid the accident investigator in assessing which areas of a PWB might be likely to cause failure. The data should include the materials and mounting configuration of the board and components. The data would need to be organized to include the various materials: glass-epoxy; ceramic; copper; epoxy; etc, as well as the size of the components and mounting style.

Failure Modes and Effects Cirticality Analysis (FMECA) is a procedure used to evaluate the effect of postulated failures on electronic equipment. This type of analysis is often required as part of the design activity for military equipment but similar analysis can be applied during accident investigation. Another similar technique, also applicable to printed wiring boards, is called sneak circuit analysis. This method was developed by BOEING for use in aerospace design and uses the principle of the formation of unintended circuit paths to predict failure effects.

7.5 Additional Work

Some of the additional work needed to make these methods generally practical for accident investigation is listed below:

1. Collect data which characterizes the effects of age on the susceptibility to various failure modes.

2. Develop procedures for examining and diagnosing printed wiring boards after post-impact damage.

3. Develop non-destructive methods to examine solder joints and copper traces.

4. Develop data on how to identify areas susceptible to solder fatigue.

5. Prepare visual guides for the examination of board features.
    a. solder defects
    b. contamination
    c. metal migration
    d. plating

6. Prepare logical organization of the procedures.

7.6 References

7.1 Printed Circuit Handbook Third Edition, C.F. Coombs, Jr., editor. 1988, McGraw Hill, New York.

7.2 Handbook of Surface Mount Technology S. W. Hinch. John Wiley & Sons, Inc., New York.

7.3 Keep Solder-Joint Stress in Check. C. Lo. (Hughes aircraft). Electronic Packaging & Production, May 1989. Volume 29, No. 5.

7.4 Handbook of Wiring, Cabling and Interconnecting for Electronics. C.A. Harper, editor. 1972, McGraw-Hill, New York.

7.5 MIL-STD-275E. Military Standard, Printed Wiring for Electronic Equipment.

7.6 Corrosion of Electronic Components. B. Dobbs. Proceedings of the 62nd AGARD Conference. April 1986 DTIC No. AD-A194 868.

8.0 - MICROELECTRONICS

This section covers failure analysis techniques that can be used on microelectronic devices - small active components (transistors, diodes) and integrated circuits (ICS). The techniques are also generally applicable to small passive components and some types of power electronic devices. A synopsis of a manual produced by Rome Air Development Center entitled "Microelectronics Failure Analysis, A Procedural Guide" is included in this section. This manual was published in 1981 and is recognized as a comprehensive source of failure analysis techniques for microelectronics.

Section 8.1: Microelectronics Failure Analysis Techniques - A Synopsis

An abbreviated Table of Contents of the RADC document [8.1] is shown in Table 8.1. The document is more than 1,000 pages in length and describes various aspects related to the failure analysis examination of integrated circuits and other microelectronic devices. Work on the document was sponsored by the Air Force Systems Command, Rome Air Development Center, Griffiss Air Force Base in New York. The work was performed primarily by the General Electric Electronics Laboratory in Syracuse, New York and the IIT Research Institute of Chicago, Illinois.

In addition to basic failure analysis techniques, the RADC report includes material on how microelectronic devices are fabricated, what kind of equipment should be used to perform the techniques and procedural guidelines for setting up laboratories to perform failure analysis. Fundamental techniques are presented in seventeen separate sections which summarize how to apply these techniques to failure analysis. Although the techniques are generally applicable to accident investigation none are specifically intended for the evaluation of components which have been subjected to post-impact damage.

8.1.1 X-Ray Radiography

Radiography is a non-destructive testing method in which an electronic component is subjected to penetrating radiation and the resulting image is produced on a sheet of photographic film.

Table 8.1 Abbreviated Table of Contents for "Microelectronics Failure Analysis, A Procedural Guide".

Inexpensive laboratory type x-ray generators are used to direct a beam of x-rays at an object and expose the x-ray film. A device called a penetrometer is used to provide references as to the penetration. A special type of penetrometer made for electronic devices is called an image quality indicator. The image quality indicator is a small device made with increasing thicknesses of steel shim stock to match the thicknesses of the electronic device enclosure. It also includes lead wires of several diameters to measure distortion and to determine the sensitivity of the x-ray image. Photographs showing the x-ray image produced for a diode and an integrated circuit package are included. Defects that x-ray images can identify are metallic particles, extraneous metal, cracked leads, tilted diode pellets, contamination and improper package lid seals. Techniques are described for producing stereo radiographs by a double exposure and other methods which allow the depth of the defect to be identified in the x-ray image. Some discussion of the process for developing x-ray film is included.

Neutron radiography is used for detecting certain materials which have high neutron absorption, but may not be detectable easily with x-rays. For example, elements such as hydrogen, lithium, boron, cadmium and some of the rare earth elements produce a shadow in a neutron image and are easier to image with neutron radiography than with x-ray radiography. Because of the development of low cost neutron sources, neutron radiography can now be inexpensively obtained. A list of the neutron absorption coefficients for various elements is given. A comparison of the x-ray and neutron radiographic images on transistors, relays and printed circuit boards is included in this section.

8.1.2 Hermeticity Techniques

Techniques in this section are designed to test the integrity of integrated circuit package seals. Mil Standard 883, "Test Methods and Procedures for Microelectronics" specifies test methods and acceptance limits for microelectronic packages. Method 1014, contained in that standard, includes testing by helium and radioisotope tracer gases, testing by fluorocarbon bubbles, dye penetrant and weight gain tests. In general failure analysis techniques for package leaking will include a visual examination to localize the leakage site, early non-destructive examination by

light microscope or SEM, device dismantling or cross-sectioning and then metallurgical analysis. Several examples of SEM imaging of glass-to-metal seals that have damage are included. Leakage conditions may involve gases and liquids leaking into the package. One of the techniques described is called the Radiflo method. The components to be tested are placed in a tank which is then evacuated. After evacuation, the tank is pressurized with Krypton-85 which soaks into any leaks in the test components. Before removing the devices from the tank, fresh air is used to remove the krypton from the external surfaces of the components. Then the components are tested for residual radioactive atoms that may have been trapped inside the packages under pressure. Krypton-85 emits gamma radiation.

The fluorocarbon gross leak test involves the pressurization of the devices using the fluorocarbon detective fluid FC-72. After pressurization for a period of time, usually at least ten hours, the devices are immersed in a fluorocarbon indicator fluid FC-40 and bubbling is observed as the indication of gross leaks in the packages.

In the dye penetrant gross leak test an ultraviolet sensitive dye is injected into the packages under pressure (if a leak exists). After removal of the pressurized dye and washing of the package, the devices are examined under an ultraviolet light source. Trapped dye penetrant in the cracks is easily visible because of the ultraviolet fluorescence.

In the weight change method the devices are immersed in a bath of the fluorocarbon FC-72 under pressure. Gross leaks are detected by noticing a weight change in the device before and after the pressurization period.

8.1.3 Package Ambient Gas Analysis Techniques

These techniques are designed to detect the composition of the ambient gas inside a hermetically sealed container. Because of the relatively small packages of integrated circuit devices gas volumes are on the order of .01 to .85 cc and highly specialized equipment is required. Microelectronic packages are usually back-filled with dry nitrogen gas at or near atmospheric

pressure before being hermetically sealed. Mass spectrometry is well suited to the identification of small amounts of contaminants in the presence of nitrogen and is used for this type of analysis. Basically, the device to be tested is placed in a vacuum chamber of a mass spectrometer. Using a remotely operable tool that can be positioned without breaking the vacuum seal, the case of the component is pierced allowing the internal gas to escape and be analyzed. A significant note is included in this section, indicating that in addition to the equipment being very expensive, it requires considerable amount of expertise and technician time to calibrate and correlate data from the equipment with data from other test facilities.

Moisture trapped inside packages can cause corrosion, electrical surface leakage, electrochemical metal migration, and degradation of bulk oxides. Oxygen in packages can cause aluminum oxidation during high temperature burn-in operations. Since argon is inert, it makes an excellent tracer gas for independent leak assessment. If a device was supposed to be sealed in a nitrogen or nitrogen/oxygen mixture, the presence of argon as a residual gas usually indicates that the package became non-hermetic sometime after sealing. Carbon dioxide can affect surface charge status and when dissolved in water forms a weak acid that can promote galvanic corrosion. The presence of helium or freon usually indicates a leak condition that is present or has occurred sometime prior to gas analysis. Methane is often produced during gas analysis as a portion of some heavier hydrocarbon, that is grease or oil. Pump oil can enter packages from contaminated processing equipment and can be a source of methane.

Chlorine is usually detected as a fractionated ion during analysis and is the result of the decomposition of a chlorinated hydrocarbon. Halogens of any type can readily initiate aluminum corrosion in the presence of traces of moisture. Hydrogen is used in the processing of some MOS devices and may be detected in small quantities from certain types of electroplated coatings. Organic vapors in semiconductor packages have been found as a result of solvent residues, photo resist processes, and epoxy bonding.

8.1.4 Package Opening and Encapsulation Removal Techniques

Package opening should come only after all electrical failure verification has been made, and all possible external causes for the failure have been explored or rejected. With sufficient care the internal contents of the package will not be damaged by the opening procedure and further electrical testing may be conducted. A variety of techniques are presented in this section for examining semiconductor devices and integrated circuit. The techniques include package grinding and acid etching. Methods for the removal of molding compounds include the use of concentrated sulfuric acid, fuming sulfuric and nitrous acid mixtures. The removal of certain types of epoxy relies on a sulfuric acid/sodium dichromate mixture. Molding compounds can be removed with nitric and sulfuric acid solutions. Urethane coatings, urethane foam and molded silicones are dissolved with a product called Uresolve Plus made by Dynaloy. Procedures for exposing the dye area of epoxy molded dips are discussed.

8.1.5 Thermal Mapping Techniques

These techniques are designed to analyze temperature patterns in operating semiconductor devices and integrated circuits. Their applications is therefore limited to operating equipment and may not be suitable for accident investigation because of damage to the circuitry. The basic method involves the use of infrared (IR) scanning equipment. It is important to simulate the thermal resistance of the device package to its environment and the ambient temperature of the environment to obtain meaningful measurements. A fundamental problem with IR scanning is that the measured temperatures depend on the IR emissivity of surface being measured. Two methods are suggested to address this problem. First, the device can be heated to a known temperature which provides the scanning equipment with a reference temperature and a measure of the emissivity. In the second method, devices are coated with a black lacquer with an emissivity of approximately one. Single spot infrared measurement equipment and scanning infrared devices are discussed.

8.1.6 Photo Response Measurement Techniques

The equipment described in this section is apparently not commercially available and must be built up from components as described in the handbook. Much of the material was based on National Bureau of Standards special publications 400-24 and 400-27. Basically the technique involves scanning a laser beam over a semiconductor device and measuring the electrical response that results because of the generation of current carriers in the semiconductor material. The device has an important application in analyzing certain types of semiconductor devices, especially MOS devices which can be damaged by electron beam energy. A number of implementations have been used and the resolution ranges from 1 to 10 microns.

8.1.7 Liquid Crystal Analysis Techniques

Two types of liquid crystal techniques are described in this section. The first technique uses cholesteric (heat sensitive) liquid crystals to locate areas of high power dissipation in microelectronic devices. The material changes color in the temperature range of 30-32°C and the colors range from red to violet. The liquid crystal material is applied directly to the integrated circuit substrate. It is dried by baking at 50°C. Indirect illumination is used while the microcircuit is operated and observed under a stereo microscope. If a short circuit exists, it can be used to provide a general heating of the liquid crystal to the violet a color level. Afterwards, the current is reduced so that the shorted areas can be identified more distinctly.

Oxide defects are located by using a nematic liquid crystal in a current sensitive scattering cell. The cell is created by first removing the integrated circuit from the device package, removing the protective glassivation and then applying the liquid crystal directly over the integrated circuit. A current sensitive cell is formed by placing a glass cover plate coated with a transparent conductive coating over the integrated circuit. By applying a dc voltage between the microcircuit substrate and the conductive surface of the glass a small current passes through the liquid crystal at the point of an oxide defect. Because the liquid crystal is optically very sensitive to current, small vortices in the fluid are created which extend around the defect and make pinholes appear much larger than they actually are. The magnification allows the detection of isolated sub-micron pinholes which would be difficult to detect optically.

A third technique called the optical voltage contrast technique uses a field effect display cell which responds to fringing electric fields associated with the integrated circuit. The analyst can observe circuit operation and can detect logical "stuck" conditions and "open" conductor faults. The technique is a complimentary optical technique to SEM voltage contrast and permits observation of devices in operation. It can be useful in determining the physical location of circuit functional blocks in complex LSI circuits. The technique is also useful in locating hot spots in integrated circuits which dissipate as little as 20 to 30 mw. Basically the technique consists of coating the integrated circuit with a liquid crystal which is trapped between the surface of a device and a glass cover plate which has been sputtered with gold. The operation of the cell causes distortion in the trapped liquid crystal and a white and dark contrast effect is observed under an optical microscope.

8.1.8 Surface Effects

These techniques are primarily applicable to MOS type structures with ionic contamination and the movement of that contamination with respect to thermally formed silicone dioxide passivation layers. One of the techniques that is used to analyze the condition of the contamination and the silicone dioxide layers is a capacitance voltage (C-V) measurement technique. The C-V plotting technique applies an alternating voltage typically at 1 Mhz superimposed on the dc bias voltage needed for device operation. In conjunction with changing the dc bias voltage, the temperature of the device is controlled over a fairly wide range up to 300°C.

Ionic contamination that can be detected can cause instability and leakage in PN junctions, parasitic MOS device formation, and other non-catastrophic instabilities. Microelectronic devices expected of having surface contamination in one or more of the layers can also be sequentially disassembled and retested to determined which layers the contamination was found in. Procedures are described for removing the epoxy, then the glassivation layer, the metallization layer and the undermetal oxide of integrated circuits.

8.1.9 Surface Topography Measurement Techniques

Surface topography is used to make a recording of the height of various layers on the integrated circuit surface. Several measurement techniques are described in this section. The first technique is a relatively simple device which uses a stylus to move over the surface of the integrated circuit. As the stylus moves up and down across the surface a strip chart recorder provides a graphical description of the height of the metallization line. These instruments are typically capable of measuring elevation differences of less than 25 angstroms to 100 microns. Unfortunately, the tracking force of these devices is high enough to be considered potentially destructive to integrated circuits.

Three types of optical topography methods are used for measuring thicknesses of integrated circuit films and metallization layers. In the Nicholson interferometer a source of monochromatic light is split into two beams. One of the beams reflects off the surface of the integrated circuit. The other beam is reflected off of a mirror. Slight differences in the optical path lengths produce interference fringes which can be used to measure the height of patterns on the integrated circuit. In a multiple-beam system a sequence of mirrors is used to produce a much larger optical path and therefore a higher sensitivity to height changes on the surface of the circuit. This technique is called a multiple beam interferometer. A polar interferometer, also known as the Nomarski technique, is a beam of light which is linearly polarized before being directed to the sample. In recombining the two polarized beams, fringes show along the step edge of the integrated circuit pattern because of the lateral displacement interference produced by the two beams. Nomarski fringes can be used to calculate the step height as with the Nicholson interferometer. A range of measurement accuracy from 150 to 300 angstroms can be obtained.

Ellipsometry is a technique based on evaluating the change in state of polarization of light reflected from the surface of the sample being measured. The practical use of the ellipsometer technique requires access to a digital computer with a program that calculates the film thickness and index of refraction. A good idea of the range of thickness being measured is required before making the measurements. Two sets of readings are obtained which are used in the computer

program to determine the step thickness and the index of refraction of the surface of the integrated circuits.

A light section microscope can be used to measure films thicker than one micron. The instrument consists basically of two microscopes. One projects a slit of light onto the sample and the other observes the slit of light by viewing it at an angle through an eyepiece equipped with a reticule and a micrometer. Films in the range of 1 to 400 microns can be measured with an accuracy of about .1 microns.

Linear measurement instruments can be used to measure the width of a metallized line. A filar eyepiece is an instrument for an optical microscope that consists of a movable reticule with a calibrated rotary thumb wheel. The instrument can be used with any microscope objective, and requires a micrometer calibration stage. Physical dimensions are made by viewing the calibrated micrometer stage with the eyepiece and recording the positions of the thumb wheel on the eyepiece. Image splitting measurements are generally regarded as more accurate than the filar type of measurements. This device also uses calibrated divisions on a microscope stage micrometer. The image splitter consists of a special prism assembly which is linked to a micrometer screw such that two portions of the prism can be moved with respect to each other. Two images appear in the objective and the relative position of the two images are used to obtain the proper calibration with respect to marks on the stage micrometer.

8.1.10 Mechanical Analysis Techniques

Procedures in this section are used in failure analysis to evaluate the integrity of some of the mechanical aspects of microelectronic assembly. The first technique, ultrasonic cleaning, is generally used in failure analysis and the processing of other electronic components. However, in using it in failure analysis the investigator should be careful because damage to weak or marginal wire or dye bonds may break during cleaning as a result of the ultrasonic energy. This could result in the loss of valuable data regarding failure.

Bond pull tests are carried out to evaluate bond strength and to determine compliance with specified bond strength requirements of applicable procedures. Tests may be applied to the wire-to-dye bond, wire-to-substrate bond, or the wire-to-package lead bond inside the packages of wire-connected integrated circuits. The connections may be made by soldering, thermal compression, ultrasonic welding, or related techniques. Apparatus for this test consists of suitable equipment for applying and measuring a specified stress to the bond.

A bond seal test is normally employed for bonds external to the device packaged. The lead or terminal is gripped in a device and a pealing stress is exerted at the specified angle between the lead and the substrate, typically 90°. A wire pull is normally applied for internal bonds by pulling on the lead in a direction normal to the surface of the die or substrate. The pulling is done on a free end of the lead after the wire has been cut. In a similar test, called the double bond test, a hook is inserted under the lead wire while both ends of the wire are still attached to the surface. Other tests include a bond shear test, a beam lead push-off test and a beam lead pull-off test.

Die shear tests are used to test the integrity of materials and procedures used to attach semiconductor die to package headers or other substrates. In this test a load is supplied evenly along the edge of the die mounted on a substrate and a force sufficient to shear the die from its mounting is applied.

Wire rebonding is sometimes desirable in microelectronic failure analysis to reconnect electrical connections to a package. For example, wires are commonly removed during fault isolation, and after a fault has been corrected, it might be desirable to reconnect the wires and retest. Gold and aluminum wires are used extensively throughout microelectronics in thicknesses between 17.8 microns and 50.8 microns with the thicker wires most often used on high power devices. Commercially available bonding machines can be used. Gold is commonly bonded by thermal compression or ultrasonic techniques.

Particle impact noise detection tests are used to identify loose particles inside a device cavity. One procedure is described in MIL Standard 883B and is identified as method 2020.1. This apparatus consists of a transducer and vibrator assembly which is used to mechanically excite the device under test and detect the presence of vibrations caused by particles inside the device package.

Pneumatic impact testing is done to detect failure or weakness in improperly assembled devices. In these tests relatively high decelerations of short duration are applied to devices under test by mounting it in a projectile and firing it at a striker plate. The striker plate is equipped with an accelerometer which allows the measurement of the shock wave generated as the carrier impacts the striker plate. The package is then disassembled and the wire bonds and other mechanical attachments examined for damage.

8.1.11 Optical Analysis Techniques

Several types of optical microscopes are available to the failure analyst. Stereo microscopes are generally low power, wide field microscopes that have long working distances. Metallurgical microscopes are the most common ones available to the failure analyst. Microelectronic circuits may be examined while still in the device package. However, one problem encountered with metallurgical microscopes is the short working distance from the objective lens to the sample. For example, magnifications of 5 to 700 are required to examine metallization patterns on LSI circuits and the working distance at that magnification is frequently insufficient to focus on a mounted sample. Some metallurgical microscope techniques are:

Bright Field - This type of illumination is commonly used with metallurgical microscopes. The light is directed normal to the surface of the object.

Oblique Illumination - Often used to enhance the examination of details. In oblique illumination light is aimed at the sample surface at an oblique angle.

Dark Field - In this form of illumination light is fed from the objective lens to the sample at an acute angle so that most of the light is reflected away from the microscope.

Differential Interference Contrast - These systems employ a polarized light source which passes through a set of prisms. A display of colors accentuating surface contours is produced by rotating the prisms relative to the angle of the polarized light.

Micro and macro photographic instruments, special illumination techniques and characteristics of lenses are covered in this chapter also. Similar systems and types of film for micro and macro photographic work are discussed. Since much of failure analysis has to do with specialized photographic techniques, this chapter covers various procedures for developing and reproducing photographic material. MIL Standard 883B, method 2009.1, External Visual Inspection, which covers inspection procedures for microelectronic devices and methods 2010.3 and 2017.1 which cover internal visual inspection, are discussed.

8.1.12 Chemical Analysis Techniques

This chapter presents methods for using a variety of acids, alkalies and solvents mostly for the removal of selected materials in failure analysis investigation. A summary of some of the materials is included as Tables 8.2, 8.3, 8.4 and 8.5.

8.1.13 Metallurgical Analysis Techniques

This chapter describes methods of locating, observing, documenting and measuring semiconductor failure sites relating to bulk semiconductor phenomenon. Detailed procedures for preparing samples by encapsulation and the subsequent mounting, sectioning, polishing and viewing steps are discussed in this section. Vacuum impregnation for epoxy mounting methods is covered. The mounting of samples in transparent mediums, such as Buehler Epoxide, and other materials is covered. PVC mounting materials are also described.

Table 8.2 Acids and Bases used in Microelectronic Failure Analysis [8.1].

ACIDS

Name	Chemical Formula	Uses
Acetic, glacial	CH_3COOH	Etchant; buffering agent
Boric	H_3BO_3	Buffering agent
Chromic	CrO_3	Etchant, stain
Formic	HCOOH	Polar solvent
Fuming Nitric	HNO_3	Plastic package opening
Fuming Sulfuric (Oleum)	$H_2S_2O_7$	Plastic package opening
Hydrobromic	HBr	Metal etchant, stain
Hydrochloric	HCl	Metal etchant
Hydrofluoric	HF	Silicon dioxide and silicon etches
Nitric	HNO_3	Metal etchant; silicon nitride etchant; used in many silicon etchants as oxidizer
Oxalic	$HOOCCOOH \cdot 2H_2O$	Etchant; stain
Phosphoric	H_3PO_4	Metal etchant; polish
Sulfuric	H_2SO_4	Etchant; strong oxidizer

BASES

Name	Chemical Formula	Uses
Ammonium hydroxide	NH_4OH	General base
Potassium hydroxide	KOH	Silicon etchant
Sodium hydroxide	NaOH	Aluminum etchant

Table 8.3 Solvents used in Microelectronic Failure Analysis [8.1].

Name	Chemical Formula	Uses
Acetone	CH_3COCH_3	Polar solvent; solvent for plastics
Benzene	C_6H_6	Nonpolar solvent
Benzyl alcohol	$C_6H_5CH_2OH$	Polar solvent; solvent for plastics
Chloroform	$CHCl_3$	Polar solvent
Cyclohexane	C_6H_{12}	Nonpolar solvent
Dimethyl formamide	$HCON(CH_3)_2$	Polar solvent; solvent for plastics
Dimethyl Sulfoxide	$(CH_3)_2SO$	Solvent
Diethylether (Ethyl Ether)	$(C_2H_5)_2O$	Organic solvent
Ethanol (Ethyl Alcohol)	C_2H_2OH	Polar solvent
Ethylene dichloride	CH_2ClCH_2Cl	Solvent
Freon (Tetrachlorodi-fluoroethane)	$C_2F_2Cl_4$	Nonpolar solvent
Hexane	C_6H_{14}	Mild nonpolar solvent
Isopropyl alcohol	$(CH_3)_2CHOH$	Polar solvent
Methyl alcohol	CH_3OH	Polar solvent
Methylene chloride	CH_2Cl_2	Solvent for plastics & epoxies
Methyl Ethyl Ketone (Butanone)	$CH_3COC_2H_5$	Solvent; solvent for PVC
Toluene	$CH_3C_6H_5$	Nonpolar solvent
Trichloroethylene	$CHCl:CCl_2$	Nonpolar solvent
Xylene	C_8H_{10}	Nonpolar solvent

Table 8.4 Other Chemicals used in Microelectronic Failure Analysis [8.1].

Name	Chemical Formula	Uses
Ammonium bifluoride	$NH_4F \cdot HF$	Silicon dioxide etch; buffering agent
Ammonium chloride	NH_4Cl	Buffering agent
Ammonium fluoride	NH_4F	Buffering agent
Ammonium persulfate	$(NH_4)_2S_2O_8$	Buffering agent
Ammonium sulfide	$(NH_4)_2S$	Source of sulfide
Bromine	Br	Constituent preferential silicon etch
Calcium carbonate	$CaCO_3$	Buffering agent
Cupric sulfate (Copper Subsulfate)	$CuSO_4$	Stain
Cupric nitrate (Copper Nitrate)	$Cu(NO_3)_2$	Constituent preferential silicon etch
Ferric chloride	$FeCl_3$	Nichrome etch
Hydrogen peroxide	H_2O_2	Etchant; stain; oxidizer
Iodine	I	Constituent silicon etch
Nickel sulfate	$NiSO_4.6H_2O$	Stain
Potassium chloride	KCl	Buffering agent; electrolyte
Potassium cyanide	KCN	Etchant
Potassium ferricyanide	$K_3Fe(CN)_6$	Constituent molybdenum, tungsten etch
Potassium iodide	KI	Constituent gold etch
Pyrocatechol	$C_6H_4(OH)_2$	Constituent silicon stain
Sodium acetate	$NaCH_3COO \cdot 3H_2O$	Buffering agent; etchant
Sodium bicarbonate	$NaHCO_3$	Buffering agent; electrolyte
Sodium chloride	NaCl	Buffering agent; electrolyte
Sodium citrate	$Na_3C_6H_5O_7 \cdot 2H_2O$	Buffering agent
Sodium cyanide	NaCN	Alkaline etchant
Sodium hypochlorite	NaOCl	Constituent silicon etch
Sodium hypophosphite	$NaH_2PO_2 \cdot H_2O$	Reducing agent
Sodium potassium tartrate	$NaKC_4H_4O_6 \cdot 4H_2O$	Buffer used in silicon crystal studies
Sodium silicate	$Na_2SiO_3 \cdot 9H_2O$	Etchant; coater
Sodium sulfide	$Na_2S \cdot 9H_2O$	Stain
Stannous chloride	$SNCl_2 \cdot 2H_2O$	Catalyst
Zinc Oxide	ZnO	Stain

Table 8.5 Proprietary Chemicals used in Microelectronic Failure Analysis [8.1].

Name	Manufacturer	Use
FL-70, Industrial detergent	Fisher Scientific	Cleaning; wetting agent
Uresolve Plus	Dynaloy, Inc.	Removal urethane; silicones; varnishes
Dynasolve 100	Dynaloy, Inc.	Removal of potting epoxies
Dynasolve 160	Dynaloy, Inc.	Removal of some potting epoxies
J-300	Indust-Ri-Chem Laboratory, Inc.	Removal of molded compounds; silicone; epoxy
DECAP	Dynaloy, Inc.	Removal of some epoxies
ECCOSTRIP	Emerson & Cumming	Removal of some epoxies
Fluorinert Liquids	3M Company	Neutral cleaning; gross leak test; testing for high power spots

8.1.14 Scanning Acoustical Microscopy

There are basically two types of scanning acoustical microscopes. The Scanning acoustic microscope (SAM) and the scanning laser acoustic microscope (SLAM). In the SAM an acoustic wave is forced into a water medium by a piezoelectric transducer. The sample is mounted on a mylar support. Transmitting and receiving transducers are mounted on opposite sides of the sample. The transducers are cylindrical sapphire rods with the ends ground concave so as to focus the acoustic beam on the surface of the sample. The transmitting transducer launches an acoustic wave which is focused on the surface of the sample. Variations in the sonic transmission are used to control the intensity of a scanned CRT display. The sample is mounted on an XY drive and the CRT display is coordinated with the drive position.

In the SLAM, the sample is viewed by placing it on a stage where it is subjected to a plain acoustic wave and illuminated with laser light. Within the sample the sound is scattered and absorbed according to the internal elastic microstructure of the sample. The principal of imaging is based on the minute displacements which occur as the sound wave propagates in the sample. Scanning in a SLAM is accomplished both by acoustical methods and by a vibrating mirror which moves the laser beam in one axis. The frequency of operation of SLAM is usually between 100 and 500 Mhz. Useful information is morphological in nature. The techniques can be used to sort and classify materials, detect and localize flaws, identify defects in optically opaque samples, and map compressibility and density variations on a microscopic scale.

8.1.14 Micro Beam Analysis Techniques

This section covers scanning electron microscopy and related techniques. These techniques are summarized in Tables 8.6. and 8.7 Characteristics of some of these techniques are summarized in Table 8.8. In a scanning electron microscope a sample is placed in a vacuum chamber and subjected to an electron beam. The beam is scanned electronically and an image is produced on

Table 8.6 Capabilities of SEM Analysis [8.1].

- Topographic or Microstructure Analysis
- X-ray Emission Elemental Analysis
  - Energy Dispersive
  - Wavelength Dispersive
- Voltage Contrast Imaging
- Electron Beam-Induced Voltage (EBIV)
- Electron Beam-Induced Current (EBIC)
- Cathodoluminescence (CL)

Table 8.7 Other types of Microbeam Analysis Methods [8.1].

- Auger Electron Spectroscopy (AES)
- Scanning Auger Microscopy (SAM)
- Secondary Ion Mass Spectrometry (SIMS)
- Scanning Secondary Ion Mass Spectrometry (SSIMS)
- Ion Surface Scattering Spectroscopy (ISSS)
- Electron Spectroscopy for Chemical Analysis (ESCA)
- Scanning Electron Spectroscopy for Chemical Analysis (SESCA)
- Scanning Electron Stimulated Desorption (SESD)
- Scanning Transmission Electron Microscopy (STEM)
- Automated Scanning Low Energy Electron Probe (ASLEEP)
- Ultraviolet Photoelectron Spectroscopy (UPS)
- Ion Microprobe Mass Analysis (IMMA)
- Electron Energy Loss Spectroscopy (EELS)

Table 8.8 Characteristics of Microanalysis Techniques [8.1].

Technique	Primary Radiation	Secondary Radiation	Constituents Measured	Lateral Resolution	Depth Resolution	Typical Detection Limit
(1) X-ray Microanalysis	Electron	X-ray	Elements $Z \geq 11$ (EDS) $Z \geq 4$ (WDS)	1 μm	1 μm	750 ppm EDS) 100 ppm (WDS)
(2) Auger Microanalysis	Electron	Electron	Elements $Z \geq 3$	0.1 - 1 μm	1 nm	0.1 percent
(3) Cathodo-luminescence	Flectron	Photon	Molecules, other	1 μm	1 μm	1 - 1000 ppm varies strongly
(4) Secondary Ion Mass Spectrometry	Ion	Ion	All elements Molecules	1 μm	1 nm	1 ppm
(5) Ion Scattering Spectrometry	Ion	Ion	Elements $Z \geq 3$	100 μm	1 atom layer	100 ppm - 0.1 percent
(6) X-ray Fluorescence	X-ray	X-ray	Elements $Z \geq 11$ (EDS)	1 mm - 1 cm	100 μm	1 - 10 ppm
(7) Laser Raman Microprobe	Photons	Photons	Molecules	1 μm	1 μm	1 percent
(8) Laser Microprobe Mass Analyzer	Photons	Ions	All elements (Molecules)	1 μm	1 - 10 μm	1 ppm
(9) Electron Energy Loss Spectroscopy	Electron		Elements $Z > 3$	$\lesssim 10$ nm	Specimen Thickness ≤ 100 nm	1000 ppm

a cathode ray tube in synchronism with the scanning procedure. SEM pictures of microelectronic devices are generally much more informative for the following reasons:

1. the depth of field is about 500 times greater than optical microscopy;
2. magnifications up to 100,000 times are possible;
3. objective-to-work distances are large enough so that focusing is not a problem;
4. surface angles up to 90° can be achieved.

The influence of accelerating voltage and charge-up on image quality are discussed. Imaging problems in SEM are discussed and several flow charts are presented which show how to resolve some of these problems. Elemental analysis by electron stimulated x-ray emission is a commonly used technique for detecting the presence of certain elements on the surface of a sample. Basically, the electron beam excites the atoms of surface elements and stimulates them to produce secondary x-ray emission. The elements can be identified either by analyzing the energy or wavelength of the x-ray emissions.

In addition to x-rays, secondary emission of electrons takes place as the beam impinges on the surface of the sample. This secondary image can be modulated by voltages on the surface of an integrated circuit. This so-called voltage dependent contrast method is used in the analysis of integrated circuit failures. While this contrast can be accomplished by dc voltages applied to the specimen leads, by operating the sample at its normal operating frequencies, or by stroboscopically scanning the beam in synchronism with the operation of the device. It is possible to analyze the waveform by holding the beam at a fixed point rather than scanning it. An alternative way for working with voltage contrast uses an electron beam induced current (EBIC) option on the SEM equipment. In effect, EBIC allows the SEM to have an independently positioned beam for exciting portions of the integrated circuit. This is particularly useful for exciting portions of the circuitry which are not accessible from the external leads.

Cathode Luminescence can be observed with relatively inexpensive accessories on the SEM. Its usefulness in microelectronics is limited primarily to certain types of semiconductor compounds.

Auger Electron Spectroscopy (AES). Auger electrons are low energy electrons ejected from a sample and are scanned by an electron beam of up to 3000 V. The energy spectrum is characteristic of the atomic number of the sample. The low energy of Auger electrons limits their escape depth from samples to only a few monolayers of the surface. AES compliments x-ray emission spectroscopy which has a low sensitivity for light elements.

Sputtered ion mass spectrometry (SIMS). Sputtering is the ejection of ions or neutral molecules when a surface is bombarded by energetic ions. The objective particles may then be identified by mass analyzers. The original instruments were called ion microprobes and embodied both electrostatic and magnetic focusing. Sensitivity is extremely high; fractions of monolayers are easily detected.

Ion scattering spectrometry (ISS) is an ion beam technique where the bombarding beam is a monoenergetic noble gas ion beam of energy lower than that needed for sputtering. It has greatest sensitivity in the high atomic numbers and produces mostly elemental identification.

Electron spectroscopy for chemical analysis (ESCA) is an analytical technique based on Einstein's photoelectric theory. It measures the energy of electrons ejected from a surface by a beam of x-rays or ultraviolet light. It is essentially non-destructive and can yield compound information on surface chemistry.

Laser microprobe mass analyzers (LAMMA) combine a laser microscope and a time-of-flight mass spectrometer. It combines spacial resolution of less than 1 micrometer, trace element sensitivity and identification of nanogram quantities of organic materials.

Alpha induced x-ray emission is a commercial instrument in which x-ray emission spectra are excited by alpha particles instead of an electron beam.

Transmission electron microscopy (TEM) requires either very thin specimens (a few micrometers at most) or carbon replicas which are time consuming and difficult to prepare. TEM offers the

highest resolution of all beam instruments and uses a fundamentally different contrast mechanism. In some cases information has been obtained on particles 30 angstroms in dimension.

Typical applications of SEM include examination or package seal integrity, electrical failures on the chip, examination of wire bonding problems. Auger analysis can give a good indication of oxides and nitrides by elemental identification. Since Auger analysis of hydrocarbon residues would mainly yield carbon peaks, ESCA techniques yields more information on hydrocarbons. Since ESCA is non-destructive it could be followed by SIMS or Auger analysis to confirm the existence of oxides or nitrides.

8.1.15 Electrical Overstress and Electrostatic Discharge

This section deals with the investigation of damage due to electrostatic and other electrical overstress conditions. The section discusses the waveforms of electrostatic discharges, their effect on devices examined under SEM, and the underlying mechanism for electrostatic build-up and discharge. Also presented in this section is a part-analysis sequence.

8.1.16 Miscellaneous Analysis Techniques

To identify failures on an integrated circuit it is sometimes necessary to identify the specific physical elements in the circuit. One of the fundamental techniques is to trace the circuit and make a circuit element lay-out map. Tracing can be done by visual examination and a comparison of the circuit diagram. Because of the multiple metallization layers and thick dielectric layers, it is often difficult to identify circuit elements. Removal of the dielectric and metallization layers and staining techniques can be used to aid in the identification of a specific circuit component. Because of the difficulty of performing these procedures in complex integrated circuits, tracing by field effect liquid crystal techniques can be used.

X-ray diffrication is frequently used to identify compounds present on electronic circuits. Knowledge of the composition of the component can help identify the materials involved. In most cases a deposit must be removed from the circuit using an optical microscope and a volume

of material of approximately 1 mm in diameter must be removed for sampling. Reference files of JCTDS data consisting of x-ray defraction patterns aid in the identification.

Trace amounts of metallic elements can be analyzed using the emission spectrograph. The material to be analyzed is burned in a carbon arc, and the emission lines and the elements are recorded on a photographic plate. Quantitative analysis is possible by comparison of proper standards. Elements may be detected in the parts per million range with sample sizes as small as .5 mg. Laser microprobe techniques may be used to analyze sample spots as small as 0.25 mm. The laser microprobe makes possible analysis of spectrum emission without direct contact with the sample.

Atomic absorption spectroscopy. Quantitative determination of metallic elements is made in liquid solutions in the 10 to 100 parts per billion range using the standard flame technique of atomic absorption. Thermal analysis techniques can be used to characterize polymers, laminated board and other materials which might be found in electronic circuit packages. Thermal mechanical analysis (TMA) provides a continuous trace of the change in dimension of the sample as a function of temperature and can be used to identify thermal coefficient of expansion problems.

Differential scanning calorimetry (DSC) can be used to detect the heat associated with the glass transition or other transition temperatures that occur during heating cycles. This technique is useful in determining the state of curing with respect to standard samples.

Thermo-Gravimetry (TGM) can be used for detecting the presence of low temperature volatiles and polymers by continuously weighing the sample as a function of temperature.

8.2 Other Methods

It is common for integrated circuit die to be sheared from the device package upon ground impact. As a result testing on loose and broken die becomes necessary. In one report [8.2] data from a PROM was extracted even though the die itself was separated from the package and had been broken. Mechanical probing was used to access and measure the individual memory cells.

Computer simulation of integrated circuit functions using circuit simulation programs such as SPICE is sometimes performed to evaluate failure modes of ICs. This can be useful in hypotheses testing which is often done as part of accident investigation.

8.3 References

8.1 Microelectronics Failure Analysis Techniques. Edited by E. Doyle, Jr., B. Morris. Rome Air Development Center. September 1981. Contract Nos; F30602-78-C-0339, F30602-78-C-0281.

8.2 Practical Observations on Recovery of Electronic Data from Aircraft Wreckage. D. Gwynne Jr. ISASI FORUM. Vol. 18 p. 2. December 1985.

CHAPTER IV

SUMMARY

1.0 SUMMARY

Failure analysis techniques for the evaluation of electrical and electronic components during aircraft accident investigation were reviewed. Techniques were summarized for: lamps, wiring, connectors, switches, magnetic materials, printed wiring boards and microelectronic devices. The construction and materials used in each type of component were also described. The potential for the techniques to distinguish pre-accident conditions from post-impact damage was discussed.

A summary of the techniques covered in this report is presented in Table 1. Next to each component type is listed: the conditions that are of interest, the basis for the analysis techniques, and some of the analysis techniques or tests that can be performed. Optical and scanning electron microscopy (SEM) were identified as fundamental analytical tools which supplement visual examination of the components. Energy Dispersive X-ray analysis (EDAX) of elemental constituents, X-ray radiography, and specialized electrical measurements are also used.

Results of the literature review suggested several areas where the accident investigator's work could be made more productive using computational tools. The first area is the collection and maintenance of data related to the condition of components. For example, a database containing the condition of all the indicator lamps on one aircraft panel would allow the investigator to conveniently correlate examination results and increase confidence levels of the conclusions. Second, modeling of physical components could be used to correlate analytical results with accident data or to perform hypotheses testing. For example, a finite element model of a mounted integrated circuit might help rule out problems related to thermal coefficient of expansion mismatch.

To establish priorities for further development of failure analysis techniques, data on the failures of aircraft electrical components was reviewed. Problems with interconnections between equipment were identified as a large contributor to the overall failure rate of electrical equipment on aircraft. A review of data from the Air Force Mishap database indicates that 36 percent of

Table 1. Summary of Accident Investigation Techniques
for Aircraft Electrical and Electronic Components

COMPONENT TYPE	CONDITION	BASIS FOR TECHNIQUE	TECHNIQUE
Lamps	ON at impact OFF at impact	Filament Deformation Filament Fracture	Opt. Micr. SEM
Wiring	Overheating - Fire Overheating - Elec. Insulation Failure Arcing Fusing	Recrystallization Insul. Tracking Conductor Melting Wire Appearance	Visual Opt. Micr. SEM/EDAX
Connectors	Insulation Failure Solder Jt. Failure Contacts High Resistance Contacts Shorted	Corrosion Contamination Poor Plating Solder Contamination	SEM/EDAX Opt. Micr. Plating Chemistry EPMA
Switches	Pos. Prior to Impact Closed - High Resistance Inconsistent Position	Contact Contamination Mech. Damage	X-Ray Visual Res. Measure SEM/EDAX
Magnetic Materials	Loss of Flux Density	Overheating Impact	Opt. Micr. Flux Measure

Table 1 Continued

COMPONENT TYPE	CONDITION	BASIS FOR TECHNIQUE	TECHNIQUE
PWBs	Solder Joint Failure - Fatigue - Contamination	Solder Composition Cracks Voids	SEM/EDAX Opt. Micr. X-Ray
	Circuit Trace Failures - Overheating	Recrystallization	Visual Opt. Micr.
	Insulation Failures - Contamination - Corrosion - Moisture	Tracking Contamination Metal Migration	SEM/EDAX Opt. Micr.
Microelectronics	Mechanical Failure - Seal - Leads - Die Bond	Seal Condition Pkg. Gas Condition Wire Bonds Loose Material Die Bond	Opt. Micr. Visual SEM Amb. Gas Analysis Bond Pull Test Impact Test Die Bond Shear
	Thermal Failure	Operating Conditions	Liquid Crystal IR Scanning
	Electrical Failure	Overcurrent ESD Contamination Corrosion Oxide Defects Surface Effects	SEM Voltage Contrast EBIC EPMA Liquid Crystal C-V Thermal

electrical failures are caused by interconnections: wiring and connectors. Environmental factors, especially corrosion, are significant causes of connector problems.

In order to assess the need for further work on failure analysis techniques for a particular type of component, three factors were considered:

1. The relative frequency with which that type of component is a causal factor in aircraft equipment failures.

2. The probability that a particular technique will provide reliable information about pre-accident conditions of the component.

3. The degree to which the techniques are presently developed.

A ranking for the components considered in this report according to these three factors is presented in Table 2. Rank values ranging from 1 to 7 have been used for each factor and are shown with the components. The rank for failure contribution was based on the failure statistics presented in Chapter II of this report. The most frequent contributors were assigned the highest ranks.

The rank for the capability of the component to provide data on pre-accident conditions was determined by considering the technical literature that was reviewed with respect to specific failure modes that could be distinguished from fire and impact damage. Components that provide the most data were assigned the highest rank.

The rank for technique maturity was based on the number, quality and age of the technical documents identified during the literature search. The techniques were considered mature only if the material described failure analysis techniques that could be applied to accident investigation, especially in the evaluation of damaged components. Photographic documentation was also considered. Techniques judged to be the most mature were assigned the lowest rank.

Table 2. Evaluation of the Need for Further Work on
Failure Analysis Techniques for Aircraft Accident Investigation

COMPONENT TYPE	FAILURE CONTRIBUTION	DATA ON PRE-ACCIDENT CONDITIONS	MATURITY OF TECHNIQUES	PRIORITY VALUE
MICROELECTRONICS	4	5	5	100
SWITCHES	7	6	2	84
WIRING	5	4	4	80
CONNECTORS	6	3	3	54
PWBs	3	2	6	36
MAGNET MTLS	2	1	7	14
LAMPS	1	7	1	7

A numerical assessment of the need to do further development work on the techniques is based on the product of the rank values which is shown in the right hand column of Table 2. The assessment presented in Table 2 suggests that additional development of accident investigation techniques is needed for microelectronic devices, switches, wiring, connectors and printed wiring boards.

2.0 RECOMMENDATIONS FOR FURTHER WORK

Recommendations for further work on failure analysis techniques for electrical and electronic components on aircraft are the following:

1. Additional testing should be performed to provide documentation to support accident investigation analysis of microelectronic devices switches, wiring, connectors and printed wiring boards.

2. Procedure guidelines are needed for the application of failure analysis techniques to these components.

3. Computer models should be developed for predicting the mechanical behavior of electronic components and devices. These models would provide additional data to help the accident investigator predict the effects of temperature and shock on components.

APPENDIX A
GLOSSARY OF FAILURE ANALYSIS TERMINOLOGY

1.0 INTRODUCTION

This chapter provides a list of failure analysis terms, definitions and abbreviations used in this report. The terms describe analytical techniques which are fundamental to the examination and analysis of electrical and other types of components. Definitions of these techniques in more detail can be found in [1]. Detailed information on the principles, instrumentation, and applications of these techniques can be found in [2].

2.0 FAILURE ANALYSIS TERMINOLOGY

SEM: Scanning Electron Microscope

In SEM, a scanned electron beam impinges on the specimen in a vacuum chamber. The interaction of the beam with the specimen causes the emission of X-rays and other forms of radiation. Two common SEM imaging methods rely on the detection of either secondary electrons or backscattered electrons which leave the surface of the specimen.

EDAX: Energy Dispersive X-ray Analysis

Apparatus for SEM which detects the energy of X-rays which are emitted from the specimen surface as a result of the electron beam. Provides quantitative information about elemental constituents of the specimen.

AES: Auger Electron Spectroscopy

In AES an electron beam is focused on the specimen area of interest. Detection is based on the emission of Auger electrons which result from a secondary reaction of the X-rays with the electron orbitals. AES analysis is used primarily for the analysis of the constituent on the surface of the specimen.

SIMS: Secondary Ion Mass Spectroscopy

Spectroscopic technique which uses ion etching to remove surface layers in conjunction with AES. Secondary ions are detected to determine surface composition.

ESCA: Electron Spectroscopy for Chemical Analysis

Also known as X-ray Photo Spectroscopy. A collimated beam of soft x-rays is directed at the specimen. Photoelectrons are generated whose energies are related to the x-ray energy and the binding energy of the electrons in the specimen. Chemical composition is determined by comparison to reference standards.

LAMMA: Laser Microprobe Mass Analysis

A laser beam is used to vaporize a small volume of the specimen. Mass spectroscopy is used to analyze the ionized material.

EPMA: Electron Probe Microanalysis

Similar to AES but effects a deeper surface region of the sample.

3.0 REFERENCES

1. Metals Handbook. Ninth Edition. Volume 11, Failure Analysis and Prevention. 1986, The American Society for Metals.

2. Metals Handbook. Ninth Edition. Volume 10, Materials Characterization. 1986, The American Society for Metals.

* U.S.Government Printing Office: 1990—748-056/24446