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The Effect of Aircraft Generated Electromagnetic Interference (EMI) on Future Avionics Systems — A Compendium

W. E. Larsen
FAA Technical Field Office
Moffett Field, CA 94035

N. O. Rasch
FAA Technical Center
Atlantic City Airport, NJ 08405

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Compendium
April 1984

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U.S. Department of Transportation
Federal Aviation Administration

FAA Technical Center
Atlantic City, New Jersey 08405

1. Report No. DOT/FAA/CT-84/9	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle THE EFFECT OF AIRCRAFT GENERATED ELECTROMAGNETIC INTERFERENCE (EMI) ON FUTURE AVIONICS SYSTEMS — A COMPENDIUM		5. Report Date April 1984	
		6. Performing Organization Code ADL-33B	
		8. Performing Organization Report No.	
7. William Larsen (editor)			
9. Performing Organization Name and Address Federal Aviation Administration FAA/Ames Development and Logistics Field Office P.O. Box 25 Moffett Field, California 94035-0025		10. Work Unit No. (TRAIS)	
		11. Contract or Grant No. NAS2-1162, NASA/Ames	
		13. Type of Report and Period Covered Conference Publication October 19-21, 1982	
12. Sponsoring Agency Name and Address Federal Aviation Administration Flight Safety Research Branch, ACT-340 FAA Technical Center Atlantic City Airport, New Jersey 08405		14. Sponsoring Agency Code	
15. Supplementary Notes The authors and their affiliations are listed in the introductory pages of the compendium, and in section 22. The conference was held in Seattle, Washington.			
16. Abstract There are various commercial standards and specifications which are aimed at making aircraft compatible with a hostile electromagnetic environment. However, most of these standards and specifications were developed for analog circuitry; before the advent of high-speed flight critical digital systems. These standards must now be reengineered to accommodate the new technology of composites and sensitive integrated micro-electronic architectures. Modern aircraft are experiencing many cases of flights into or near heavy electromagnetic fields from various sources such as lightning, switching of heavy aircraft electrical loads, or radio transmissions during their life span. This EMI environment has caused and is causing hazardous incidents to aircraft by impairing the normal operation of some flight-critical and flight-essential equipment. Special precautions must also be taken to protect this sensitive digital avionics during maintenance operations. For this reason these standards and specifications must be revised and new design, manufacturing, and testing methods introduced. These presentations contain ongoing and planned research, hardening techniques, and testing criteria for EMC that will assure protection for commercial aircraft against all but the most severe electromagnetic phenomena. The presentations also recommend verification techniques for such protection.			
17. Key Words Digital Avionics Electromagnetic Compatibility Digital Systems Failure Mechanisms Electromagnetic Interference ESD Transients, Test Methods		18. Distribution Statement This document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161 Unlimited, Subject category 60	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 324	22. Price A14

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PREFACE

As editor, I should like to exercise my prerogative to intrude, at this point, and express my sincere appreciation to all my friends and colleagues whose efforts made this workshop successful and this compendium possible. I refer to Mr. Nickolus Rasch of the Federal Aviation Administration Technical Center who made the initial contacts with some of the authors; Mr. Stan Schneider and Mr. Jim Bogart of the Boeing Company, where the workshop was held, for their extraordinary efforts in handling the arrangements as hosts; and the Boyer Court Recording Service, for translating the verbal presentations to writing. Also, I want to express my gratitude to the various authors and their companies for the extra effort that made this workshop possible.

These authors and their companies are:

Mr. Nickolus Rasch	Federal Aviation Administration
Mr. Stan Schneider	The Boeing Company
Mr. Chris Kendall	Chris Kendall Consultants
Mr. Keith Kalanquin	The Boeing Company
Dr. Gerry Masson	Johns Hopkins University
Dr. David Auckland	Syracuse Research Corporation
Mr. John Small	The Boeing Company
Dr. Hussein Youssef	Lockheed Aircraft Company
Dr. Cliff Scouby	McDonnell Aircraft Company
Mr. Robert Norton	The Boeing Company
Mr. I. Mehdi	The Boeing Company
Dr. William Cooley	The Boeing Company

Each of the companies listed above contributed the travel and time of the various authors, and the Boeing Company contributed the plant facilities. Then I also want to thank the FAA for allowing me to participate in this workshop.

Finally I want to emphasize that the various presentations represent past and present work, and the future plans of the different speakers, and do not represent a policy position by their company. A draft of each presentation was returned to its author for comment and the addition of any artwork. When these comments and the artwork were available, they were inserted into the text. No particular format was imposed on the authors, thus the particular style remains their creation. I again wish to thank the authors and their companies for their support, and the audience for participation, interest, and thought provoking questions.

William E. Larsen
Federal Aviation Administration

INTRODUCTION

Nickolus Rasch

Federal Aviation Administration Technical Center
Atlantic City Airport, New Jersey

MR. RASCH: Good morning. I want to welcome you to the EMI (Electromagnetic Interference) Workshop. Our intent is to develop some EMC concepts for your consideration and potential application.

This workshop started as a deliverable on a project that the FAA has established. The project is managed out of the Ames Research Center by Bill Larsen.

This workshop is one facet of the advanced aircraft systems program. There are four program managers on the program; we are going to discuss EMI in detail throughout this workshop.

PROGRAM SUBELEMENTS

- DIGITAL SYSTEMS
- LIGHTNING AND EMI
- FLYING QUALITIES AIRWORTHINESS
- SPECIAL PROJECTS

Other program subelements are digital systems, lightning, flying qualities, airworthiness, and special projects, each with program manager responsibility. The digital systems manager is Don Eldredge; I manage lightning and EMI; and the flying qualities and airworthiness manager is Joe Traybar. Bill Larsen, in addition to the previous mentioned program managers, works on special projects.

PROBLEM

INDUSTRY AND FAA CERTIFICATION AUTHORITIES NEED NEW STANDARD AND GUIDELINES THAT FORM AN INTEGRATED SYSTEMS APPROACH:

- INTEGRATED SYSTEMS NOW DICTATE DESIGN
- NEW TECHNOLOGIES ARE NEEDED IN AVIONICS AND CONTROL
- CURRENT STANDARDS ARE SEPARATE SYSTEM DESIGN

We have defined certain areas of concern where both industry and the FAA certification authorities are in need of new standards and guidelines as a result of the ever-increasing integration of the aircraft systems. As we get into the more sophisticated microelectronics and composites, we are going to have to change our ways of thinking and do a better job of keeping aircraft flying.

The new technology is systems integration in avionics and control systems now dictates and will continue to dictate aircraft design. These advances in technology have brought our current standards under careful scrutiny.

The objectives of the electromagnetic compatibility portion of our program involve the complete avionics systems, the electrical power systems, and the airframe.

OBJECTIVES

- ESTABLISH AND MAINTAIN INTERFACE WITH INDUSTRY, NASA, AND DOD IN ADVANCE CONCEPTS
- RECOMMEND REVISIONS AND NEW REGULATIONS AND PROCEDURES
- PROVIDE SYSTEMS ENGINEERING AND FLYING QUALITIES EXPERTISE AND SUPPORT

This program got its start about 3 years ago; at that time, we took a hard look at the concerns being raised and made some decisions as to where we are today and where we should go.

ELECTROMAGNETIC COMPATIBILITY

- AVIONIC SYSTEMS
- ELECTRICAL POWER SYSTEMS
- AIRFRAMES

Quite a few of you participated in our workshop of February 1980. We defined some guidelines, and decided to establish interagency agreements with the Air Force, the Army, the Navy, NASA, NOAA, etc., in an effort to conserve resources and element redundancy in our activities.

ELECTROMAGNETIC COMPATIBILITY PROJECTS

- NATIONAL ATMOSPHERIC ELECTRICITY HAZARDS PROTECTION PROGRAM
- DIRECT STRIKE LIGHTNING TESTS (F-106, LANGLEY)
- LIGHTNING STRIKE STATISTICS PROGRAM
- AIRCRAFT GENERATED EMI COUPLING
- ADVANCED DEVELOPMENT PROGRAM
- HANDBOOKS, PUBLICATIONS, TRAINING

A National Interagency Coordination Group (NICG) was established to handle these responsibilities, and we meet twice a year.

Our next step was to look at lightning characterization. To do this, we joined forces with NASA and established the F-106 direct lightning strike program. In this program, an F-106 is flown directly into the path of a thunderstorm. The F-106 is equipped with a special instrumentation package to record the lightning strike data. We have recorded 150 direct lightning strikes during the 1982 thunderstorm season, and believe all of the data are valid.

Historically, the only lightning data we had came from a Management Information System lightning strike statistics program. In this program, all the data came from pilot reports. In order to get a better statistical overview of lightning strikes, the FAA joined forces with the Naval Air Development Center (NADC) in

Warminster, Pennsylvania. This union spawned a program which placed a piece of relatively inexpensive equipment on commercial transports. The equipment is designed to record every lightning strike parameter.

Aircraft-generated EMI coupling effect is what this workshop is all about. Bill Larsen is the project manager. He will go into greater detail later in the workshop.

Another element in the overall program is the Advanced Development Program (ADP) in which the FAA joined forces with the Air Force, Navy, Army, NASA, Defense Nuclear Agency (DNA), etc. A subelement of this program will be defined later by Dr. Bill Cooley from the Boeing Military Aircraft Company.

We are also working on publications, handbooks, and training.

How did the FAA arrive at this plan? We developed a road map of the technology area (fig. 1-1) and integrated this with the concerns identified by both industry and the FAA certification people.

Unfortunately, limited resources have prevented conducting all facets of the program at this time. We have the aircraft accident data being inputted into our Management Information System, and are postured to commence the analysis.

This plan has contributed to the general interactive process where the aircraft structural and avionics system are developed to withstand both external and internal EMI threats, and from this evolve design guidelines, airworthiness standards, and compliance procedures.

DIRECT STRIKE LIGHTNING TESTS AND EMC STUDIES

OBJECTIVES

1. DETERMINE EFFECT OF LIGHTNING AND STATIC DISCHARGE
2. PROVIDE OVERALL EMC FOR FUTURE AVIONIC SYSTEMS

GOALS

1. LIGHTNING HAZARD PARAMETERS
2. CHARACTERIZATION OF LIGHTNING
3. INFORMATION TO AID IN DEVELOPMENT OF AIRWORTHINESS SPECIFICATIONS AND CRITERIA

Now to backtrack to the direct-strike program which we talked about a little while earlier. The objective of this effort is to (1) define the lightning characterization and (2) provide an overall EMC for future avionic systems.

AIRCRAFT LIGHTNING STRIKE STATISTICS PROGRAM

OBJECTIVES

1. LIGHTNING STRIKE/AIRCRAFT EFFECTS
2. EXPANDING THE LIGHTNING STRIKE DATA BASE

GOALS

1. GAIN A GOOD AIRBORNE LIGHTNING STRIKE DATA BASE
2. REFINER STATISTICS ON STRIKE DATA
3. DEFINE LIGHTNING STRIKE HAZARDS OVER WIDE GEOGRAPHIC DATA BASE

The lightning strike statistics program is a viable program, and it is very important to us. It will provide us with a good geographical data base, which is not now available. It also provides us with some very good strike data. If the aircraft is struck at 30,000 ft (91,440 km), what does this mean? If it gets struck at 3000 ft (9144 km), what does this mean? These are some of the areas that will be addressed through the program.

ADVANCED DEVELOPMENT PROGRAM

- DEVELOP EMI HARDENING TECHNIQUES
 - AGENCIES INVOLVED
 - USAF
 - USA
 - DNA
 - FAA
 - NASA
 - BOEING MILITARY AIRCRAFT COMPANY
 - COMMENCE APRIL 1982

The Advanced Development Program (ADP) for future aircraft defines the lightning threat characterization with the aircraft in the interaction, although it does not provide direct strike data. It only provides indirect strike and indirect information.

There are a number of different agencies involved. It is a multimillion dollar 5-year contract with the Boeing Military Aircraft Company, Seattle, Washington, as the prime contractor. Boeing was awarded the contract last April, and presently is in phase one of the program.

AIRCRAFT GENERATED EM COUPLING EFFECTS ON DIGITAL AVIONIC SYSTEMS

OBJECTIVES

1. DEVELOP A DATA BASE
2. DETERMINE EMI/EMC TEST
3. DEFINE HARDENING PROTECTION GUIDELINES
4. DEVELOP GROUND TEST METHODOLOGY

GOALS

1. AIRCRAFT GENERATED EMI EFFECTS
2. RECOMMENDED HARDENING CRITERIA DEVELOPED

We will be presenting a portion of this program during the next 2-1/2 days. Parallel to this program we are going to develop a data base from our aircraft-generated EMI program, with the goal of identifying aircraft-generated EMI effects and recommending hardening criteria. We hope to have a viable product here.

LIGHTNING AND EMI

OBJECTIVE

RECOMMEND NEW STANDARDS, CRITERIA, AND PROCEDURES FOR PROTECTION OF ADVANCED AIRCRAFT AND SYSTEMS

APPROACH

- JOINT GOVERNMENT PROGRAM (USAF, USN, USA, NOAA, NASA, FAA) — NAEHP
- IA — NASA-LaRC — DIRECT STRIKE/LIGHTNING CHARACTERIZATION
- IA — USAF-FDL — EMI HARDENING TECHNIQUES
- IA — NASA-ARC — AIRCRAFT GENERATED EMI

STATUS

- NATIONAL ATMOSPHERIC ELECTRICITY HAZARDS PROTECTION PROGRAM (USAF-FDL, NASA-LaRC, U.S. NAVY, U.S. ARMY, NOAA)
- DIRECT STRIKE LIGHTNING TESTS (NASA-LaRC)
- EMI HARDENING TECHNIQUES (NAEHP MEMBERS/BOEING COMPANY)

DELIVERABLES

- AIRCRAFT GENERATED EMI COUPLING ADVISORY CIRCULAT (NASA-ARC AND FAA TECHNICAL CENTER) — NOVEMBER 1983
- FUEL SYSTEMS PROTECTION ADVISORY CIRCULAR (LIGHTNING TECHNOLOGIES/SAE-AE4L/FAA TECHNICAL CENTER) — APRIL 1983

PUBLICATIONS, HANDBOOKS, TRAINING

- LIGHTNING PROTECTION OF AIRCRAFT
- HANDBOOK REFERENCE MANUAL
- POST-LIGHTNING STRIKE PILOT'S GUIDE
- POST-LIGHTNING STRIKE INSPECTION

- REGION/HEADQUARTERS TRAINING PROGRAM
- TECHNICAL SUPPORT - SPECIAL CERTIFICATION REVIEW

The last area of activity we have is a catch-all which includes publications, handbooks, and training. We also would like to revise the handbook on lightning protection for aircraft, a NASA publication authored by Plummer and Fischer which I believe most of you are aware of.

We also would like to develop a handbook reference manual or the post-lightning strike pilot's guide. Unfortunately, insufficient information is presently available to guide pilots on what to do after their aircraft have sustained a lightning strike.

Another area of concern is a post-lightning strike inspection; no inspection criteria exist presently.

Last, we want to develop a regional and headquarters training program encompassing the latest technology. This program also includes support activities during the certification process.

To summarize, our objective is to recommend new standards, criteria, and procedures for the protection of advanced aircraft and their systems.

Our approach, because of limited resources, has been to establish joint agreements with different agencies including the Air Force, Navy, and NASA.

I am optimistic that an aircraft-generated EMI coupling advisory circular will be completed by November 1984. At present, we are working on a fuel system protection against lightning advisory circular. Our original draft should be available for review by July 1983.

I will turn this over to Bill Larsen who will introduce our next speaker.

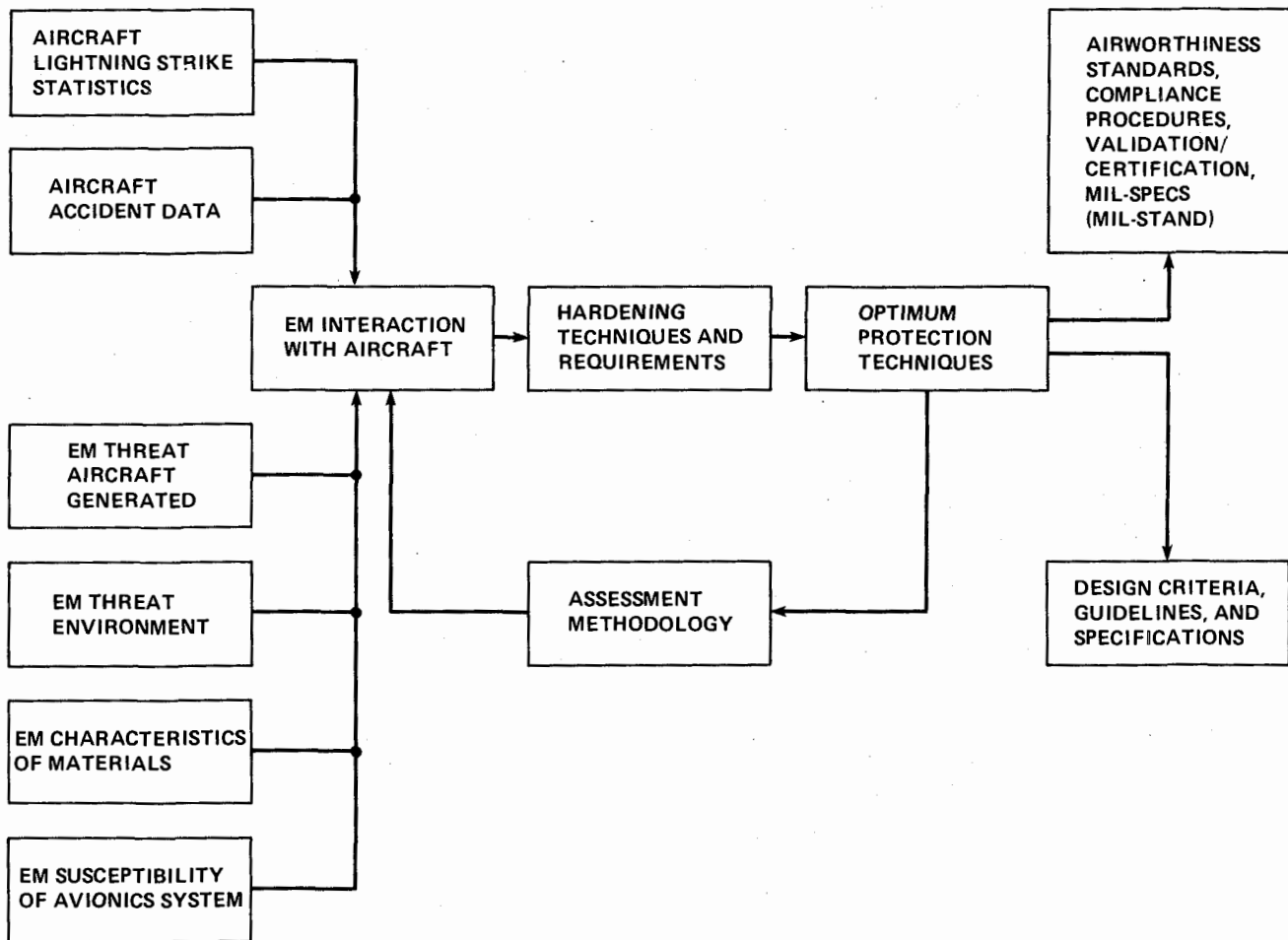


Figure 1-1.- Technology Roadmap.

WORKSHOP OVERVIEW
Problem Definition, Proposed Solutions, Validation Methodology

Chris Kendall

Chris Kendall Consultants
Mariposa, California

MR. LARSEN: I am Bill Larsen from Ames Research Center.

As Nick Rasch previously mentioned, we have a program dealing with aircraft-Generated EMI. This work shop is a subelement of that program, and was initiated to expose some of the knowledge of one of the contractors. Initially it was to have been held in April. Before I introduce our main speaker, I would like to thank Boeing for their effort in providing several of the speakers as well as hosting the workshop.

Chris Kendall, our main speaker this morning, has had extensive experience in the EMI/EMC (Electromagnetic Interference/Electromagnetic Compatibility) area. He graduated in applied physics and nuclear engineering a few years ago. He worked for several companies — Sprague, Litton, and Genesco — before opening his own consulting business. While he was at Genesco, Chris headed up the EMI engineering and test department.

As a consultant, he has worked with several aircraft manufacturers and has been involved with most of the recent commercial airplane and avionics manufacturing companies, in one way or another, in areas involving EMI.

He has also worked on a great number of military airplanes; many times preparing EMI impact studies, working with the design teams, and then making sure (after the equipment was installed) that the installation met specifications.

Based on this background, we decided to contract with Chris to put together a program plan on this subject for the FAA.

This morning I would like to introduce Chris to you. He has the responsibility for the bulk of the presentations during the workshop. Feel free to ask him questions.

Chris has taught over 60 courses worldwide in the field of EMI. He has also done a great deal of problem solving and consulting with the companies of Silicon Valley, where I come from. When I want to reach him, I have to find out what company he is working with.

Here is Chris.

MR. KENDALL: I think I'll go get a job with that recommendation.

We started this project a number of months ago, and have been working hard to come up with concepts we think might be workable. We have been researching some of the problems we suspect the airborne computers are going to have, mainly from the experience of people like Bill and Nick, and we have tried to correlate

some of this information. During this workshop I will share that information with you.

The workshop will be productive because we're all able to share our own expertise, understanding, and observations.

I think we all have heard a lot of horror stories over the years. I have heard a fair share, and I'm sure you have, too; not always related to airplanes. But I think these stories relate to the problems we're faced with.

I have worked quite a bit with commercial computer houses as well, and some of the things I have seen there are perhaps indicative of what we might be faced with in aircraft and avionics systems as we have worked with them, too.

We all have heard the stories of computers doing strange things at strange times for unexplained reasons. From the point of emissions from computers, we had a situation which is certainly a concern of any airplane integrator, where a computer jammed essential radio communications. This happened to be in Louisiana. The 32nd harmonic of the 1-MHz clock, which was a delay line clock (so it was a rather old machine), was jamming police radio communications. As soon as the police cars had moved 300-400 yd away from the police station, all one could hear was the line printer, the tape handlers, and other obvious characteristics of the computer - not the radio voice transmissions. In case of an emergency, that could have been serious.

The number of stories in this area makes us appreciate that computers are, indeed, an emitting source as well as a source of reception.

If we look back at the history of avionics, it's obvious that a lot of it has come from an analog background. With analog systems, we have had the luxury, to some extent, to ponder data, to virtually sit there and look at what we were receiving and see if it was good, for rather extended periods of time. Most of the data we looked at was RMS, so if an occasional transient of a few nanoseconds happened, it would be ignored because of the long-term duration of observing a particular indication or sensor.

Today, however, we are changing all of that. We're taking systems that have been well proven over the years, and adding a degree of sophistication. We call it digital avionics. Perhaps we now look at that same sensor, or that same port for much, much shorter periods of time by using systems that multiplex the data.

What happens if we're looking at a particular sensor for a piece of information and that information is coincident with a transient? The data read could be in error.

Of course, there are ways of voting against this, and the clever software people have come up with schemes of voting. This is very helpful when we look at the port not once but perhaps three times or more to ensure that that particular information was, indeed, the same three times in a row. At that point we can accept the data or perhaps receive it for even more intervals.

One of the things I think we have to be impressed with is the EMC test results of an analog black box or an avionics system as soon as we run the same test on its counterpart. We have done a lot of this. A lot of the companies I work

with had an analog device originally and decided to upgrade that device to a digital system.

One of the things we see is that the radiation profile of the original system perhaps was very acceptable with the analog version. But now we have something that's totally unacceptable.

The main concern is that when a system is being updated from an old system, there are certain restrictions placed on its design. Probably the most important one is that the cabling must not change. Right? We cannot rewire the aircraft.

As such, we have to live with the original shielding or lack thereof, the original grounding techniques, and even the referencing. After all, we have all come from an analog world. Most of the grounding concerns, rules, and procedures have involved something called single point grounding.

What does this mean in terms of digital avionics? These are some of the things that we had to explore. We'll be sharing with you some of these concerns.

Incidentally, when we looked at the new data from the black box, where there was just one little digital board added containing one microprocessor and one clock oscillator, the radiation profile levels had increased by over 50 dB. Sixty decibels would represent a thousand-to-one change. Fifty is just about a third of that.

The emissions were tremendously different in the VHF bands. The reason was obvious. The digital device can become a very broad multiharmonic transmitter seeking some unknown receiver.

Another concern was in the area of the analog equipment. Most of the analog response times, as mentioned earlier, were slow, rather than rapid. We could sit there and ponder the data for some time.

What we have created is a very-broad-band receiver (called a digital logic gate), as well as a broad-band transmitter. In many respects that's just what it is, and we like to look at it as nothing more than a broad-band receiver. A lot of people have mathematically described the bandwidth of the logic gate as simply equal to $1/\pi T_r$ where T_r is the rise time of that particular gate.

If that's the case and we looked at a simple T^2L device with a rise time of approximately 10 nsec, and followed the simple rule of thumb of dividing 300 MHz by the rise time in nanoseconds, 300 divided by 10 would yield a 30-MHz-wide response. In a sense we have a 30-MHz-wide broad-band receiver capable of receiving almost anything.

When we couple this broad reception capability with capacitive and inductive crosstalk that we'll talk about later, we reach a maximum signal transfer capability at around 10 to 15 MHz. When this phenomenon is considered in light of the aircraft avionic cabling reaching its first resonant frequency, and therefore also able to receive information, we have a potential crisis that we never had experienced with analog devices.

We now have a broad-band receiver connected to an almost perfect antenna called the I/O cable, connected in parallel with other cables in the aircraft which are

reaching their maximum transfer capabilities. There now exists a potential situation where we can really do a lot of coupling into these devices if we're not careful.

One of the promises and hopes of digital was that we wouldn't be seeing problems as we were used to in the case of analog systems because of the digital's tremendous noise insensitivity. After all, the digital game is immune to some extent because of the dc noise immunity built into the gate itself.

Typically in a T^2L device, the noise immunity varies from 0.4 V to a more nominal value of 1 V dc noise immunity. This usually means that it takes a signal induced into that gate above this threshold before any adverse interaction will occur. Compared to the analog world in which maybe a millivolt or even less would cause potential upset, this was a significant benefit.

Unfortunately, it's been negated by other potential hazards. The fact is we are now in an area called an electrically long region, as opposed to an electrically short region, of the cable length.

We talk about electrical length in terms of its ability to act like an antenna. Any cable will act like an antenna for a particular frequency when the cable length becomes $\lambda/4$, the quarter wavelength frequency. We compute this simply taking 3×10^8 , the speed of light, and dividing it by four times the length of the cable or wire segment. If the cable is 1 m in length, its approximate resonant frequency is simply 75 MHz.

We now see that fairly short lengths of cable which were typically not in the response band of an analog device are now in the center of the digital response bandwidth. If we marry this with where we're going, digitally speaking, we can perhaps use the example of the home computer. The big splash today is the 16-bit processor, an example, the 8088 -- and what's the big claim? Speed.

One of the features that separate the various microcomputers that we might want to buy has to be speed. How fast is it?

If you're out there buying something, it's like the automobile used to be -- you want to go faster and faster. You want to buy, in a sense, a hot rod.

Similarly, a computer is in the same ballpark. We all want to buy the "hot rod" of the microprocessors. The same thing happens as we look at avionics, we'll want to go faster and faster.

We look at some of the Navy programs, and find they are doing research in the 10 megabit and faster data transfer rates. That's a pretty high data transfer rate.

If these rates are real (and we believe they are), and people want to be able to transmit data, gather data, and crunch data at this speed on board aircraft, then we have to use a different type of logic family.

The logic we have to choose must have even faster rise times than before, which means it has a bandwidth much greater than before; consequently, much shorter interconnect distances will be required and yet this will create major interference problems.

Some of these areas we're talking about, or will explore a little later, are the various noise sources that are seen in avionics systems and how they interact with the noise sources on commercial and even some military aircraft.

We have heard this morning some talk about lightning. Lightning used to be best simulated on the power mains by a test referenced as CS06 in the military, and its civilian counterpart, DO-160. This test was typically a pulse with a rise time of approximately 1 μ sec, a pulse duration of about 10, and a voltage range varying from 100 to perhaps as high as 600 V.

More recent studies have shown that lightning doesn't necessarily have such a slow rise time. Perhaps it has rise times in the nanosecond region; not quite as fast as logic, perhaps, but certainly in the 100-nanosecond region. Some say it's even faster than that.

If this is the case, combining fast broadband transient phenomena with a fast responsive computer could have some serious consequences: first, in how to redesign the product and second, in how to reintegrate this product to ensure compatibility.

To give you an example of my concern, let's assume that the floor I'm standing on is made of pure copper, 1 in. thick. And let's suppose that we plate this floor with 1/2 in. of silver. Then let's add 1/4 in. of pure gold. We have to admit that this floor is pretty conductive. If you were looking for a ground reference, we would all agree that that's not too bad.

Let's put the cockpit controls of our airplane at one end of this ground plane, and the on-board flight computer at the opposite end of this room on this ground plane. Now let's try to transmit data between the cockpit of our airplane and the flight computer. Our transmission frequency will be the precise frequency where the distance of separation over the ground plane is $\lambda/4$. What is the impedance of the ground? Is it zero? Is it low?

Those of you who have RF experience would know that it is anything but low. We have reached a situation in which this ground, gold and silver and whatever, has reached an almost infinite impedance despite its dc resistance. There is no such thing as ground. There is no ground reference.

When we're dealing with digital avionics systems and high-speed data transfer, there is no such thing as ground.

That raises a lot of interesting issues, hopefully, and some concerns. How on earth can we communicate over such a high-impedance reference?

Obviously we worry about that all the time. We hear people say if something doesn't work, it's a grounding problem. It's got to be a ground loop problem or a ground problem (fig. 2-1 identifies some of the concerns for digital avionics).

Indeed it may be. But how do we define a situation in which, for the airplane itself, there is no ground reference. This distance, this floor, and this room are quite large. I have used the example in much smaller rooms and the problem is still realistic. As far as the bandwidth of data transfer, the reference we're dealing with doesn't exist, and we have to ask how can we communicate across a ground situation where the impedance is so drastically different and the transient stimulations from the airplane are so real.

Fortunately, there are some answers that we can take from the high-speed computers of today. We do look at these high-speed computers quite a bit and find that the answer lies in transmission lines.

The only way we can communicate over large variations in impedance is through the magic of a transmission line where the rms voltage and current is equal everywhere. That is a very important part of digital transfer.

How do we transfer data in future aircraft, and do it with the degree of hardening that we want to have, against the noise sources and the air frame and the environment as mentioned earlier? Lightning, P-static, and static discharge within the frame itself, metal-to-metal contact, relays, solenoids, etc., are noise sources that are real and hard to suppress. It's very hard to put an RC time constant to a lightning strike.

So in such a situation, we have to deal with how to harden a system, and how to make sure that the transmission line concepts are employed in digital transfer. These are some of the issues I would like to share with you, and to get your opinion of, and your concerns in dealing with these issues.

What we're saying is that we have gone a long way when we have changed that analog box for a digital equivalent. Really it's not equivalent at all. It's a whole different ballgame where the rules of single reference grounding, which are only applicable in what we call the electrically short region, are no longer valid. Yet that's the way the cable ground was initially anticipated. The data sensed were analog, and therefore we put a shield on it — and what did we do with the shield? We grounded it at one end and left the other end floating. That was great. As long as the impedance across that shield was near zero, there was no problem.

Now put that same sheath or shield on a digital cable where fast-rise-time transients occur and connect it to a broad-band receiver, and what do we have? We have a situation in which the antenna wire segment, the shield itself, becomes the antenna, just like a CB antenna.

What do you do? You reference one end to the receiver; the other end sticks up in the air. That's virtually what you have in cables where the shield has been grounded at one end.

So you say, "Don't tell me you propose to ground it at both ends?" Yes, we do. But we also have to recognize that whatever technique we use also has to be compatible with any analog systems that are still going to be maintained.

No one said the other end had to be grounded dc-wise. It only has to be grounded ac-wise. But the other end of the cable has to be at the zero potential as far as the shield excitation is concerned. Therefore, the concept of terminating shields with capacitors as opposed to dc shunts becomes viable.

Let us look at a counterpart in the commercial sector. It's called ether net. There is a coaxial cable many thousands of meters long that you can tap into with a shielded box and a drop cable connected to a safety wire that plugs into the wall.

If the coaxial cable were grounded at each one of these junction points and the drop cable was also, we would have multiple connections to the safety ground of

the system, or building, or facility. And the cry for ground loops might be an interesting one to raise.

The way they solved this problem was to have the main multibus cable that comes into the shielded box terminate into a PC board with two ground planes. The shield terminates to the first, the second terminates to the box chassis, and in between lies six 0.001- μ F capacitors.

Ac-wise the shield has been grounded to the box potential. Whatever happens outside stays outside, and the integrity of the shield tap box is maintained. The shield has been terminated.

The capacitor voltage value is rated for around 2 kV. You don't want it to blow every time a healthy transient comes down the line.

This system has withstood a 25,000-V static discharge directly to the sheath of the coaxial cable with no perturbation of data.

So we see that there is perhaps a new way to think. Can we live with that 8-in. pigtail shield termination through a pin in a connector?

Another pet concern of mine is how do you ground a shield? We used to be able to take a shield through a pin in a connector and ground it to the chassis inside, a clever technique.

If we do the same on a digital bus, it won't work. That 8-in. pigtail has enough electrical length, in the presence of a static discharge, or a P-static, or lightning effect, to transmit into the box (which is simply nothing more than a resonant cavity in many respects). As such, that transient can induce currents to flow into the microprocessor and cause hardovers and other disturbances to the memory or to the processor itself.

We have to rethink a lot of areas as we begin to look at digital. I'm sure the concern we all have is just what's going to work. We should be concerned if we see a cable harness where we have 4 or 5 in. of exposure and a little wire going through a pin in a connector, and we know it's the major computer on board the aircraft. Will it work? There is a high probability it won't unless some secondary protection, either in the form of filter pin connections or their equivalent, has allowed that cable electrically to be shorted to the case.

These are our concerns, and we'll be sharing more about these concerns in the days to come.

Another concern we have is trying to define the threat. What on board the airplane is going to give us these concerns? What is our source of headaches?

Let's look at the simple dc motor. I did that recently, and I was amazed at what I saw. The instrumentation today is awesome. I was able to use a new, very-high-speed oscilloscope, and connect it to a simple device called a dc motor. We looked at the dc motor, and what I call steady-state transients. (I love the dichotomy of the statement.) We found that a dc motor creates a wave form I had never seen before. A transient is given off every time the commutator breaks its contact at a fairly high rate.

The windings inside are little inductors, and every time they break contact, it creates a very interesting transient. It creates a pulse of 10 V in amplitude, with a rise time of 1 to 2 nsec and a duration of approximately 50 to 100 nsec with a higher frequency on top. This is an important finding because if such transients do exist on a dc motor, and we take a computer cable or a digital sensor cable and route it next to this particular cable, the crosstalk can be very damaging.

Now, we recognize that even if the cable has a voting scheme, the dc motor operates so fast in rpm that the transients can occur at a rate rapid enough for them to couple into a cable and outvote the voting scheme. Therein lies the concern. It's a game of probability and statistics.

We ran this motor cable next to a microprocessor cable that was a twisted, shielded pair, terminated using present day aircraft technology (about an inch or two of exposed lead with a drain wire going through a pin in a multipin connector). About every 20 min that microprocessor got clobbered, and it had a three-way voting system. It would actually insist that the data being read had to be the same three times in a row. That's kind of scary, especially when I was sitting on an airplane the other day coming back from Washington, D.C., and I flew for 4-1/2 hr.

I'm not saying that this is going to happen. I'm saying the probabilities are there, and we have to think these things through and make sure we have done sufficient testing in our design techniques to address these subtle issues.

That's only one of many possible threats on board an aircraft, and I'm sure you know more than I do about some of the potential threats, such as vibration of metal parts that aren't well bonded together. Lightning is another awesome threat. What about static discharge? The cockpit is dry and the pilot reaches to press a button. Will he draw an arc? Or worse yet, will he draw a transient?

The human body cannot feel a discharge of around 2000 V or less. You don't feel it because it didn't burn enough. You didn't create enough current for the fingers to feel it. An arc can actually occur. You can create arcs of about 1 mJ, or so, at a voltage level less than 2000 V right from the tip of your finger. What will happen when these discharges occur to something that the pilot touches?

If you look at some of the papers from the symposium held in Santa Clara in 1982, they show some wave forms from the human body at levels of less than 2000 V. The rise time in some cases was claimed to actually be in the picosecond region — picoseconds from the human body. We're creating quite a lot of noise out there. And it's possible that this noise is another potential threat that we have to address, especially with synthetic clothing added to it, creating buildup by just sitting in a seat.

We have had a lot of computers where the computer operator did nothing more than sit in the chair, reach for the computer, pull himself up, and have the whole computer power down because his fingers drew an arc. The movement relative to the chair, the triboelectric effect, the stripping of electrons stored in the capacitor (which we all are) was enough to cause this.

Some of us have different values. We portly people have a different capacitive value than you thin, tall people. We also have different resonant frequencies.

I always feel sorry for the tall people in the audience because you resonate at a much lower frequency than short people.

Nonetheless, as we create an arc, we are an antenna, we are a radiator, and we are a conductor. We may not be very good, but perhaps good enough to raise concern. One of the great concerns of the computer industry today lies in the area of the human body discharge.

We recognize that it is not that difficult to create discharges. We have heard of production line situations in which a person will pick up a chip, look at it, and put it down — and destroy the chip. He won't know it because he never drew an arc, never felt anything, didn't burn.

Can you imagine what would have happened if he had drawn an arc? You have all experienced ESD; you have walked across a carpet and reached out, only to see a blue flame come from the tip of your finger. If you looked at the tip of your finger you would find a very intense burn mark, very small, at the tip of the finger. Even if you reach out with a key, hoping to draw an arc, you still feel the current, even with your fingers pressed tightly against the key — especially on a dry day, which creates quite a bit of energy.

Now, we're not saying that would happen. But can you imagine the stress to a very-wide-band receiver with perfect antennas called I/O cables connected to it? Someday we may have something that will put everyone in the EMC community out of business. It's called fiber optics. We could all go home and retire, and maybe that would be the answer.

But even there, we have some interesting problems in the hybrids that make up the receivers. How well do they get grounded through the silver epoxies that hold the substrate into the shielding can?

Continuing with the idea of threats, then, we have looked at the aircraft and transients as threats, and talked about the dc motor. We have talked about human discharge, and the airplane itself.

A lot of data have been accumulated on precipitation static as an airplane passes through the air on a moist day. These crystals can form static right on the airplane itself. As the static builds up it can create arcing.

It's similar to your automobile. That little ball on the tip of your antenna that you probably thought was decorative is called a Corona ball. Its aim is to keep the static buildup low enough that you will not detect the transient in the radio.

So I think we recognize that precipitation static is another area of concern. How do we best deal with that problem? Do we make the surface slightly conductive so that it can't build up? That's pretty hard to do if you're getting precipitation static because of the formation of the crystals.

These arcs are going to happen. You see them in space. Space programs are fighting this problem as well as a similar problem. When the Sun comes up, it creates a static polarity on the space vehicle which can create arcing, too.

Nonetheless, we know that fast rise times are there and are real, but the interesting thing is we haven't worried about them. We're worried about lightning,

but we generally don't have to worry about fast rise times unless they have enough intensity to do damage to the analog systems. An analog system had a lot to worry about in the low end, but not as far as transients are concerned.

Now we have created something where we really have to worry about transients. Precipitation statics, lightning, dc motors: all of these are potential threats and need to be documented, to some extent, so we have a better feel for their intensity in terms of speed, rise time, and wave form characteristics. We can document the threat, get a better feel for the wave forms, analyze these wave forms, and, in conjunction, solve the transfer coupling equations that relate to the crosstalk that is due to capacitance and inductance. Then, I think, we probably will have a decent understanding as far as design techniques go.

Another concern we have looked at is inductive coupling or crosstalk. We used to worry about this phenomenon in the analog systems. Most of us have associated the capacitive crosstalk as the worst threat we have as the frequency increases. We felt that inductive crosstalk was a low frequency problem, associated with high current and low frequencies; not much of a concern at high frequencies.

However, recent data have shown it to be just the opposite. Inductive crosstalk is becoming a major issue because, under the single reference grounding rules, there was an unwritten rule that was rarely followed. That rule stated that if you use single reference grounding, you must exercise loop control. Therefore, there would have to be no net loop area in existence during a single reference ground scheme.

If you didn't follow that rule, you could open up a net loop area such that two loops nearby, following the same basic principles of single reference grounding, could begin to communicate.

We can show the problem with loop area, and we'll talk about this a little more. It's becoming a very important part of controlling digital systems (see fig. 2-2 for a typical example).

I have done this at a very elementary level, the PC board, but it could be the same in an aircraft. In the first circuit, E-1 to S-1, we have a signal being transmitted so that the only way the current associated with that signal can get back to the source is through the ground bus structure on the board, namely the ground rail. You could see the same thing in a building, the safety ground in the building becoming the central ground reference, and the only way the current returns is back through this reference.

The loop area subtended by the lines connecting E-1 to S-1, and then back through the ground rail, represents a net loop area subtended by that circuit. The current flow is going to have a magnetic field associated with it.

We have on the exact same board, and in the same plane, a second loop because of our grounding scheme between S-2 and E-2. And that also has a net loop area subtended by the trace on the board connecting to the reference ground on the board.

Suppose we pulse the first circuit so that the current for an instant, or for very short intervals, could be substantial. What would happen to the second circuit?

Magnetically it's a perfect coupling. As the first circuit turns on or off, the second one follows. We all know that two-sided boards are the least expensive and therefore the most valuable way to go. But in high-speed logic, it won't be very long before these two circuits interact.

The interaction of these two magnetic fields is very critical to digital operation. We can spot its occurrence by looking at some of the charts. In a capacitive situation we recognize that capacitance exists between two adjacent wires, so that when one wire experiences a change of state, the second wire will try to follow.

By multiplying C times the rate of change of voltage with respect to time, we could get a feel for the voltage swing. As signal E1-S1 changes state, current would be pulled from circuit S2-E2 because of the intertrace capacitance. The time constant equal to the product of the intertrace capacitance and the impedances of the S2-E2 circuit should result in a very narrow transient width that would decay fairly fast, maybe 2 or 3 nsec, depending upon the logic speed.

But now we have another problem of one loop area talking to another loop area. One of the things we find with crosstalk, be it capacitance or inductance, is that the higher you go in frequency, the greater the coupling becomes. You eventually reach some parameter limitations of the circuitry so that, as the frequencies go up, these loops become able to talk more and more. If it's a transient situation where we're looking at a broad spectrum of transient distributions, voltage versus frequency, we get quite a bit of coupling.

Usually on a PC board this coupling reaches its maximum around 10 MHz. So the greatest amount of coupling can occur as low as 5 MHz depending upon dimensions. But in the 5- to 10-MHz region we reach peak coupling inductively and generally capacitively (see figs. 2-3 and 2-4).

One of the problems, then, is that single reference grounding that uses this common PCB bus as the reference, begins to have a problem with more than just the shared impedance of the bus.

Almost any book you pick up on grounding makes you concerned about the impedance of this common PCB trace, which indeed is a real impedance. But it's nothing compared to the problem of loop-to-loop coupling in high-speed logic swings.

We cannot live with this excessive loop luxury. We find, as the speeds go into shocky speeds of 5 nsec and faster, that you cannot use two-sided technology in this form if you're really doing fast number crunching. You have to consider transmission lines as the way to solve this problem.

The next figure is a case of capacitive coupling. When we look at the first signal and relate it to what gets induced in the second signal, we see from capacitive coupling this type of induced waveform. However, if we look at the equivalent in inductive coupling on the other figure, we begin to see ringing pulses. We can see ringing effects at any time because circuits are usually not properly terminated impedance-wise in most logic boards, especially on two-sided PC boards. It would be very difficult to do that.

We're now going to look at this type of coupling and ask ourselves if we are well protected against this type of coupling phenomena. In light of the threat sources on the aircraft, can we expect a hardened system? To add insult to

injury, we don't have just one noise source. Another serious problem that we have been investigating recently is logic-to-logic coupling. Cables that rely on multitwisted pairs or gross shielded pairs to transfer digital data are beginning to have some serious problems in the region of interaction of logic to logic. Especially if the logic is out of sequence so that you have noise blips on the normal wave form.

Couple this with a lightning strike, or with some other potential transients like ESD or an operating dc motor, and you get a composite threat. Or you can get a composite threat if the phases are properly added together. If this occurs, we have to worry about budgeted noise so that we can no longer accept every incident that happens on an aircraft as being divorced from any other incident of noise. If we already have a high amount of noise built into our logic circuit, then when we get a slight transient on the line the opportunity of exceeding our dc noise immunity is much higher.

As a consequence, interaction can now occur at even less amplitudes of threat than if the system was durable to begin with and had a very low noise-to-signal ratio in its normal data transfer. So now there is the possibility of interacting noise causing a composite threat to the system when we look at it in terms of time duration.

This may mean that as designers and as system integrators, we may have to concern ourselves with noise budget allocations. We may have to limit the maximum induced noise due to ESD separate from induced motor noises compared to the normal level permitted on the data bus itself. This could create new problems in terms of measurement. Some form of test modifications may have to be considered, to address this potential threat.

Now if we have these threats, what can we do about them? What are some of the options available to us? One of the options is analysis.

There have been many models, studies, and dollars expended attempting mathematically to predict the phenomena. And the models are getting pretty good in their ability to accurately assess the situation. So that if we know certain threats exist on an aircraft, the power bus, the I/O cable, the fuselage, wherever they occur - and know what their intensities are - we can mathematically analyze the probability or the levels that will be induced into given cables.

We can begin to look at these levels of inducement, compared to the logic families built in noise immunity or the 429 digital bus. Now we can look at the potential threats in this particular fashion. We can also look at the capacitive and inductive crosstalk mathematically. If we know the intensity, we can look at amps-per-meter threat of the lightning, and we can then couple that into circuits mathematically.

The models may not be perfect but they are excellent as far as telling us that we have no threat at all, meaning that the mathematical assessment shows us with no threat into a particular cable. Or they can tell us if we have an obvious threat. Perhaps we have exceeded the noise threshold by 600 V. Well, that would be an obvious threat to digital electronics and we would have to do something about it.

The analysis may tell us we're in a gray area; we simply don't know if a problem will occur. The answer could go either way -- and then you can go to Las Vegas and get the outcome!

Better yet, you can devise a test and concentrate on those areas of risk rather than solving all areas of risk by methods of testing.

The computer models can weed out a lot of problems that don't need our attention so we can concentrate on those areas that do.

A few years ago I had the privilege of being on an audit team on a rather sophisticated airplane that is now flying. One of the concerns of the audit was the mathematical tools that had been used to determine potential areas of concern. A well-known computer analysis package aimed at the system level had been used. I think they had analyzed the crosstalk of some hundred thousand wire segments, which was a tremendous amount of analysis.

The interesting thing was that after they completed the study, 90% of the potential crosstalk situations had no problem at all. Only 10% had problems.

This type of analysis or assessment would give us the ability to concentrate on the areas of real concern and not bother with things that are usually no concern at all. We can better use our resources and our money to investigate those particular areas of concern. And I think that is one hope we have for analytical methods of evaluating systems.

Someone might come up with a new widget and claim that if you use this widget, all of your problems will go away. You see this in the commercial papers all of the time; you read about little magic boxes. If you plug your power cord into these magic boxes, no more problems from transients or lightning or anything else. We all look for that cure-all.

It may be that's not the problem at all. The whole problem may be that the operator had discharged to the keyboard and wiped out the entire computer, and the problem had nothing to do with power. But you might feel good if you spent hundreds of dollars on this widget. You know that there is that concern. Can we mathematically say that a given widget will not solve the problem? If we could, we could save resources.

I think the power of analysis is to free us to best use our resources in studying problems that really exist as opposed to ones that we think could exist. It's to focus on an area where a problem really has a high probability of existing.

Then we like to talk about some of the basic things we see as an industry. As far as design techniques, what are some of the things you look for? If you were given a computer, is there anything you could make an opinion on? Is there anything that you could look at and say, "that looks great," or, "this really concerns me."

We're going to share some of the things that we have found out, areas of concern, and use them as a way of evaluating designs. A checklist gives one the opportunity to ask questions of the manufacturer or the integrator as to what are they going to do about potentially high risk designs.

If someone hands you a box and it's all plastic, or all fiberglass, or all composite — or we have a computer with fiberglass, instead of aluminum everywhere, would you be concerned? Certainly you would.

You would worry about the shielding. How do they handle it? Maybe the manufacturers will say they flame-sprayed the inside, and therefore it has the same or similar shield qualities as the original aluminum. Maybe that's the right answer. Then again, the material might flake off in flight, fall down into the electronics, and cause a short. That's another issue, but those are things we want to be concerned about.

I think we can learn a lot from the commercial end of the business. They try to build many computers out of plastic. Most of them have not succeeded, but some have. I think we can learn a lot from the failures and successes. Analysis can lead us to design techniques. By using analysis, experience, and test data, we can find out what we want to know from a design point of view. Digital cables with shielding grounded at one end can just about be guaranteed to be a problem to you. How do you solve it?

We had a test done recently by a reputable company in which they took two computing devices, interconnected the data cable between them, discharged to the first box a 10,000-V static discharge, and meticulously measured the induced voltage across the gate inside the second box. They happened to use a shielded ribbon cable. (They've produced an excellent paper on the results.)

One of the things they found was if they shielded the entire length of the cable, and grounded the shield at one end with no lead exposure, and didn't ground it at the opposite end with no lead exposure, they measured 600 V induced across a 100-ohm load.

Then they grounded both ends, and the 600 V reduced to 0.4 V. Pretty impressive numbers.

Could they have done the same thing with capacitive shield termination? Certainly. Although the paper didn't get into that, conversations I have had with the author have indicated that's an excellent solution, also.

So we have to now rethink some of these areas. Analysis and experience can be very useful, and we'll get into some of these areas and discuss them.

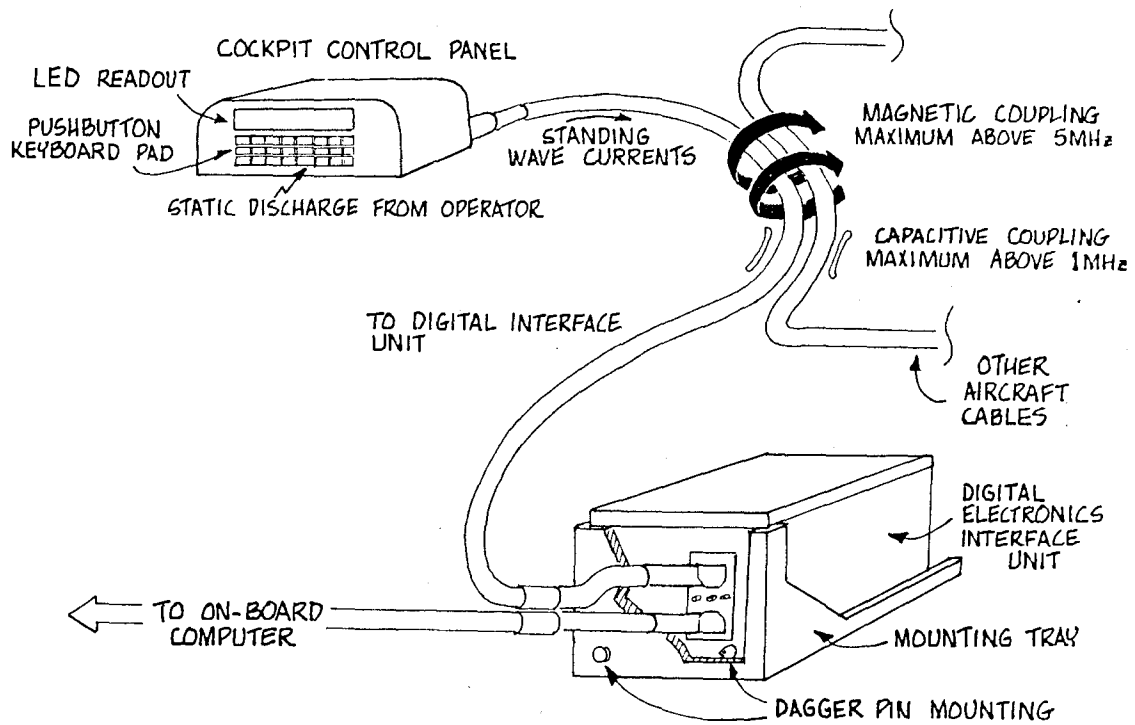


Figure 2-1.- Example of concerns for digital avionics.

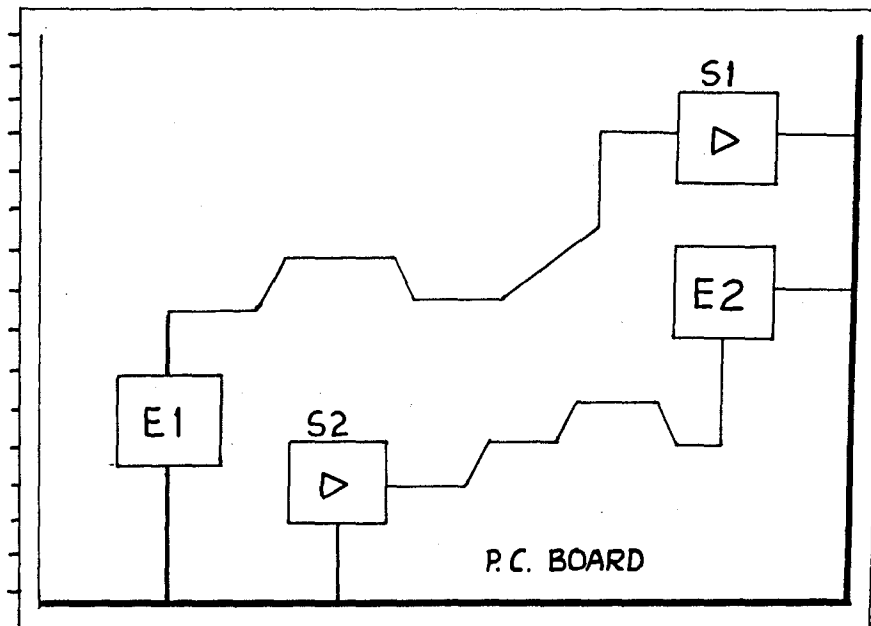


Figure 2-2.- Example of PC board layout problems.

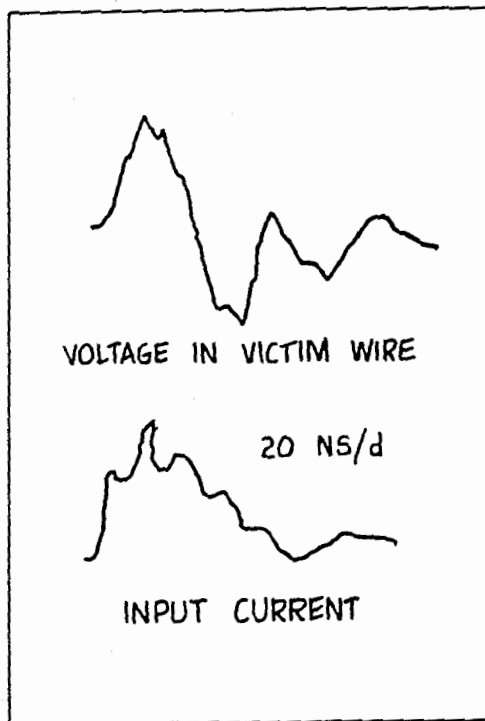


Figure 2-3.- Response to predominant capacitive coupling.

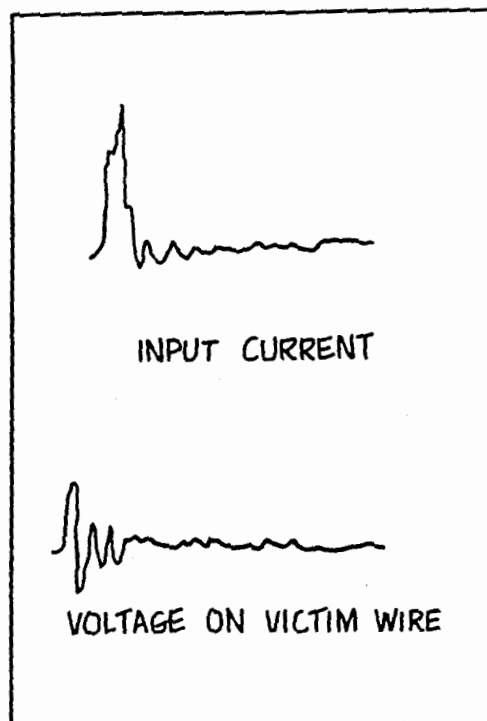


Figure 2-4.- Response to predominant inductive coupling.

EMI SPECIFICATIONS

Keith M. Kalanquin

The Boeing Company
Seattle, Washington

MR. STAN SCHNEIDER: I'm going to introduce the next speaker. I have worked with him for many years, perhaps 15 or 16 yr, and until recently I didn't realize how extensive his experience in EMI was. He was involved as the EMI lead engineer in the 707, 727, KC-135, 747, the SST, and more recently the 757 and 767. On these two new programs, he is also the Designated Engineering Representative.

In addition, he serves as a Boeing member on the Radio Technical Commission for Aeronautics, Committee 135, which put together the DO-160 document.

An individual who is known by many of you, I'm proud to introduce Mr. Keith Kalanquin.

MR. KALANQUIN: I was asked yesterday morning if I would give a dissertation on the comparison of our EMC document, D6-16050, and RTCA document, DO-160. As Stan mentioned, I was active on the RTCA Committee that updated DO-138 to DO-160, and I am familiar with it.

Before I go into that, I would like to introduce you to a few of the EMC fellows I have worked with at the Boeing Company during my time with the company. All of them I'm proud of. On the 767-757 program, Mr. Cliff Clarke and Mr. John Walls worked with me.

Going back a long time, I have been associated with Mr. Sy Young. We have been together for about 22 to 25 yr.

There is another member of the group I don't see here today. That's Mr. John Tinner, who supports the 707, 727, and 737 programs. He and I have worked together for a long time. We have all worked for Mr. Earl Jobe who is now retired from Boeing. This is a very fine group of people to have been associated with and I hope I have supported them as much as they have supported me.

I would like to say just a few words about DO-160. You have to recognize what the purpose of DO-160 is in comparison to our document.

We build a lot of equipment for our commercial transports that is designed solely for our transports. We apply different requirements to that equipment, and we should have the ability to do that.

The communication and navigation equipment on the airplane is made by many different equipment manufacturers and is used on many different aircraft. That equipment is designed to DO-160 and is licensed by the FAA to Technical Standard Order (TSO). The majority of that equipment stays within defined areas of the fuselage.

Consequently, you will find that some of the radiated levels that are in DO-160, or some of the susceptibility levels that are in the document, will appear to be quite low compared to levels specified for the outside environment. That is because the document was designed basically for the type of equipment which stays within the main fuselage's equipment bay.

This point was really brought home to me when I wanted some higher level requirements, and I cited the High-Frequency (HF) antenna coupler. As you know, on the 747 and some of our other airplanes, that coupler is located in the wing tip. You wouldn't apply the same requirements to that unit as you would to equipment which is inside the fuselage. Not only that, the equipment is generally designed for operation with a specific antenna and is designed to a requirement put out by the airframe manufacturer.

You will find that our document is different from DO-160, basically because we're covering equipment for a general requirement that allows the equipment to be located any place in the fuselage.

The D6-16050 series was originally generated in 1964 by John Tinner and myself. The -0 document is still in use on the 707, 727, and 737. It is now up to revision D.

The -1 document was written for the SST, and the -2 for the 757 and 767. The -2 document was started in about 1975, shortly after the original release of RTCA document DO-160.

The -2 document has three categories in it; table 3-1 relates to category 3 and two subcategories, 3Z and 3A. As you see, categories 3Z and 3A do provide recognition for the DO-160 document, categories Z and A. I did this because much of the equipment, the COMM/NAV equipment, is TSOed to either category Z or category A. I wanted to provide some recognition of those test levels and how we would implement those into our airplane. Categories A and Z are used by the FAA in the TSO process.

TABLE 3-1.- EMC CONTROL DOCUMENTS

D6-16050-2 Rev A 11/20/78 electromagnetic interference control requirements

- Category 3 — Provides baseline general requirement for all systems which can be susceptible to the environment
- Categories 3Z & 3A — Provides recognition of DO-160 categories Z and A; provides definition for their use

RTCA document DO-160 2/28/75 environmental conditions & test procedures for airborne electronic/electrical equipment & instruments

- Categories A & Z used by the FAA in the TSO process
 - Most BFE Comm/Nav equipment will be TSO'd
 - D6-44588 electrical requirements for utilization equipment installed on commercial transport airplanes
-

DO-160 also has one other category in the EMC area in that document, and that's category B. That's a category the general aviation industry uses for smaller airplanes.

We have another document in house that also defines electrical requirements, our power quality document D6-44588.

Table 3-2 shows some of the guidelines of how we implement our basic requirement and also the category Z and category A requirements of DO-160.

TABLE 3-2.- GUIDELINES

D6-16050-2 & DO-160 Categories			
D6-16050-2	DO-160	Length of aircraft wiring	System component locations
3	-	100 ft	All systems with components inside or outside pressurized fuselage
3Z	Z	50 ft	Prefer containment within pressurized fuselage
3A	A	20 ft	Must remain within pressurized fuselage
3X	-		Provides a definition of test requirements or environments more rigid than Cat 3. Must be specifically identified to be applicable. Lightning induced transient susceptibility is in this category

Our basic requirement on that airplane is that we would like to have the airplane wiring compatible for 100 ft. (I spent a good many years working on the 747, and it's not unusual on that airplane to find a wire 150 ft long and have to worry about its compatibility problems.) That's our baseline requirement. We want the wiring length to be compatible for 100 ft.

The category Z requirement, I feel, is compatible with aircraft wiring of about 50 ft and the category A requirement for about 20 ft.

Twenty feet, as you know, is not very long in airplane wiring, but from a safety standpoint (and that's what we're concerned about in the certification), that gives us the ability to get that system wiring out from the equipment shelf or out from behind the panel area in the flight deck to the side walls. Back to where, if you need to, you can get some space separation. And that's about what category A does for us.

From the location standpoint, the susceptibility levels of category 3, we would say we could locate the equipment outside the fuselage, providing it's not directly exposed to high-level RF fields.

The category Z requirement is somewhat lower. We would prefer it to remain within the fuselage, but on an individual basis you can make a judgment whether or not you could go outside.

The category A level of DO-160 we feel should stay inside the fuselage.

I have added one other level in the document, which I have called 3X. That's a specific test that would involve having a component directly exposed to an outside field where equipment could see a 100 V/m high-level RF-radiated field, and/or it could be exposed to lightning-induced transient.

In D6-16050-2 this table (table 3-3) shows all the test requirements in the document and identifies which requirements belong in which category.

The EMI requirements are called out for each piece of equipment that is installed on the airplane. We maintain a source control drawing written for each piece of equipment. That source control drawing will state what the equipment must comply with in the D6-16050-2 document, and it will specify the particular category. Generally, it will say it must comply with category 3 of D6-16050-2. And if it has some 3X requirements, it will list the specific paragraph.

Category 1 in the document covers only two areas, power quality and short duration. I have had trouble with paragraph 7.1, on power quality because the intent was not properly defined, and many of our equipment manufacturers have misunderstood. The intent was that the equipment should meet the power quality requirement that's specified for the equipment. If it's a motor, it should stay within the overcurrent limits or the undervoltage limits. Or if it's a system that can be susceptible, it should live within the power variation test specified for it, the high voltage limits, the low voltage limits.

MR. SMITH: Hector Smith, Douglas Aircraft. When you have a composite skin, do you specify a higher level than you would otherwise?

MR. KALANQUIN: Let me answer that question when I get to the lightning transient thing. That's where we have gotten into the composite skin area.

The only place we have wiring outside the fuselage where it sees composite structure is the leading edge of the wing. I'll cover that question with the lightning transient.

Category 1 is generally equipment that can generate only a short-duration transient, such as relays, power transformers, and that sort of thing. Category 2 is equipment that can generate only interference, such as static inverters, TR units, dc motors, and things of that nature.

The equipment that can be both a source of and susceptible to interference must meet our category 3 requirement, or we may elect on an individual basis to call out 3Z or 3A. That choice has been accomplished on certain systems within the guidelines.

The category 3 requirement differs from DO-160. We have an audio frequency beat frequency test, (para. 7.2.5) that is not in DO-160. That doesn't bother me because that gets you into a system where you have two sources of 115-V

TABLE 3-3.- APPLICABLE TESTS AND EQUIPMENT CATEGORY

Para.	Test	General guidelines					
		Prime		Cat 3 alternates			
		1	2	3	3X	3Z	3A
7.0	<u>Susceptibility</u>						
7.1	<u>Power quality</u>	X	X	X		X	X
7.2	<u>Audio frequency</u>						
7.2.1	AF conducted			X		X	X
7.2.2	AF E-fields, wiring			X	X	X	X
7.2.3	AF H-fields, wiring			X		X	X
7.2.4	AF H-fields, equipment			X		X	X
7.2.5	AF beat frequencies			X			
7.3	<u>Radio frequency</u>						
7.3.1	RF conducted			X		X	X
7.3.2	RF radiated (to 35 MHz)			X	X	X	X
7.3.3	RF radiated (to 40 GHz)			X	X	X	X
7.4	<u>Transients</u>						
7.4.1	Powerline spikes			X		X	X
7.4.2	Induced spikes			X	X	X	X
7.4.3	Bus switching			X			
7.5	<u>Lightning transients</u>						A
7.5.1	Induced ground potential				X		A
7.5.2	Induced inter-wire				X		A
8.0	<u>Interference generation</u>						
8.1	<u>Noise voltages</u>			X			
8.2	<u>Short duration</u>	X	X	X		X	X
8.3	<u>Audio frequency</u>						
8.3.1	AF capacitive				X		
8.3.2	AF inductive		X	X			
8.4	<u>Radio frequency</u>						
8.4.1	RF conducted		X	X		X	X
8.4.2	RF radiated		X	X		X	X

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power coming into the same box. We have not had that problem so much on our current airplane as we did on some of the older airplanes where you had synchros involved. I remember one incident on a KC-135; we really had a spinning top going. We had a bearing heading direction indicator on the airplane that took two sources of power. One inadvertently came from the No. 1 engine, and the other one came from the electronic bus. Part of our EMC ground test is to run engines. When we run engines, we always isolate the generators. The moment we isolated those generators, the needle on the bearing heading indicator spun like a top, as you can well imagine.

This test ferrets out any type of beat frequency problem that can occur within the equipment due to isolated generators — and we have had a few problems like that occur. We felt it important enough to continue to include in the document.

The other area that's not covered in DO-160 is the lightning transient, and I'll cover that a little later.

We also had a test that is new to our document, and that's paragraph 8.1, which is the noise voltage on signal lines. If you look at your EMI documents, you will find that you measure noise generation on interconnecting wires, either by putting a current probe around a bundle and measuring the net unbalanced current that's flowing, or you measure it with a radiating means, an antenna.

What you don't find out is, if you have a twisted pair circuit running between unit A and unit B, you don't see what kind of noise voltages you have on that twisted pair, particularly if unit A is made by one manufacturer and unit B is made by another manufacturer. These manufacturers don't talk to each other. They always come to the middleman, us, and say, "those guys are doing this to me." We had this problem on a program in the mid-1970s. I felt the problem was worthwhile addressing in the document.

What this means is that unit A cannot send noise over to unit B in excess of 300 mV peak to peak. We have only uncovered one problem of that nature on this program, and that was with a tach signal on a common shaft in a dedicated generator. The dedicated generator was supplying power to a switching regulator power supply. I don't know how many of you are familiar with switching regulator power supplies, but those things are atrocious for noise. The switching regulator was feeding noise spikes back into the generator winding. The noise on the dedicated generator circuit was then coupling over into the tach winding which was on a common shaft.

The problem was uncovered with this test, and the equipment manufacturer called us and said, "Hey, Boeing, how do you feel about that?"

We said, "Fix it. You have to meet the requirement. Do whatever you need to fix it."

They ended up designing a filter to eliminate the noise on the tach signal. Since the tach signal fed four different units on the airplane, it was impossible to state whether there would be a problem.

We've got one other set of generated test that's different from DO-160, and that's these two audio frequency tests. The AF capacitive test, we have had in the EMC document since about 1970, when we released revision C of our old document. It's been a good test, but we have not uncovered any real problems with it. In the -2 document I elected to show it as a special test where we could call it out if required.

The AF Inductive Coupled Test has been a good test. I like it particularly because what you record for this test looks exactly like the wave forms on the airplane and you can obtain very decent correlation.

The two generated radio frequency tests are the same as DO-160. When we revise the document, we will make it the same as the DO-160.

I'll show you a little bit of the differences between these various tests of ours and the DO-160.

MR. ISTWAN: Dale Istwan, Airline Pilots Association. Is your transient test under susceptibility and the voltage test essentially the same procedure called for in DO-160A?

MR. KALANQUIN: Yes.

MR. ISTWAN: Was any consideration given toward the rise time constraints of the DO-160A test in terms of digital rise time? And also I think in the DO-160 test specification, the test is not independent from the power supply source impedance or the coupling length between the supply and the inductive coupling in the transient. I just wondered if that was looked at in your document?

MR. KALANQUIN: Let me see if I can answer your question when I get to that.

This (fig. 3-1) is the audio frequency electric field test category A of DO-160. It's a 1200 V-ft test. The Z level is 6000 V-ft. What you do is divide 115 V or 120 V and you obtain the length of the coupling.

The reason I said that category A is good for about 20 ft of coupling is because you have a certain distance from where you leave your disconnect panel until you get back to where you're common with other wiring. You normally have from 1 to 5 ft before you get into common wiring. I utilized this thought when I said the A level is probably good for 20 ft of coupling. The Z at 50 ft of coupling is the 6000 V ft divided by 120 V.

The basic requirement we would like to see all equipment meet is a 12,000 V ft coupling level, which is 120 V times 100 ft. Scaling down on a line to 15 KHz at a 6-dB slope. You might say that is somewhat high, but yet on the other hand you see some equipment manufacturers who like to operate LVDTs and RVDTs at 1800 and 3500 Hz, where they get more sensitivity.

In DO-160, the audio frequency magnetic field (fig. 3-2) has a 60 A-ft requirement for category A, and category Z has a 100 A-ft requirement with a scan to 15 kHz. Our requirement is 400 A-ft at 400 cycles.

If you look at most of the power quality documents, you'll find a requirement for any load over 500 V-A to be three phase. This gives a maximum single phase load current of about 4.3 A. That's what we used to establish our 100-ft baseline — a 500 V-A requirement for a load, or approximately 400 A-ft.

For our general scan requirement we backed off to 200 A-ft at 400 cycles and came down on a linear slope. This when coupled into a single point or structure return circuit would induce about 250 mV rms, at 40 Hz and the general scan would induce about 125 mV rms as a constant.

We call out (table 3-4) a conducted RF susceptibility test, and you will see that we have a couple of differences from DO-160. One, we pick up the range from 2 to 30 MHz at a higher level. Category A is at 10 mV, Z is at 100 mV, and our own requirement is a 500-mV level. That is to take into account High Frequency Radio transmissions on the airplane.

TABLE 3-4.- RADIO FREQUENCY SUSCEPTIBILITY TESTS

7.3 RADIO FREQUENCY SUSCEPTIBILITY TESTS**7.3.1 RADIO FREQUENCY CONDUCTED SUSCEPTIBILITY TESTS****7.3.1 Requirement**

The equipment shall comply with the applicable equipment performance standard when the following RF signals are coupled onto the power input leads or associated interconnecting wiring. The required RF level is the unmodulated level prior to being amplitude modulated at the percent modulation given with either 400 or 1000 Hz. The method of coupling shall be as described in figure 7.3.1(a) or 7.3.1(b).

Frequency	Signal level: MV-RMS/% Mod.				
	Power lines			Wiring	
	Cat. 3	Cat. 3Z	Cat 3A	Cat 3Z	Cat 3A
15 to 50 kHz	None	None	None	100/30	10/30
50 to 100 kHz	100/30	None	None	100/30	10/30
0.1 to 2 MHz	100/80	100/80	10/80	100/80	10/80
2 to 30 MHz	500/80	100/80	10/80	100/80	10/80
30 to 150 MHz	None	None	None	100/80	None
Applicable figure	7.3.1-A	7.3.1-B	7.3.1-B	7.3.1-A	7.3.1-A

7.3.1.2 Test Procedure

For the RF current probe coupled test of figure 7.3.1(a), the RF signal shall be established in the one turn loop with an RF voltmeter. For the LISN of figure 7.3.1(b) the RF signal shall be established at the RF input to the LISN. The system shall be operated in each of its operating modes, including mode switching. The test procedure shall be as follows:

- (a) Wire bundles may be tested in sections if the current probe will not fit around the complete wire bundles. Chassis or circuit grounds not normally routed with the interconnecting wiring shall be measured individually and shall not be included in the wire bundle under test. Power ground return leads shall not be placed in the probe with a power input lead.
- (b) Set the signal source for maximum output with required modulation, and slowly scan from 15 kHz to 30 MHz. At those frequencies where a response is noted, reduce the signal source output and determine the threshold of susceptibility of the power lead or wire bundle and determine compliance during mode switching. If no susceptibility is evident, compliance during mode changing shall be verified every 3 MHz. When a response is found on an interconnecting wire bundle, probe each wire in the bundle separately to determine the susceptible wire(s). Threshold susceptibility data is desired for any wire whose threshold is less than 1 V. Corrective action is only required when the threshold is below the required level. Record and include in the test report the threshold of susceptibility data (frequency, amplitude and description of response).

I was working the SC-135 committee and the DO-160A revision. I looked at all of the problems that we had on the 747 with HF susceptibility and found that with one exception every problem we had was with wiring that went out to the engine for engine instrumentation. The N-1 tach transmitter, the EGT-S — there were about six circuits we had problems with.

Once inside the fuselage, we didn't have any real problem. We had one minor problem from a tape machine. I feel that inside the fuselage where you have a good metallic shielding the 100-mV level is adequate.

We had a number of problems early on where we were using a 10-mV level. I feel 10 mV is too low. RF susceptibility does create some problems with specific systems, not necessarily digital, particularly in the low frequency range up to 2 MHz. Your ADF receiver is probably the most sensitive system in the airplane, and it has a difficult job meeting that requirement. Normally we have to give it a fair amount of space separation. For the radiated susceptibility (table 3-5) in the 15- to 35-MHz range, we do our tests differently than category A and category Z do, and it's difficult to compare these levels. This is the first place my X category shows up and is required to meet a 10-V requirement, where our standard category 3 is a 300-mV requirement.

MR. CHRISTENSON: Neil Christenson, FAA, Fort Worth. In your comparison operation, are you using DO-160 or DO-16A as the comparison document?

MR. KALANQUIN: These comparisons are DO-160. In DO-160A this level has gone to 500 mV. And I don't think radiationwise any of these levels change. I would have to confirm that.

MR. NELSON: Lauren Nelson, Eastern Airlines. You mentioned that you had a problem on the 747 when the HF was interfering with the engine instrument where the wires went along the wing. What was Boeing's approach to resolving that?

MR. KALANQUIN: We resolved every one of those problems by circuit redesign or a change to the installation.

MR. NELSON: Not by shielding and grounding the wires going to the engine?

MR. KALANQUIN: That's right. It was a circuit redesign or a local installation change. In the case of the N-1 tach transmitter, the resolution was by shortening a dc ground that was on the airplane.

MR. NELSON: Are any of them requiring the redesign of the black boxes?

MR. KALANQUIN: Yes.

MR. SMITH: Hector Smith, Douglas. We had a case where the flight guidance computers are interfering with the VOR. If all of these boxes qualified for the DO-160, do you feel that the levels from these transients would take care of some of the problem, or is there any problem of revising the DO-160A document?

MR. KALANQUIN: The SC-135 committee is presently inactive. It has never been disbanded. The last meeting SC-135 had was about 3 yr ago, and the intent at that time was to review the DO-160 requirements in about 5 yr to see what areas needed to be updated or improved.

TABLE 3-5.- RADIO FREQUENCY RADIATED SUSCEPTIBILITY — 15 kHz TO 35 MHz

7.3.2 RADIO FREQUENCY RADIATED SUSCEPTIBILITY — 15 kHz TO 35 MHz7.3.2.1 Requirement

The equipment shall comply with the applicable equipment performance standard when exposed to a radiated RF field established in the following manner. The RF level is the unmodulated level prior to being amplitude modulated at the percent modulation given with either 400 or 1000 Hz.

Category 3X and 3: The field is established by a parallel stripline as shown in figure 7.3.2(a). The signal level specified below is measured across the stripline load.

Category 3Z and 3A: The field is established by a single turn 3-in. diam loop probe located within 1 in. of the equipment as shown on figure 7.3.2(b). The signal level is obtained using an appropriate signal generator, loaded into 50 ohms, and set for the output specified.

Frequency	Signal level: MV-RMS/% Mod.			
	Cat 3X	Cat 3	Cat 3Z	Cat 3A
15 to 100 kHz	None	None	10/30	10/30
0.1 to 35 MHz	10 V/80*	300/80*	10/80	10/30

*This is the stripline voltage

7.3.2.2 Test Procedure

Category 3X and 3: Set up the equipment as shown in figure 7.3.2A with special emphasis on placing the test sample as much to the center of the line as possible. The equipment shall be tested at a minimum of two orientations: upright with the front face directed out toward the side of the line, and upright with the front face directed along the length of the line.

Check each mode of operation for a susceptible response as the signal source is swept slowly across the required frequency range with the level maintained above the limit. At any frequency where susceptibility is noted, reduce level to limit and determine compliance for each mode of operation and while mode switching.

Category 3Z and 3A: The typical test setup will be similar to that of figure 7.3.2(b). The loop probe is placed in close proximity (approximately 1 in.) to the point of maximum susceptibility of equipment under test. (The antenna input fitting is shown in figure 7.3.2(b), as an illustration of a point of maximum susceptibility.) Care shall be taken to insure that all sides of the equipment under test, including the top and bottom, are adequately probed at the critical frequencies to determine the point of maximum susceptibility. The entire frequency range shall be scanned in each mode of operation. At any frequency where susceptibility is noted, compliance during mode switching shall be verified.

MR. SMITH: When are you going to do that?

MR. KALANQUIN: That's not really up to me to say. That's up to RTCA to decide when they get enough inputs from industry to reactivate the committee.

MR. SMITH: We'll give it to them.

MR. KALANQUIN: That's what you need to do. As a matter of fact, I have a few things I would like to see changed, too.

Here (fig. 3-3) is the reason that our RF radiated test procedure cannot really be related to the DO-160 test procedure in a low-frequency range up to 35 MHz. We do our test with a stripline, and the 300 mV peak-to-peak requirement that we have represents about 0.5 V/m. The 10-V requirement for the 3X category is in the neighborhood of 20 V/m.

The DO-160 does a test with a 3-in. probe, and you have to run that probe around the box looking for the most susceptible area.

From a test investigation standpoint, it's a good test. But from a qualification standpoint, it's a poor test. It is difficult for the equipment manufacturer to determine that at all frequencies he has the most susceptible location on the box. We couldn't agree on a different test procedure for DO-160. Therefore, SC-135 stayed with the procedure of the earlier document, DO-138.

CAPT. VOGEL: Ray Vogel, Air Force Aeronautical Systems Division. Are these tests to be conducted in a shielded room, or is there a requirement for an anechoic chamber?

MR. KALANQUIN: There is not a requirement in the commercial EMC spec to do it in the anechoic chamber. They are done in a shielded room. You're addressing reflections, right?

CAPT. VOGEL: Yes.

MR. KALANQUIN: With respect to reflections, if industry required that the equipment manufacturers do all of their testing in an anechoic chamber, we have put a real cost burden on them. That's the other side of the story the commercial group worries about.

Up to now we haven't had a real need for that. But I'm not going to say it's not coming. I think there are some areas that I have seen the last year or so which indicate you probably do need to worry about reflections.

For radiated radio frequency, about 30 MHz (table 3-6), we have a high-level test of 100 V/m that we require on certain equipment. On the 767 we applied that requirement to our proximity switches located on our landing gear because during the landing approach those switches become exposed to some very high level fields.

For example, flying into Heathrow when the winds are in the wrong direction from the normal pattern, you land right over the top of their GCA radar, which operates at 600 MHz. This exposes your equipment to a field of that order of magnitude.

TABLE 3-6.- RADIO FREQUENCY RADIATED SUSCEPTIBILITY -- 35 MHz TO 40 GHz

7.3.3 RADIO FREQUENCY RADIATED SUSCEPTIBILITY -- 35 MHz TO 40 GHz7.3.3.1 Requirement

The equipment shall comply with the applicable equipment performance standard when exposed to a radiated RF field established by a 50 ohm generator driving the specified antennas at the required levels as shown below. Except for category 3X, the RF signal shall have 400 or 1000 Hz modulation at the minimum percent modulation given.

Frequency	Signal level			
	Cat. 3X	Category 3, 3Z and 3A		
		Unmod. level	Mod.	Antenna
35 to 400 MHz	100 V/m min.	fig. 7.3.2(a)	80%	1/2 λ dipole
400 to 1000 MHz	100 V/m min.	fig. 7.2.3(a)	30%	1/2 λ dipole
1000 to 1215 MHz	--	fig. 7.2.3(a)	30%	Horn
1 to 40 GHz	100 V/m min.	No requirement		

For category 3X, the method of achieving the required field strength (antenna type, power source and monitoring method) shall be defined in the EMC Test Procedure/Plan. Use 400 or 1000 Hz 80% AM modulation to 400 MHz. Above 400 MHz, the same modulation may be used; however, pulse modulation with a PRT of approximately 1 msec and a PW of 2-5 μ sec is preferred.

7.3.3.2 Test Procedure

The typical test setup is given in figure 7.3.3(b). A typical test procedure is as follows:

- (a) Set the RF signal generator for maximum output with the required modulation and slowly scan the frequency range 35 to 1215 MHz. Dipole antenna length may be adjusted for the center frequency of each of the following bands for this scan: 35-100, 100-150, 150-300, 300-600, and 600-1000.
- (b) At each frequency where a response is noted, adjust the dipole to the correct length and adjust the signal generator to provide the required level. Determine compliance with the applicable performance standard.

The (fig. 3-4) RF requirements of DO-160, as represented by categories 3Z and 3A are low. At the time we worked the DO-160 document and I communicated with Lockheed and Douglas, none of us had any particular concern about RF radiated susceptibility provided the equipment met the RF conducted susceptibility requirements. Other areas of the document were more important, and we didn't really push for raising this level in DO-160, even though we were running our

own susceptibility tests at a much higher level. It was just that radiated susceptibility tests in that frequency range were not the real problem on commercial airplanes.

We require (table 3-7) the same powerline spike tests that DO-160 does, but the spec is slightly different.

TABLE 3-7.- TRANSIENT SUSCEPTIBILITY TESTS

7.4 TRANSIENT SUSCEPTIBILITY TESTS

7.4.1 POWER LINE SPIKE SUSCEPTIBILITY TEST

7.4.1.1 Requirement

The equipment shall comply with the applicable equipment performance standard when its power input leads are subjected to the spike waveform of figure 7.4.1(a). The equipment shall be subjected to both positive and negative spikes and a minimum of 50 spikes shall be applied within a period of one minute.

7.4.1.2 Test Procedure

A typical test setup is shown in figure 7.4.1(b). The spike generator is adequate; however, other methods of generating the spike may be used if the waveform complies with figure 7.4.1(a).

The spike waveshape shall be verified with the equipment under test disconnected and S2 open. Adjustment is made with a 0-350 V dc supply. With the equipment operating at its design voltage(s), apply to each primary power input a series of positive and negative spikes. Apply 50 spikes of each polarity within a period of one minute for each polarity.

7.4.1.3 Designer's Note

The spike used in this test is a simulation of one arc-over of the typical inductive switching transient that occurs when either ac or dc inductive loads are deenergized. For the purpose of this test, this simulation is considered adequate; however, the complete inductive switching transient is as illustrated in figure 7.4.1(c).

The occurrence of these spikes on the aircraft are infrequent and occur on those systems whose operational states are changed once or twice per flight. Because of the infrequency of this spike the design engineer should note that the minimum design requirement is that the equipment shall not experience component failure and shall not have a response detrimental to aircraft safety. Unless otherwise directed by the applicable performance standard, the equipment may respond to the spikes, provided that normal operation automatically resumes upon cessation of the spikes, and provided that there are no visual or audible responses which will cause flight crew complaints or passenger concern.

We require that the equipment meet its applicable performance standard when it's subjected to the transient. DO-160 says that you subject the equipment to the transient, and after the transient is complete you determine compliance.

The difference is that if a glitch occurs during a transient, we want to know what it is so we can assess whether we want that type of a glitch on the airplane.

DO-160 simply says that when the transient is complete you must not have changed state. It cannot go off somewhere to an extent that you have to do something manually to restore it.

The problem with these types of spikes is that when you see them on the airplane there are many of them that you can tolerate. But what you don't want to tolerate are those transients that cause the equipment to stop performing its function so that the flight crew has to take manual action to restore it. Both DO-160 and our document say the same thing in that regard, if you really interpret DO-160 the way it's written.

Here's something that clarifies this a bit. Sometimes the equipment documents don't really say what the requirement is. In the -2 document, we elected to include what we called designer notes, which is just a little explanation of what the requirement is all about. This sentence here states that, "Unless otherwise directed by the applicable performance standard, the equipment may respond to the spikes provided that normal operation automatically resumes upon cessation of the spike and provided that there are not visual or audible responses which may cause flight crew concern or passenger concern."

That's the minimum requirement. But if a response occurs, the equipment manufacturer has a requirement to tell us what the response is so we can decide.

The passenger concern area comes up on some of our other airplanes -- where a transient would cause the chimes to sound. The correction we put into the airplane was very simple. It was just two capacitors to slow the transistor down.

On the interconnecting wire (fig. 3-5) we also require a transient test, and this is the same test that's in DO-160. A gentleman asked me about the rise time of the power line spike. That pulse, I believe, is supposed to be 100 nsec. DO-160 reduced the transient duration from 10 μ sec to 5 μ sec as a result of inputs from other people.

MR. ISTWAN: Dale Istwan, Airline Pilots Association.

That is the consideration; whether or not the rise times are conservative enough from the standpoint of susceptibility of digital equipment. In terms of the analog systems, it is certainly very conservative.

The other point I would like to look at is the requirement for setting up and verifying the wave form. We do that with the source short-circuited, and then of course the actual test is conducted with the source on-line.

I have often wondered why there is not some sort of a consideration with respect to the overall change in the impedance and the load on the spike generator between preliminary setup and the actual test.

Should the rise time be changed in subsequent revision of DO-160A? Then, also, the supply line length between the supply and the induced transient coupling

becomes somewhat more critical because we could adjust that length alone; for example, to have quarter- or half-wave length multiples there and dramatically affect what the outcome pulse is in the equipment or test. It seemed to me there was room for improvement in this particular test.

MR. KALANQUIN: I don't have that particular test. But that wave form generator is set up for 600 V open circuit, and it is defined as a 50-ohm source impedance, and they do say in that section if you put 50 ohms across it, it should drop to half value.

MR. ISTWAN: I think it specifies load impedance and the dummy for load impedance, but there is no specification in the source impedance. I'm talking about in the supply.

MR. KALANQUIN: The transient source or the power source?

MR. ISTWAN: The power supply.

MR. KALANQUIN: That, I believe, is shorted out by a capacitor, if I'm not mistaken, in the transient generator, either 0.3 ufd or 1.0 ufd capacitor. I'll have to look at the circuit.

There was another thing that you mentioned about the adequacy of this test with digital equipment.

I have had some concern myself about that power line spike. It is just one spike, and I have had some concern that it is not adequate. This (fig. 3-12) is also part of the designer note that's in the document. If you look at a regular inductive transient, and you stretch the thing out so you could really see it, it would look something like what is shown here. The total time can be anywhere from 50 to 1000 μ sec. Typically the figure 3-5, category 3 relay will generate a transient in the neighborhood of 200 μ sec.

The 10- μ sec transient is generally derived from the fast rise time. It's a little slower than this rise time and I think that's one of the reasons why some people wanted to decrease the time to 5 μ sec.

My concern was that this power line spike would not give you the same response as this longer duration with a full string of spikes.

Whenever we had a piece of equipment in the lab for an EMI evaluation, on the 767-757 program I place a sign on the inside of my screen room door that tells my technician for power line spikes to run three transients. First, you run the normal power line spike and see if it passes. Then the full-duration spike test and finally we have run a test which couples it very close for 75 ft. We didn't have an opportunity to test a great amount of equipment, but I found in all of the testing only one system that the power line spike was not adequate. I still have a concern in that area.

MR. ISTWAN: Was that digital equipment?

MR. KALANQUIN: Yes.

MR. CINCOTTA: Joseph Cincotta, FAA. In the testing of the 767, we are experiencing some reaction to the EICAS messages. Yet we find no problems on the systems, but

the maintenance pages are coming up with alerts. Has this been looked at as a transient response?

MR. KALANQUIN: Yes. We have a lab over in Renton that's called a Digital Avionics and Flight Controls Laboratory, where all of the digital systems for the 767/757 have been interfaced in an operational situation with a Harris computer and an Eclipse computer. They can fully operate the systems over there. They have the EICAS, the EFISs, FCC, the Thrust Management Computer, the whole works in a completely operational mode. We have been over there any number of times and run the transient tests and other tests on all of those systems. Transientwise we have not been able to show that those types of problems in EICAS are associated with any transient that we have been able to put on the system.

MR. CINCOTTA: The flight crews are not seeing any abnormalities; there's no flight tech effect. But when we call up the maintenance pages, we record any number of what appears to be malfunctions. We reset circuit breakers and they go away.

The question is, during the flight are we experiencing some kind of a transient that's tripping these alerts?

MR. PEACOCK: Max Peacock, FAA. You might want, for the benefit of those who aren't familiar with what EICAS stands for, to explain that.

MR. KALANQUIN: Okay. EICAS stands for Engine Indication Crew Alerting System. It is a CRT display on the flight deck that displays your engine parameters, your N-1, N-2, EGT, EPR, and they have a large display. They take up a major part of the CRT.

The pages he is talking about take up the caution enunciation part of the circuit, and it displays a number of functions that are of lesser priority if you call them up, and you can shift them.

You can call up your hydraulics fluid quantity on one page, and then you have another page associated with the APU parameters, your generator parameters, and I'm not sure where fuel flow and oil quantity show up. I think those show up on the status page and are presented all the time.

I don't really have a good answer to your question. I would have to get together with Cliff and the EICAS fellows and see what the real status is. There were so many of the systems that we had early problems with where the power transients would cause them to do something you didn't want them to do. Depending on the mod block status of the equipment, you almost have to know that to know what state the equipment is in and whether all of the corrections are into the system.

CAPT. VOGEL: Ray Vogel, Air Force Aeronautical Systems Division.

I'm interested in your relay transient test. How does this standard account for the differences among various relays, the fact that no two different types of relays are going to develop the same rise time of transient?

We have done extensive testing with regard to what's known as the chattering relay test in the laboratory, and we have not been able to find any similarity

even among the relays that have the same manufacturers' designation on them.

MR. KALANQUIN: I agree. If any of you are equipment manufacturers, you're going to take the other side, but from my view point, that's the beauty of the test because you can't predict what that transient is going to look like, in the laboratory or on the airplane.

Each one of them is going to be different, and the only way you can protect against that transient is by a brute force method. If you try to model that transient and say you have designed a suppression to fit that model, you have lost the ballgame.

There are so many sources of inductive transients on the airplane that you cannot suppress them. And even if you try, you have the question of how am I going to know that that suppression was there?

If you have designed your equipment without considering those transients and you put that equipment on the airplane, it will work fine until you lose one suppression diode or capacitor on the inductive transient source that will allow that transient to be generated. You won't know what is going to happen.

I understand your question. But every transient is different. And regardless of what you measure in the lab, they are going to be different on the airplane.

CAPT. VOGEL: In your opinion, would it be in error for us to choose a signal generator or some sort of a digital synthesized signal that would approximate that situation and put that out as a standard for everybody to live to?

MR. KALANQUIN: Yes. I took this test (fig. 3-5, cat. 3 setup) and I put a load on the coupled wire -- just a single wire.

I ran one test where I had it loaded with 100 ohms on either end, and I generated an idealized wave form, a sawtooth wave with the fly back when it reached the arc over voltage.

Then I increased the resistors to 1 K, which unloaded the line and you could see ringing start to occur.

You're going to see that in the airplane, depending on the length of the line and how it's loaded and what your coupling is. You're going to generate different types of ringing.

If you were to try to model this with an idealized wave form, it could be completely different than what you see in the airplane.

CAPT. VOGEL: That works well for you, as a contractor examining your own gear. But for us as the government looking at somebody else's method of test procedure, it's more difficult. You can be rigorous when you want to satisfy yourself that it works, but if you're trying to satisfy another party, then the rigorousness, the level of stress imposed on the system, is really not very well defined using that relay.

I can live with your answer. I think you have done a very good job answering. I'm satisfied. Thank you.

MR. KALANQUIN: The thing we have tried to do with that transient is to be somewhat realistic in our method of coupling. And this is how it is coupled in. DO-160A specifies more correctly what this relay is. As a matter of fact, I had almost given up hope of getting this test into DO-160. It was at almost the last meeting on DO-160 that we got this in. We were at Douglas having a meeting, and this test procedure happens to be a test procedure that Walter Forbes at Douglas used at that time.

The relay specification is for a Douglas relay, and it's a relay that in the energized position has an inductance of 1.5 H. It is a good sized inductor.

DR. MASSON: Geral Masson, Johns Hopkins.

I'm not familiar with digital avionics. When you say that you're doing testing, are you subjecting digital avionics to the transient faults?

Are you talking about digital avionics along the lines of microprocessor based devices, when you are running these programs, or are you talking about sequential circuit types of devices where there is a function that's being performed? What complexity? Are these medium-scale integration? Large-scale integration?

MR. KALANQUIN: When we refer to digital avionics, I cannot tell you what type of components our equipment manufacturers have used inside the box.

What the tests require from an EMC is that the interface tolerates the transient.

Now, how the manufacturers accomplish tolerance inside their boxes is their choice. And the type of components used inside their boxes is up to them. We have defined the system requirements to them, the EMI requirements, all the environmental requirements. How they choose to meet those requirements is their design responsibility.

If they use a large-scale integration or some other, they have got to provide us with the reliability data for this choice of design and the other things that go along with it.

If they choose a circuit board layout that addresses the loop areas that the gentleman before me addressed, that's their responsibility to design the interior of the box to live with itself.

We have defined the interface with the aircraft wiring and what that interface and that circuit configuration, as it's used in the aircraft wiring, must tolerate.

MR. TREACY: Jim Treacy, FAA.

One of the concerns we have with the digital equipment associated with the power supply is that if you have a power interrupt on a Kolman filter, you lose the storage products of the time constants on the filters. When you come back and reinitialize, all the filters are reinitialized in the wrong state although the mode of operation of the equipment may be correct. The problem is associated with the turn-on of high loads of motors particularly bus switching on the airplanes.

DO-160 doesn't really seem to address itself to that kind of a power interrupt problem, and we are forced to do that pretty much on the airplane by throwing switches and turning on loads.

Is there any activity in the works to generate a laboratory qualification test to deal with that problem, the 50- to 100-msec power interrupt problem?

MR. KALANQUIN: DO-160 covers the power interrupt in paragraph 16. It covers two power interrupts, it says they must be separated by 10 msec.

MR. TREACY: The problem is they are not very realistic of the kinds of things we see on the airplane.

MR. KALANQUIN: This would say you could have 40-msec, one interrupt at 10 msec and another at 50 msec. I would agree with you. We don't think that is completely adequate, either. That's an area where DO-160 can tolerate some changes.

Let me show you what we have done in-house (table 3-8). That requirement really got picked up in our power quality document, D6-44588. There is a paragraph for normal ac voltage transients, abnormal transients, and dc voltage transients, both normal and abnormal. We say the equipment shall perform its normal function without manual intervention for all three of those cases.

The requirement (table 3-9) is that a series of transients runs on all equipment. It's a much more extensive list than what's in DO-160.

You never known where you're going to run into a problem with these transients because, depending on how the power supply voltage decays, you could have a problem at 10 msec. In another system, it may be at 25 or 35 msec where the decay gets you into a problem. We have seen that corrections have been implemented into those boxes to correct that type of problem.

I would like to point out another paragraph (table 3-10) D6-44588 with respect to abnormal input power characteristics. These are the requirements that are applied to the equipment, even on abnormal transients: (1) It should sustain no damage and remain safe, (2) reliability and life should not be affected, and, (3) it automatically resumes normal function.

DR. MASSON: Gerald Masson, Johns Hopkins.

What does that mean, "resume normal operation or function?" I could have a program and glitch it, and after the glitch dies I would have the same program. But between the time the transient occurred and the time the activity of the transient died down, a lot of things could occur, such as storage of data and registers, memory, things like that.

By normal operation, do I understand correctly that situation cannot occur, that the system is in the same sort of sequential circuit state with all the registers and memories the same?

MR. KALANQUIN: Yes, that's the intent.

In the case of the flight management computer, it would mean that all the way points that you inserted in the memory are exactly the same.

TABLE 3-8

3.5.3.8.1 NORMAL AC VOLTAGE TRANSIENTS

On all equipment with memory devices add to the DO-160 tests the applicable normal and transfer tests in Table 3.5.3-1 (attached) except when modified by values from the analysis and/or engineering test indicated in Para. 3.5.3.8 above.

The equipment shall perform its normal function without manual interventions.

3.5.3.8.2 ABNORMAL AC VOLTAGE TRANSIENTS

Similar to Para. 3.5.3.8.1 above except:

- a) The abnormal test points in the Table 3.5.3-1 apply and the equipment shall perform as indicated in Para. 3.4.3.2 (D6-44588), plus this Para. 3.5.3.8.

3.5.3.8.3 NORMAL DC VOLTAGE TRANSIENTS

Similar to Para. 3.5.3.8.1 above except:

- a) Table 3.5.3-2 applies for Type I dc power equipment.
- b) Table 3.5.3-3 applies for Type II dc.
- c) Table 3.5.3-4 applies for Type III dc.
- d) The equipment shall perform normally without manual intervention.

3.5.3.8.4 ABNORMAL DC VOLTAGE TRANSIENTS

Similar to Para. 3.5.3.8.3 above except:

- a) The abnormal test points of Tables 3.5.3-2, 3.5.2-3 and 3.5.3-4 apply.
 - b) The equipment shall perform as indicated in Para. 3.4.3.2 (D6-44588), plus this Para. 3.5.3.8.
-

In the case of the EFIS or in the CRT displays, during the transient you would possibly see a flicker on the screen. You might say that's acceptable, it's a judgment call.

The intent is for the digital system to be in the exact state at the end of the event that it was at the beginning of the event.

MR. THOMAS: Ron Thomas, Sperry.

We have identified three areas of transients as far as what the circuit will respond to. No. 1, the internal voltages will remain to specification during the power transient; No. 2, the second type of transient will freeze everything; finally, No. 3, the third type of transient causes everything to be dropped and the circuit must power up again.

TABLE 3-9.- VOLTAGE TRANSIENT TEST REQUIREMENT IMPOSED IN D6-44588

3.5.3-1 Overvoltage and undervoltage transients for 115 V ac equipment with memory devices

Transient voltage-time test conditions					
Time duration, sec	Voltage, and transient nature				
	0 V	60 V	80 V	148 V	180 V
0.001	T	A	N		
.010	T	A	N		
.020	T	A	N		
.030	T	A	N		
.040	T	A	N		
.050	T	A	N		
.086			N		
.100					A
.200	A				
1.00	A			A	
10.00	A	A			

Do you have time durations for any of these three? We have addressed them ourselves and picked values. For instance, the first transient on the bus will not cause any change in the power within the circuit or the box itself.

MR. KALANQUIN: There are notes that go along with this table in the D6-44588 document. The T stands for bus transfers, the A stands for abnormal transient, and the N stands for normal transient. For all normal transients, the equipment would be expected to absorb the transient and remain in the same state. I think for these longer-duration abnormal transients, particularly the 1- and 10-sec transients, the equipment could shut down and repower itself up.

MR. THOMAS: During the 1-sec time period, for instance, does everything get frozen? Does it operate during that period? Does the flight control system disconnect, or does it remain on line?

MR. KALANQUIN: The first requirement is it must remain safe. Whatever it does, it must remain safe. I can't answer that. Every system is somewhat different.

We have two transients for lightning in the document, one that we call a ground potential transient (fig. 3-6). That transient was originally used on the 747 airplane, 10-12 yr ago. The thing we did for the 767 was speed up the rise time.

The other transient is what we call an induced interconnect wire transient (fig. 3-7). It's a 1-MHz damped cosine wave with a rise time specified at 100 nsec.

TABLE 3-10.- PERFORMANCE

3.4.3 Performance

3.4.3.1 Performance with Normal Input Power Characteristics

Load equipment shall meet all performance requirements of the applicable load equipment detail specifications when supplied with electrical power having normal steady-state and transient characteristics as defined by tables 3.3-1 and 3.3-3. An exception to the performance requirements is permitted during normal power interruptions (source transfers) as shown per item 2.1 in table 3.3-1 and per item 6.1 in table 3.3-3. The load equipment shall meet the requirements of paragraph 3.4.3.2 during and after the power interruptions.

The power characteristics defined in column "B" are applicable unless otherwise stated in the detail specification.

3.4.3.2 Performance with Abnormal Input Power Characteristics

When electrical power with abnormal steady-state and transient characteristics as defined in tables 3.3-2 and 3.3-4 is applied to load equipment, or when power is interrupted to any one or more of the ac or dc input terminals (with normal power applied to the remaining terminals), the equipment shall meet the following requirements:

- a) sustain no damage and remain safe
- b) reliability and life shall be unaffected
- c) automatically recover full performance capability when power with normal characteristics is reestablished at the input terminals.
- d) operate within the performance limits, if any, defined in the detail specification for these conditions.

If circuit protection is required to meet requirements a) through d), above, such protection shall be an integral part of the load equipment and shall be subject to approval by the buyer.

Again, on these transients, we have imposed the same three sets of criteria for our lightning transient requirement: (1) the equipment remain safe; (2) it remain undamaged; and, (3) it recover automatically to specified performance. Those are all of the susceptibility tests in the document.

The generation tests are contained in paragraph 8, the first one being the interference voltage on the signal lines. As I said earlier, I specified that at 0.3 V peak to peak, and required them to look at it with an oscilloscope.

In the document I tried to put a definition for short-duration interference. Any transient we have on the airplane that occurs on a repetitive basis, we require to meet the limits of the document. For nonrepetitive transient, we allow a 20-dB deviation. Any transient which occurs just once or twice per flight due to actuation or turn-on of the system, we require to stay within the power quality limit. Spike generation must stay within a ± 600 -V envelope.

This is the audio frequency inductive coupling (fig. 3-8) test setup for generation that we use. We take a standard current probe, connect it around the wire bundle, and look at it on an oscilloscope.

The Stoddard current probe, the 91550-1, in this particular test setup looks like 10 ft of aircraft wire coupling. From that you can virtually proportion it to the wire run you're concerned about. A picture from the lab, and the same picture in the aircraft, look very much alike.

Section 10 of our document defines the test setup requirements. The reason I brought this up is because we have a couple of items in it that some of our equipment manufacturers don't like or some of the testing agencies don't like. One is ground leads; power ground leads and chassis ground leads must not be less than 3 ft or more than 5 ft long.

Many of the testing agencies will make these grounds just as short as they can. If I were a testing agency I would do the same thing because in order to meet generated limits or some of your susceptibility requirements, you want to get rid of that inductance. That creates problems.

In the aircraft installation, particularly if you have looked at any of the equipment rack installations on either our airplanes or those of other airframe manufacturers, you will find that grounds are generally 3 to 5 ft long. You won't find a ground stud right behind the disconnect. It will be back at a convenient point on the back of the shelf someplace.

We have also required them to use normal aircraft wiring. I intend to make some changes to this section in the next document.

The other thing that a testing agency would not do is to put a 6-in. pigtail on a shield ground. Again for best EMI control, if you have a ground on that shield, you're going to make it just as short as you can. I have seen them less than an inch long.

From normal aircraft installation practices as we do it here, you will never see a shield ground 1 in. long. You come up to a connector, and by the time you connect a pigtail to the shield, go through a disconnect pin, and then grounds on the bulkhead side of the disconnect, you have at least 6 in. of ground wire, possibly 8 in.

In order to make our test realistic, we put in these requirements. Basically I would like to know if that shield ground or that short power ground is important to the system in order to meet susceptibility requirements or generation requirements. I would like to know if there is a firm requirement so if we need to we can do one of two things: Either we can make every possible effort to shorten that ground in our airplane installation, or we can tell the equipment manufacturers to redesign their equipment to tolerate those ground lengths.

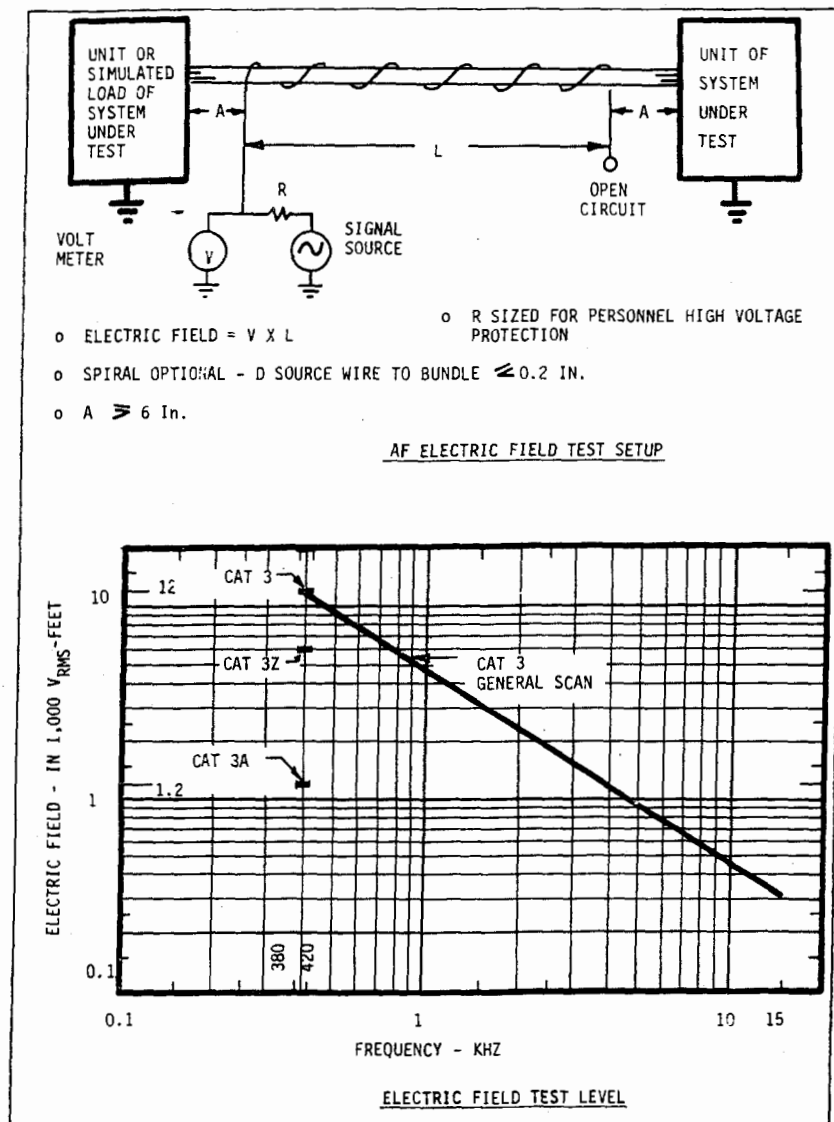


Figure 3-1

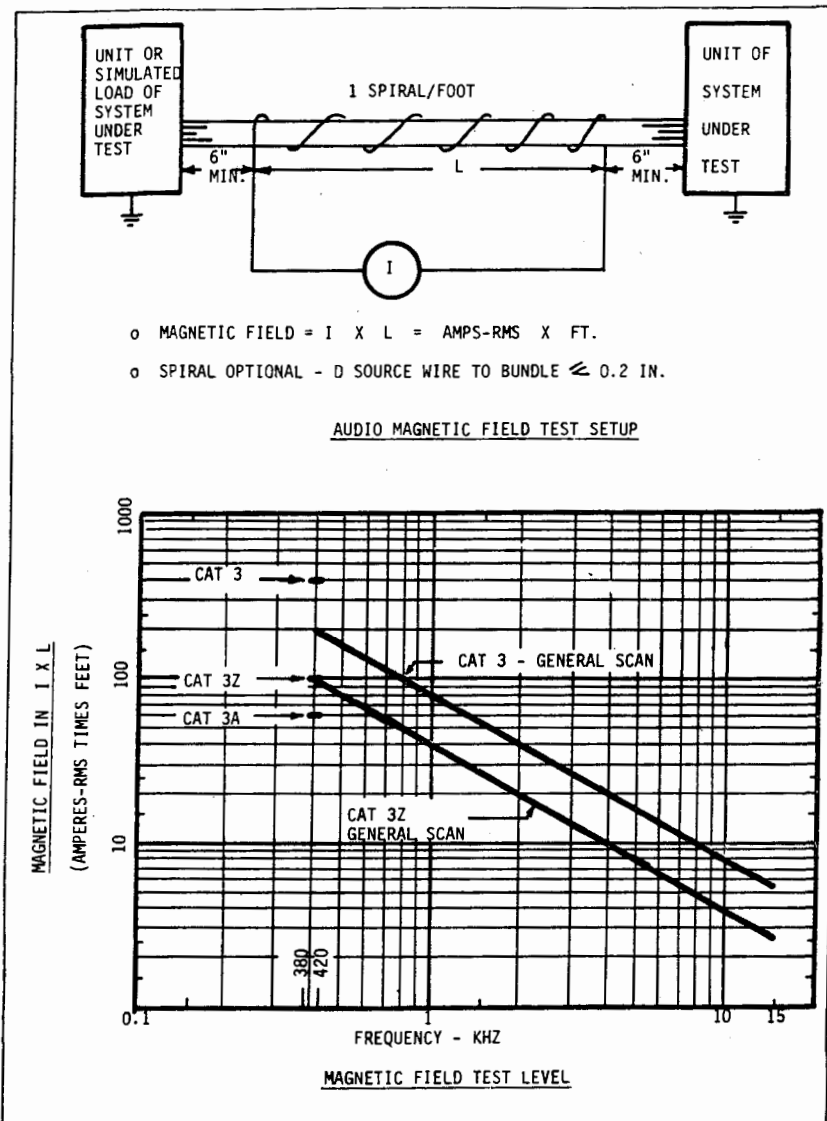


Figure 3-2

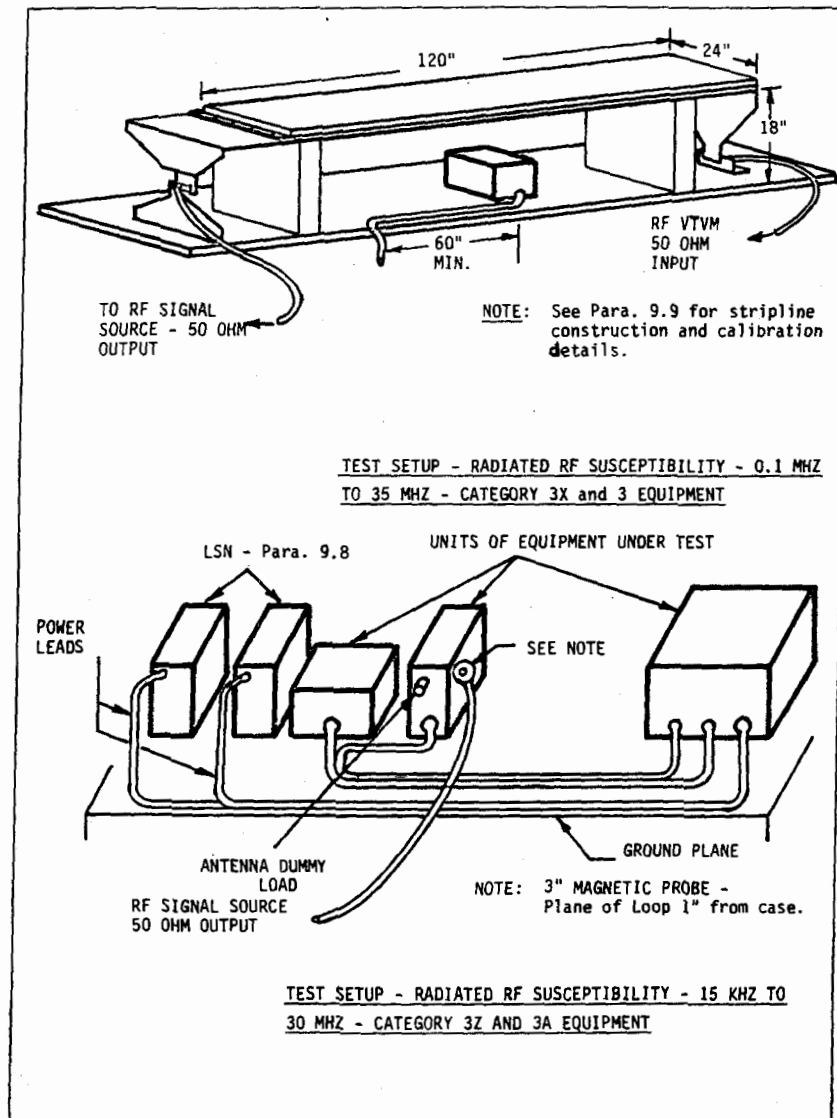


Figure 3-3

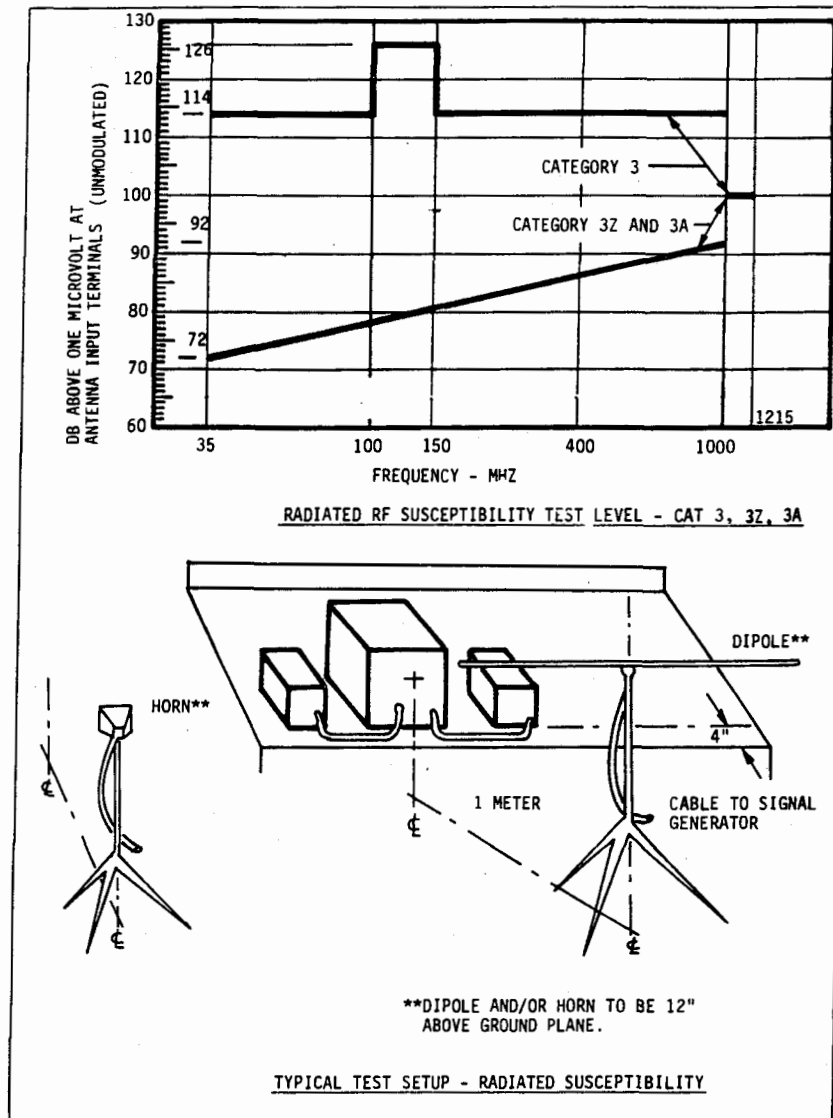


Figure 3-4

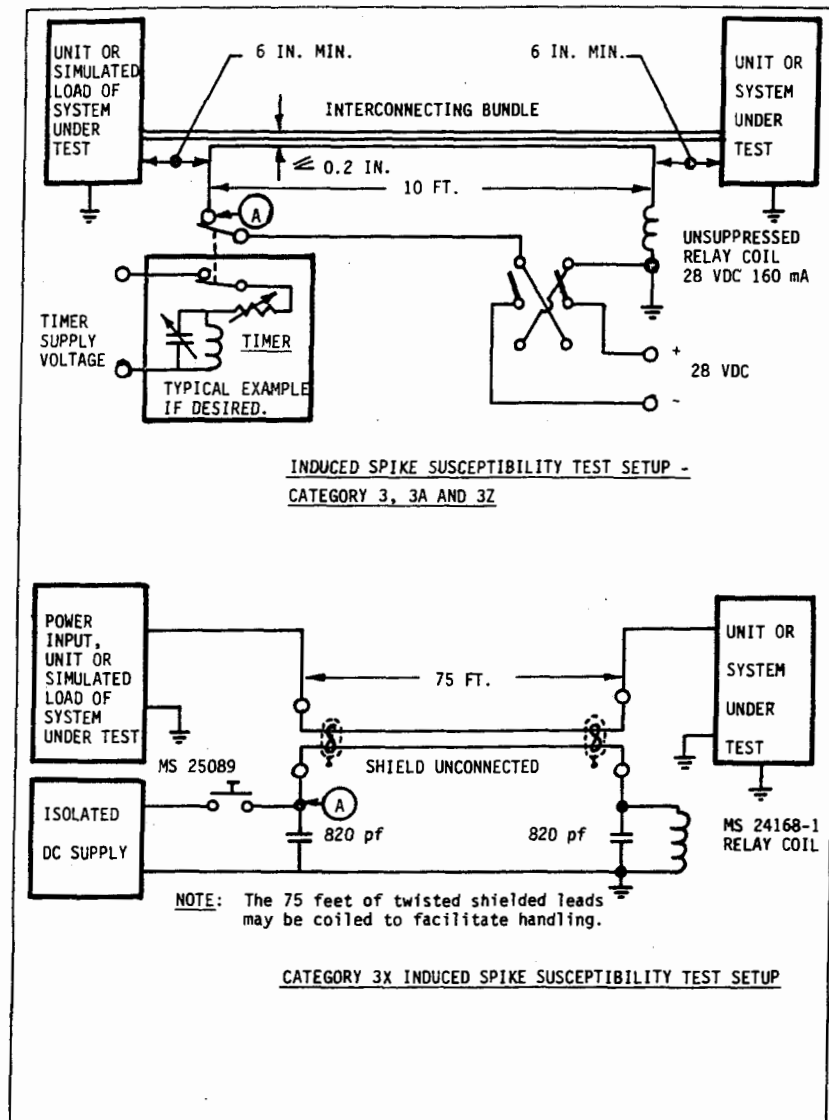


Figure 3-5

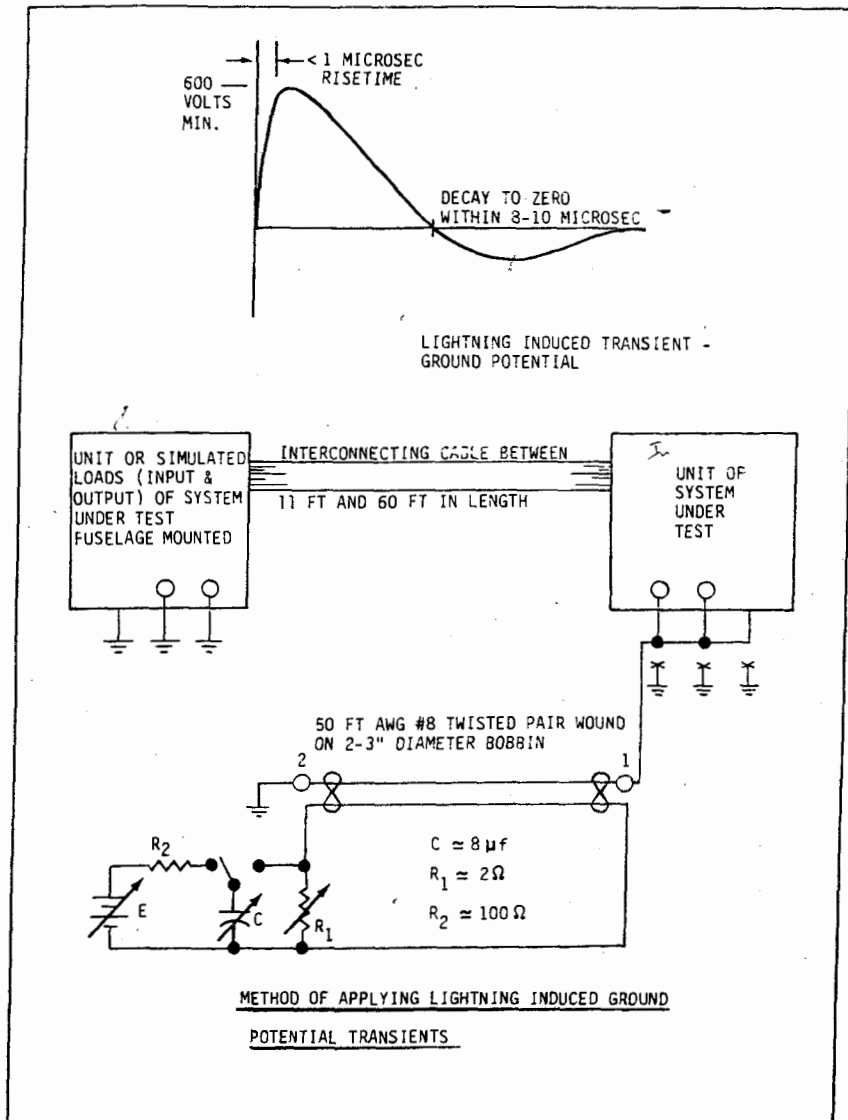


Figure 3-6

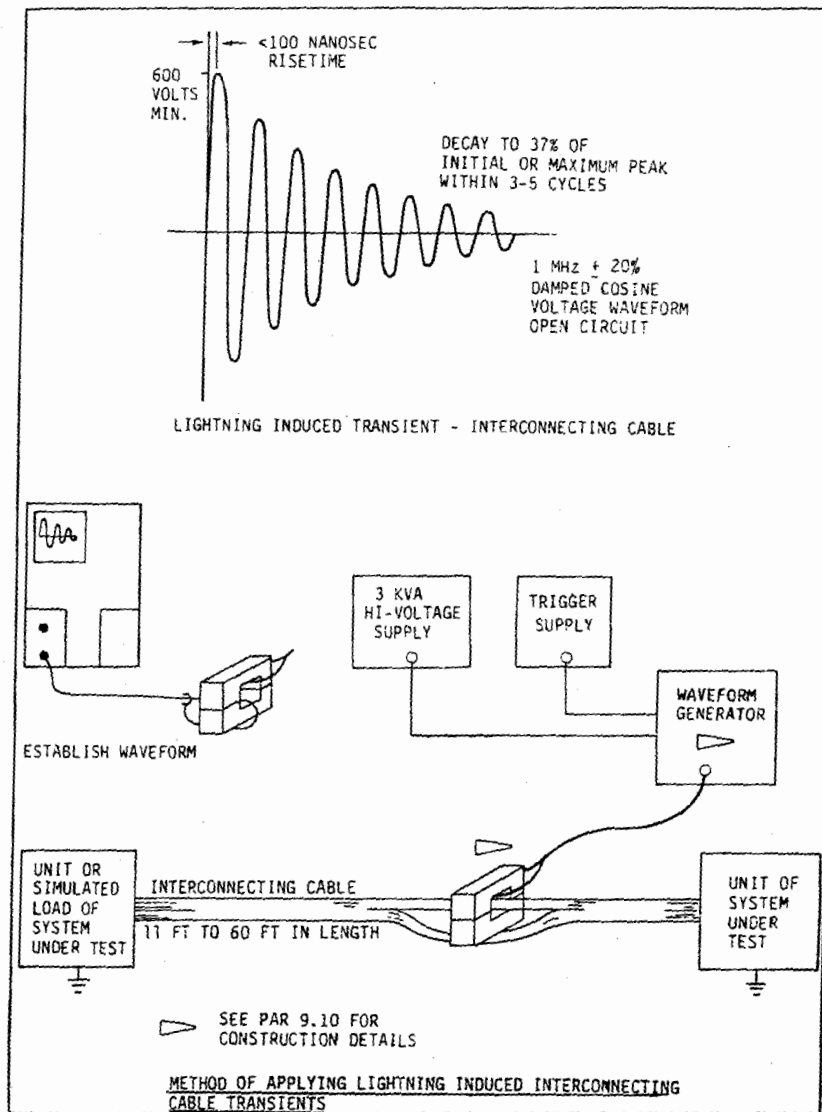


Figure 3-7

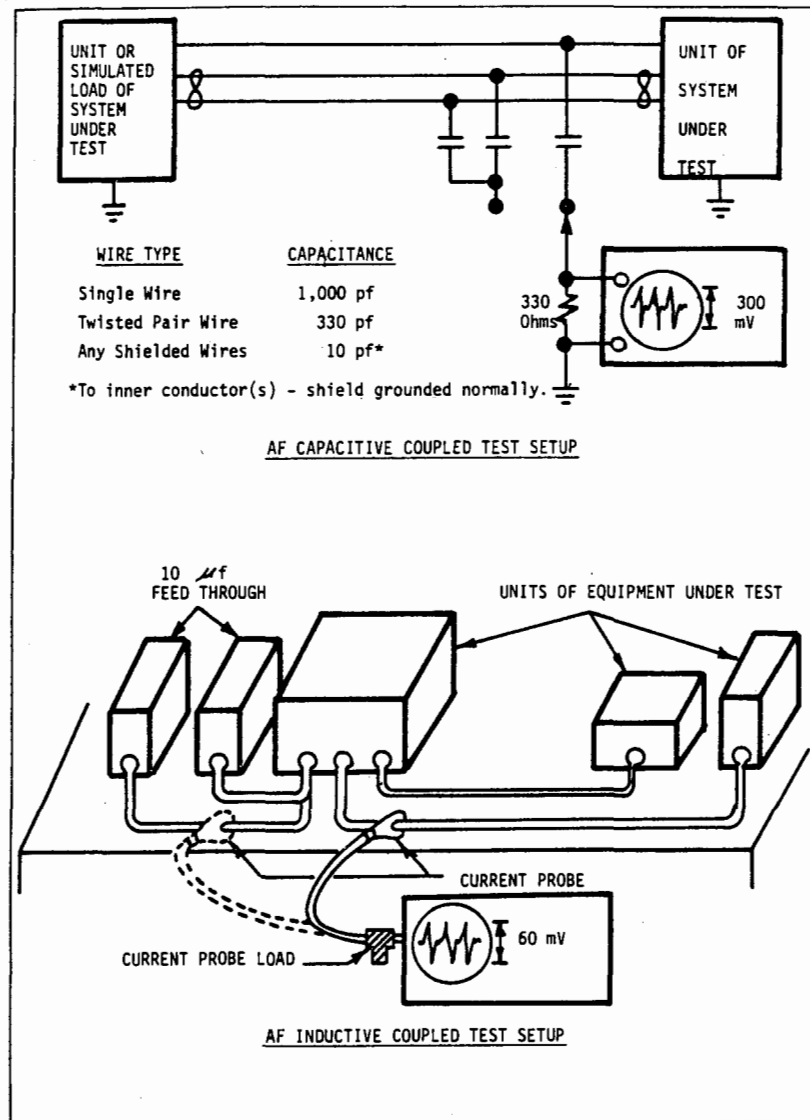


Figure 3-8

EMI THREAT ENVIRONMENT

A Generic Probe Into the Noise Environment in Which an Avionics System Will be Immersed and Expected to Function Satisfactorily. This Encompasses Steady State and Transient Noise from Aircraft-Generated Sources.

Chris Kendall

Chris Kendall Consultants
Mariposa, California

MR. KENDALL: I don't know if there are any questions from the session I did this morning or from Keith's excellent session.

MR. SMITH: Yes, there are. I would like to comment on the response of TTL gate, or similar gate, or whatever, as a program receiver.

If you have a transient that approximates an impulse, that's a very wide bandwidth. Under the broad-band receiver model, the gate would respond to it, and under a time-domain model we would not know the progress from the impulse of the signals. I wonder if it wouldn't be more appropriate to get the three logic gates, instead of the receivers, to recognize that they do not respond to all transients?

MR. KENDALL: The question was, should we best look at a transient phenomenon in time domain as opposed to frequency domain for logic circuits. And quite frankly, I think both are applicable. You can use it in both techniques.

The problem you run into is one of phase information. Supposing I take a pulse in time domain and I fully analyze that pulse into frequency domain, depending upon how it was generated — whether it was coherent or incoherent broad band (meaning random versus an in-phase relationship to the harmonic content). Then when I do a transfer function, a radiated transfer function, or a crosstalk transfer function, I lose phase information again. What I end up with is a composite curve of what gets induced into the lead.

At this point, if I did my homework correctly and did a reverse transform, I would be back into time domain correctly.

If you do your transformations correctly, there is no problem. If you do them incorrectly, there could be a problem. I would like to remind you that from an analytical point of view, if you take the transient threat, convert it to frequency domain, do a transformation in frequency domain (which is easier), and then get a composite frequency domain induced spectrum and integrate that directly, the worst thing you could do is overpredict the effects.

From an analytical point of view, depending upon accuracy, we in the EMC community tend to throw 6 dB around among friends, and that's a 2 to 1 difference in predicted levels.

If we're looking at the analysis with a window of maybe 12 dB, which is a 4 to 1 difference, that's not too much error.

MR. SMITH: I agree that if you take an impulse type signal and use your broad-band receiver, you're going to respond to that signal, and you're going to lose phase anyway.

MR. KENDALL: There are lots of things you can do analytically.

MR. SMITH: The other point was in solving analytical problems at higher frequencies; for instance, the classic one of wire coupling where you have two wires over a ground plane When you get into the megahertz range, it's hard to tell what the load looks like when you have capacitance. How do you treat that problem?

MR. KENDALL: The question is: How do we treat crosstalk in the higher-frequency range?

In fact, it gets even more complicated if you take crosstalk in the electrically long regions. So you have what we call a standing wave phenomenon.

Say you have two wire segments and you want to know the crosstalk between them. If you are in an electrically short region, you only have to worry about the things that you are referring to; namely, the reactive impedance of a load and its phase relationships.

If you take the vector sum at any given frequency, that would be most accurate, but it would be somewhat difficult to do because some of those are very complicated loads. The problem gets further complicated if the wires become electrically long. Now you have standing waves as well as phase relationships.

There have been some excellent studies in that area. If you look at some of the material coming out of Rome Air Development Center, Clayton Paul and others have done some excellent work in the area of analyzing electrically long wire segment crosstalk.

As soon as you make the model more complicated, you also restrict the use of the model. So you would like to come up with a model that's reasonably useful without suffering large degrees of error. You have to compensate error for usability of the model.

We have done quite a bit of crosstalk analysis using our software, and one of the things we find is that when you do integrate the results over the bandwidth, the resultant amplitudes reflect actual measured data. We're doing the transient pulse spectrum analysis conversion from time to frequency domain, then we're doing the frequency domain crosstalk, and then we're integrating back up. We find generally the model is not far off when you finish.

MR. SMITH: What are you doing with the load at the high frequency . . . ?

MR. KENDALL: Let's take a look at that for a minute. Sometimes we worry about the details and not the whole picture.

For instance, I think I had an earlier slide that showed you some terrible wave form that might exist. Let's take the figure labeled "Response to predominant capacitive coupling." That's probably similar to what you're really going to see (see fig. 4-1).

Now, if I wanted to do an analysis of this wave form to convert time domain to frequency domain (I want amplitude versus frequency as opposed to amplitude versus time, which is what I presently have), one of the things I can do is smooth up this model and make it look like a triangular wave form. That's one approximation of this model. If I did and I was not interested in the exact amplitude at any given harmonic, but only the composite or the loci of maximum harmonics, then I have lost very little in making this assumption. Therein lies the answer.

If I take a model such as this capacitive coupling waveform (we'll be talking about models a little later), after I do the conversion I'll end up with something that looks like a triangular spectrum in terms of frequency domain.

This is the loci of maximums that says there will be harmonics that will reach this peak envelope - not all of them, but some.

We still have the $\sin x/x$ functions in the frequency spectrum that are going to cause grouping, and your spectra lines, if harmonically related, would reside here.

Not all of the harmonics will come to this curve, but some will. As a system integrator, what I'm probably most interested in is the composite threat compared to the composite protection I need, not necessarily the result of each individual harmonic. If I overlay this composite with the specified limit that I have selected, the delta difference shown between these two curves represents the worst case cabinet and/or cable shielding for that system. It doesn't represent the average or a particular amount of shielding at a particular frequency, but rather the composite needs of the shield.

MR. SMITH: Does that limit it to a periodic waveform analysis?

MR. KENDALL: Yes. Say this was periodic. If it isn't, all that's going to happen is the spectral lines are going to get very close together. Taking the example to its limit, you end up with a pure broadband spectrum that may look like the periodic spectrum filled in.

But again I'm not interested so much in $\sin x/x$ curvature as I am interested in the loci line (even if it was a single pulse) because the single pulse loci of the frequency domain spectrum determines the amount of case shielding I'm going to need.

MR. SMITH: Are you making the calculation directly from the time domain?

MR. KENDALL: No. The problem you get into in time domain is that you first have to gather information that tells you what you can survive in time domain. That is not as easy as one might first guess.

My gate response to a discrete pulse versus a damped sinusoid, is different.

Now you get approximation problems. I don't think analysis is here to tell us the precise answer. It is here either to tell us we are clearly in trouble or we're clearly not in trouble. If we're in between, we're going to have to do some more work.

I think this is where we can use the models best.

Any other questions now? We'll go over this again in case there are any more questions.

What I thought we would do is cover four or five important areas. First of all, we had our little introduction session this morning. We're going to talk about the threats in more detail. We're going to talk about analyzing those threats. We're going to talk about designing against those threats. And then finally we're going to talk about testing to those threats. Those will be the subjects that I would like to cover. We're going to have some other excellent papers that will stimulate our thinking and increase our opportunities to approach situations we think may be problems.

Coming back to the threat; it's not unusual in avionics systems today, especially for control functions, to have two or three, or maybe even more, black boxes that make up a subsystem (see fig. 4-2).

In this case I'm showing a two-box system. I'm showing some type of a cockpit control panel that might consist of pushbuttons and LED displays, just a way of inputting data.

The second box would be an interface, a digital interface electronics box that's shown here on a tray, which is pretty much how we see systems today with a standard ARINC connector.

This box is where all the electronics are. There are no displays and no controls on the box, and the control panel is the input-output device. In conjunction with this, there is probably an on-board computer. So in a sense this represents the digital interface and maybe subprocessing for that particular subsystem.

When we talk about threats, there are many ways in which we could threaten the system because of on-board transients that were discussed by Keith. Keith mentioned some excellent examples of relays that sometimes lose their suppression, and other types of transient phenomena that can occur, virtually unimpeded. How can these transient effects couple into a real system as experienced on an airplane?

Here is the cabling. There are two ways that the cabling can interact. One is through inductive coupling, and there are two aspects to that, also. When most of us look at a schematic, whether it's a cable harness or box, we look at what I refer to as the pin-to-pin characteristics of that box. The high side of the circuit references its return. And in that mode a certain amount of coupling transpires. But generally it is addressed by the system integrator and the black box manufacturer because it's on the schematic. They will twist the cables to reduce certain phenomena.

Another form of coupling that is less obvious is the common mode coupling, that looped area formed by cables referenced to the fuselage of the airplane.

There is a loop there that is of grave concern as frequencies of the coupling phenomena increase. We call this pin-to-ground effects, normally not shown on the schematic itself.

So there are two aspects, pin-to-pin and pin-to-ground. The ground occurs because of the presence of the fuselage. In a sense it forms a transmission to that fuselage and we're concerned with what that might look like.

When we're talking about coupling let us consider the figure entitled "Reduced Circuit Coupling." We could have the loop area formed by the two individual pairs, Cable 1 Loop Area talking to Cable 2 Loop Area (fig. 4-3).

That generally is not a problem. It could be, but generally it's well controlled and addressed in the equipment manufacturing process.

However, there is also current flowing in each cable referenced to the fuselage. There is a possibility of inducing currents on this cable in the same type of looped area, namely pin-to-ground. These pin-to-ground effects generally are not significant until we get above 5 to 10 MHz, and then they can be very significant.

If we were going to elect filtering, as opposed to shielding or twisting, as it comes into the unit we would have to filter it pin to chassis, not pin-to-pin. If you put a pin-to-pin filter in, this problem would not be solved. That's the point I want to make here.

There are techniques of solving this problem other than capacitive decoupling. They use common mode chokes very effectively to solve this same problem.

The second part of this is capacitive coupling. Wire-to-wire, straight capacitance allows crosstalk between the bundles. It also occurs within the bundles themselves. Again, we have the same situation. We have capacitive coupling because of the pin-to-pin effect and the pin-to-ground effect, and we have to look at both effects to come up with a proper design mechanism.

I was impressed with Keith's presentation because he talked about this in terms of testing. He discussed lifting the ground, or adding extra length to the ground (so that there is a very nebulous chassis reference), in hopes of creating some of these common mode effects that we often see in digital systems, and other systems as well. But they are usually more bandwidth limited, so the effect is not as pronounced.

The coupling is an important one, and some of the test methods over the years have aimed at these techniques. The crosstalk analysis for this is possible, within the limits that we talked about just a few minutes ago.

The next problem is that once the crosstalk occurs from cable 1 to cable 2, the amount of coupling is a function of the speed. If I hit this with a very fast rise time transient or even a logic change of state, the crosstalk to the second cable is rather complex. What happens if the cable is electrically long? Depending upon where the crosstalk is induced, current will actually travel in both directions.

When that transient gets to the load (wherever it may be and whenever it happens), if the load is a capacitive shunt, the transient will be reflected. The reflection has nothing to do with the signal reflection or the signal transitions. It has to do with the time it gets to that point.

That reflection, then, is asynchronous to the data stream. It's not in phase necessarily. It could be, but that would be very happenstance.

So you get a net damped sinusoidal response, and you can therefore accurately determine the length of your I/O cable if you measure the interval of time between the two adjacent peaks (fig. 4-4).

The damped sinusoidal pulse inducement due to a single pulse has to be caused by the electrical length characteristics of the cable.

We have used this as a troubleshooting aid many times because the damped sinusoid is equal to this length. You know there is a problem with the ground termination of the shield, if a shielded cable is used. Or there is a problem with impedance, if you're using filter pins.

It's a useful technique. We see this also in lightning, and I'm seeing many papers on the subject dealing with this damped sinusoidal effect. Even this morning Keith mentioned a 1-MHz damped sinusoidal stress to simulate lightning or some type of surge. This damped 1-MHz signal is commonplace. We also see it in the commercial sector. It shows up under IEEE Standard 472, the surge withstanding test. They use a 1- or 1.5-MHz damped sinusoidal pulse as a stress mechanism for powerline cables.

There is some question about that technique, incidentally. I suggest you look at the frequency domain equivalent of a damped sinusoidal pulse.

If you look at the frequency domain equivalent of the damped sinusoidal pulse, you would get a peaking effect. The frequency, F_0 , where the peak amplitude occurs in frequency domain obviously coincides with the frequency of separation of the damped sinusoidal pulse. When you're using a burst or a damped sinusoidal stress, the bulk of the energy is being damped at one frequency or within one range, and you're not evenly stressing the system. Therefore, it works great if the only type of frequency stress occurs at 1 MHz, which obviously would not be the case.

In many respects people feel that it's much better not to use a damped sinusoid, but a unipulse, and let the unipulse find the natural resonance of the system rather than trying to perturbate the system with a given frequency content.

We'll let others argue that. But I wanted to point out that particular problem.

Getting back to our threat concerns. We're concerned about the source of the threat, which we can't do much about because we don't know if a relay is properly suppressed — and we can't do much about filtering out the lightning effects. We have to recognize that the transient is going to occur. We can't do much about the wave form shaping that transient, but we have to harden the system.

Our system consists of the black box and the shielding integrity of the black box. It also consists of the filtering or lack of filtering at the port of entry. And it also consists of the cable. Having dealt with numerous manufacturers, one of the problems (and I'm sure the system integrators have noticed this as well) is that no one wants to accept responsibility for the cable. Everyone will say they designed the black box to pass all of these tests, but the cable is all yours — it's your fault.

We all recognize the system cannot work very well without a cable. And we recognize that that cable, and how it's configured, will make a difference on the response of a system.

We should tell the black box manufacturers that they are to supply the cable and the black box as a system. Sometimes it gets a little confusing, especially if this black box manufacturer is told to interface with a computer but is not told what the cable looks like. That's potentially a rather serious problem.

So we have to know exactly what we're in for. What is the cable going to be? What if we elect, for instance, not to shield any cables in the system, which is a possible alternative? What if we told you to build a black box and that you must work with any cable we put on there? I'm not sure that you would sign up for that contract. But if you did, that would mean that you would have to do something at the pins or do something regarding all of the possible environmental threats. And you could not rely on the cable, other than to do you wrong. The cable will be the port of entry because it's the antenna to the system.

To couple energy, we have to have antennas, and the most likely antenna in the system is the I/O cable.

How do we protect against this threat? It's easy to say let's use filter pins. Let's go ahead and filter all these signals. And then we're going to have another requirement in the specs to transmit 10 megabits.

If you put any capacitor on a data line trying to pass 10 megabits, you're going to have a rather difficult time of it unless it's an extremely small value capacitor.

So we find that there are things that have to be addressed. You can't just solve the problem by using filter pins or by using heavy armored cable or conduit. Both are unrealistic.

But I don't think we can take the posture that these special digital problems can be solved exclusively by filter pins or filtering at the port of entry, or that they can be solved exclusively by a shielded cable.

From the practicality of shield termination that we heard about this morning, there's a possibility of difficulty in terminating shields other than through 6-in. drain wires. That restricts the shielding efficiency of the cable drastically.

I think what we have to do is realize that these systems require more than just one solution. Cable shielding may be one answer, but possibly integrated with filtering. Someone has got to make that decision: How much filtering versus how much shielding? That's not an easy one.

As long as we understand the problems, I think we can address them. The first phase of this workshop is trying to develop an understanding of where we are and where we might have to go.

Now, we often see another problem with computers. A computer is something that you don't redesign every 6 months. Once you get a computer that's working pretty well, you debug it for 4 or 5 yr and feel comfortable with it, you would like to use it for another 4 or 5 yr — even though it might be outdated.

But it takes a long time to get certification on some of this equipment; therefore, we can't expect it to change overnight. So, we have to live with existing equipment. That puts further constraints on the ability to filter and shield the

interface cables. We may be using standard data buses, which might be differentially driven. Incidentally, any of you who think differentials are going to solve your EMI problems dealing with these transients are in for a surprise. It's very difficult to solve these problems with differential line drivers and receivers. The reason is obvious. Have you ever tried to keep a differential pair differential above 2 or 3 MHz? The impedance of each line has to be precisely controlled, generally to 1%.

Take a twisted shielded pair of cables and try to control the impedance to 1% above a few megahertz. It's a very difficult challenge.

So differential line drivers and receivers do not answer the problem of line-to-ground effects, and line-to-ground effects in the high frequency - 10, 20, 30 MHz - is where the bulk of our problems will probably reside.

We have seen in the commercial computer industry that the greatest threat to the computer by fast-rise-time transients occurs between 5 and 200 MHz. Below that the antennas are not efficient. The coupling is not efficient where transients and crosstalk become a serious problem in the 5- to 200-MHz range.

We expect the same things to be true here. You can see this if you look at the radiated emissions. Take an airborne computer. Look at the fundamental frequency clock; perhaps it's 10 MHz. Maybe it's divided so the system clock is operating at 3 or 4 MHz. Look at the radiation of 3 and 4 MHz. It's very low. Look at the radiation at 40 and 50 MHz. It's very high. Why? Because your I/O interconnect is not a good antenna at 4 MHz, but it's a marvelous antenna at 40 MHz (see fig. 4-5).

Also, crosstalk within the logic boards for those I/O cables may be at a much slower data rate than the internal high-frequency clock, which is generally the case. You may be communicating at only 100 kHz, or maybe at 1 megabit. But what's going to radiate is not the 1-megabit signal, but the harmonics of the internal crystal. They are going to be there, and they are going to be enriched at the frequencies where the I/O cable reaches $\lambda/4$, $3\lambda/4$, $5\lambda/4$. That's where our problem will be.

So now we see that if the radiation is very low at the low frequency, it becomes a "crescendo" at the 50- to 100-MHz range, and then begins to die off because of the natural Fourier analysis of the wave form.

We should suspect a susceptibility does the exact same thing in reverse: If we are going to get into that system, we're not necessarily going to get into it at 3 MHz and 4 MHz unless we're dealing with a very strong signal. We're going to penetrate the same way that radiation exited. We're going to penetrate where the coupling is most precise and where the electrical lengths have reached antenna lengths.

Now, that brings up another issue in dealing with the threat: How do these signals get into these boxes? I would like to show a diagram of a cable after it's been hit with a transient. And I want to reference some of the excellent papers given at the symposium on the subject.

Let me take a black box and install a gate, a logic gate, and send it out of Box A over to Box B where I have a logic receiver. So far so good. Now, I have to have a return for this signal. So let me assume that I take the return, and

I twist it with the high side. That isn't always the case. To keep costs down, especially the number of leads in the cable, a lot of people would like to run 32 signals and one return. That doesn't work too well because it's not a very good transmission line, and you have lots of loop-to-loop coupling in the cable.

So let's assume that we are dealing with at least a twisted pair: a given return for a given signal. Now, let's put a shield on this cable, and use our analog background to terminate the shield. We heard this morning that one way to do this is to come in through a pin in the connector and allow this to be outside by about 6 in., as I recall.

So we have a 6-in. run. On the opposite end there is a lot of concern. Do we ground it or not? Ground loops, that marvelous subject. So let's just leave it floating for a moment and see what happens.

We now hit this cable with a fast rise time transient disturbance or some signal. The cable will have a $\lambda/4$ length to it. At that point the standing wave voltage on the cable will look something like the figure labeled "Radiation Penetration into Improperly Terminated Shielded Cables." Where the cable is grounded, the voltage is obviously going to be 0 except for the impedance across the 6-in. drain wire (fig. 4-6).

At the opposite end, which is left open and is generally terminated outside the connector area that it's about to enter, there will be a very high standing wave voltage. Let's call it V_{max} . The cabinet is bonded to the airframe itself, so its potential is very low.

Now, if we remember just a little bit of physics. When we have a situation in which the voltage is very high, and right next to it we put another surface in which the voltage is very low, what has to happen? E-field flux lines have to occur between the two voltages. It's called an E-field intensity. And it's going to occur right between the end of the cable shield and Case A, right where you don't want it to occur.

You now have maybe an inch or two of lead exposure, and you have buried that unshielded length of cable, that wire segment, in a very intense E-field. As a consequence, it couples into the leads and brings them inside where they go through harnesses to the mother board and then to the daughter board, where they ultimately may be operated on. It's a very poor design because of that very intense E-field.

Now, you might say, I can get rid of that E-field. All I have to do is hook a wire to it, take it through a pin in the connector, using our analog background, and ground it.

Let's assume for a minute that that was a low impedance. If it is, as soon as you ground the shield through the pin, the voltage goes to 0. Correct?

But what happens to the standing wave current? Boom, it has to go to maximum. Now you have the entire maximum standing wave current going through a pin in the connector. A very intense amount of current.

The old right-hand rule of physics says put your thumb in the direction of current flow and your fingers represent the magnetic field. And do you know

something? I have yet to see a connector in which the pins inside the connector were twisted to prevent magnetic coupling.

So what happens? The magnetic field couples into those pin areas and induces noise. So you couple, but you have still killed the system, digitally speaking. You are between a rock and a hard place. If you ground the cable you're in trouble; if you float it you're in trouble. And we haven't even talked about ground loops. We're just talking about standing wave effects, a whole different ballgame from the analog world; but the analog didn't even see it. It was filtered away before, in most cases.

Of course, analog is changing, too. Some of the op-amps on the market today are extremely broad band, and their ability to react to some of this is increasing significantly.

Now we have a problem for which the shield hasn't helped us; that is, to terminate this shield properly, we have to terminate it where we don't want to. We concentrate the current on one lead, and where we don't take it through a pin. To make this work, if the shield is doing anything at all, we have to have a broad connection to the outside surface of the cabinet. That way, the current can flow with a much smaller J vector density, and flow out onto the cabinet and not disturb the leads inside magnetically. That will happen because of the skin effects, if we do a determination correctly.

But that's a whole different ballgame compared to our analog predecessors. We're used to running 6-in. leads and going through pins in connectors, which is not a very good option for digital systems.

With the digital situation, we have a whole different problem than we had in our analog counterpart. We have a much higher frequency problem. We have a standing wave. We have E-field intensities that we never had to deal with much in the lower-frequency areas.

Someone asked me earlier: What would happen if we flew an airplane over a very strong radio frequency radio station like an FM?

Well, if the frequency of transmission was close to the resonant length of this cable and/or was within the bandwidth of the logic, the radio frequency signal could enter just as easily as I have shown the digital or the transient entering.

The difference here would be that normally to get a response we have to either (1) DC-rectify that radio frequency signal, giving it a DC component that might offset or exceed the noise threshold of the logic family (and any diode would do that), or (2) we have to strip the modulation where the modulation itself has a high enough amplitude and is low enough in frequency to cause response in the logic family. Both of those things happen all of the time, or can happen all of the time, under very strong radiation conditions.

A little bit later, maybe when we get in the analog mode, we'll talk about how we analyze that and how you can get a feel for the amount that would be transferred.

Now we see a situation in which the cabling becomes a key issue, and the question is how do we solve the problem? We'll talk about that, and we'll try to get into some of the design concepts that might solve this problem.

The same problem exists, incidentally, for EMP. I don't know if any of you have any interest in EMP, but the same thing applies to EMP; very intense, very fast rise times, dealing with what we call NEMP (nuclear electromagnetic pulse) effects.

I see that this last issue of the IEEE's "Spectrum" had an excellent overall summary of EMP effects on all types of systems, including avionics systems. So you might read Spectrum, I think it's the October 1982 issue. I think you would find that very exciting reading.

Let's eliminate the shield and just have the leads with the ground going its own way, even leave it twisted. Now let's look at the transfer. If we hit this again with radiation, transient or steady state, again within the limitation that the cables are electrically long, generally what will happen is that we will be inducing common mode currents in this system. We will induce currents that flow in the one lead and in the opposite lead in the same direction. These currents will be induced in the same direction because of the common mode impedance effect. And because the load is finite, you will get a voltage developed across the receiver or across the transmitter (fig. 4-7).

Because of the cable's pin-to-chassis loop area that is irradiated, the entire area is irradiated with either E- or H-field, or both. Therefore, common mode currents are going to be induced. Even though you twist the leads tightly to eliminate the coupling pin-to-pin, that's not the problem. Pin-to-ground is the problem. It's the effects of common mode currents flowing in the two leads to the common reference. One flows across the load, giving you a net delta voltage. The second wire doesn't give much protection; some, but not a great deal.

The question then becomes, how do we break up this current? How can we eliminate it? Well, we can't exactly eliminate it, but we can reduce the effects. One technique is called the common mode choke.

A common mode choke has no net inductance for normal mode currents. Maybe I should define normal mode and common mode.

If I had a circuit and an oscillator, and I sent the oscillator signal down to a resistor or load, returning it back to the oscillator source, currents would flow the way you would normally expect them to flow. I call that normal mode. Some call it differential mode.

What we see there is the current flowing the way you would expect it to flow — normal mode, the normal way of flowing, or differential mode. Now let's introduce the fuselage of an airplane. As the frequency increases, there is a stray impedance to the ground plane. It's somewhat distributed, but it's usually never homogeneous.

Because of the common mode impedances and because of the possibility that we might hard-ground one end anyway, in keeping with the tradition of single reference grounding, we have a reference for the circuit. (Incidentally, single point grounding doesn't exist; there is only single reference grounding.)

As a consequence, we can cause a lot of misery because of the currents that try to flow into both circuit legs in the same direction. Common flow of directionality. For that reason we call it common mode. Some people call it longitudinal mode.

That's the problem, no matter what you call it. The common mode effects give us the most difficulty, mainly because they are not addressed on schematics, and generally they are not referenced in the design itself.

When the current flows, we want to break it up. If we look at a common mode choke, from the current flowing in on the first wire, we get a magnetizing force in the clockwise direction. Then the current goes out to its load and back on the other lead.

At this point the current is flowing in the opposite direction, and there is an equal and opposite magnetizing force flowing in the counterclockwise direction. This gives me no net inductance to the flow of normal mode currents. I have not disturbed the proper operation of the circuit. That's a key ingredient here.

But now let me take the common mode currents and put it then into the common mode choke. We now have currents trying to flow in the same direction, and I get a net magnetizing force that is additive. Therefore, I get a lot of inductance. I could get too much; I could saturate. So I have to be cautious. Generally that's not the problem.

Here I've picked a high ferrite material, and I've wound it with an exact number of turns on both sides bi-filter. I will now get that common mode current to see a very high impedance. Then I come down to a common mode choke with the two dots indicating that it is a bi-filter common mode. That gives you a lot of common load impedance, and you have raised the common mode impedance. Therefore, you have reduced the flow of the current to the common mode.

This is a very effective way of protecting against common mode influences, providing you only need 15 to 25 dB of protection. Any more than about 15 to 25, and the stray capacitance will talk across the balun or the common mode choke, and therefore limit its effectiveness.

An excellent paper was given by the Basic Four Corporation at the symposium in Santa Clara dealing with the practical limitations of common mode chokes. They showed mathematically that 15 to 25 dB is about the best you can hope for above 5 to 10 MHz. But even that is helpful. It may be enough to help protect the circuit. This is a potential solution for this type of problem. Any questions?

MR. KENDALL: (In answer to an inaudible question.) You don't want to saturate the core. Otherwise, the game is over. You have to keep it within the saturation.

For a power line you try to be a little more cautious. Most of the EMI filters have common mode chokes now because the leakage current criteria limits the amount of line-to-chassis capacitance.

One of the things a common mode choke does well is cause the impedance to become balanced. So in a sense it does help you a great deal.

Just briefly, these are some of the techniques. There is a lot more we could talk about. For example, what kind of cable configuration should you choose? Should you choose 32 twisted pairs, gross shielded, or no shield? Should you choose twisted shield pairs versus the multi-twisted pairs, gross shielded? Which one is better? Should you choose coaxial cable? Fiberoptics?

We have a lot of choices to make here yet. What should the cable look like for maximum protection against threat, and for the greatest amount of containment of the radiation from these cables? Should the cable be braided, or should it be foiled?

What kind of configuration? Braided cables have a severe problem here? Not in the low frequency. They are great in the low frequency. Braided cables have their greatest weakness above about 10 to 20 MHz.

Where do our problems begin? That's the problem. Braided cables may not be our ultimate answer if we are going to use that as the solution. And there again is the tradeoff that we have to begin to address.

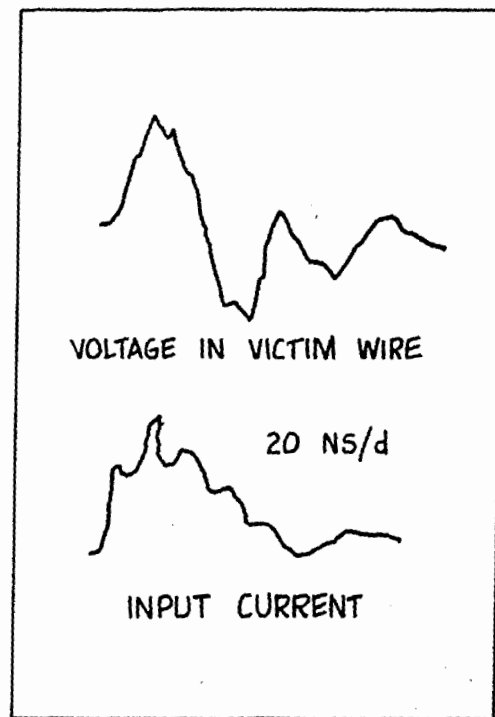


Figure 4-1.- Response to predominant capacitive coupling.

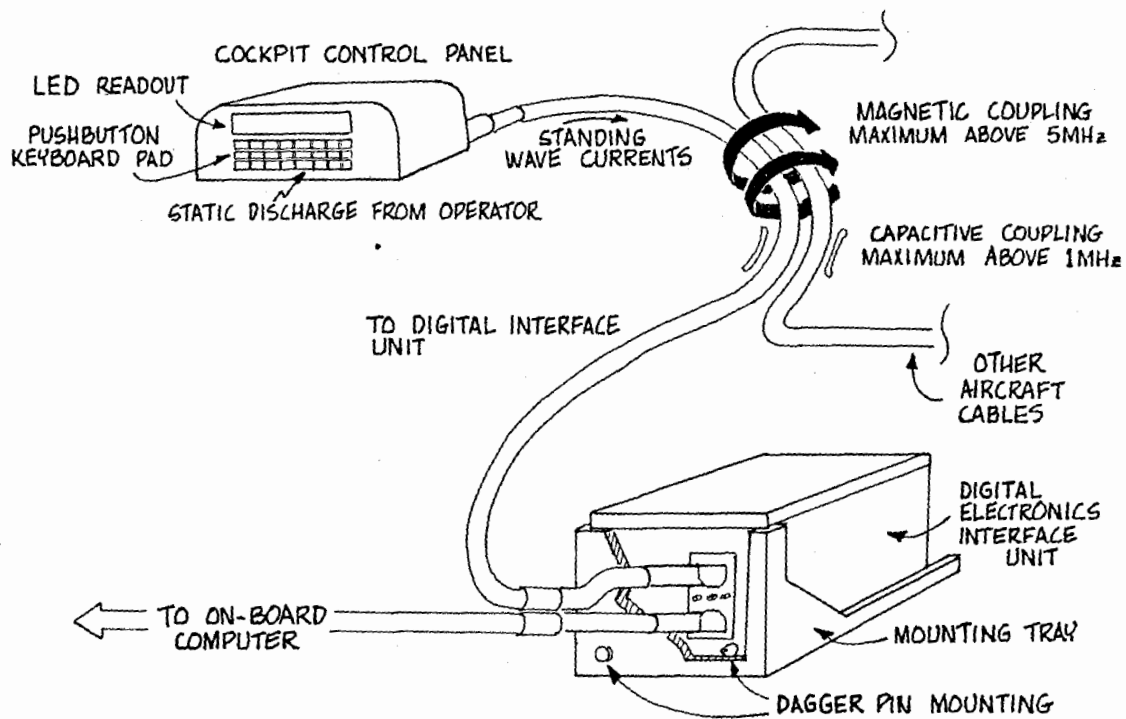
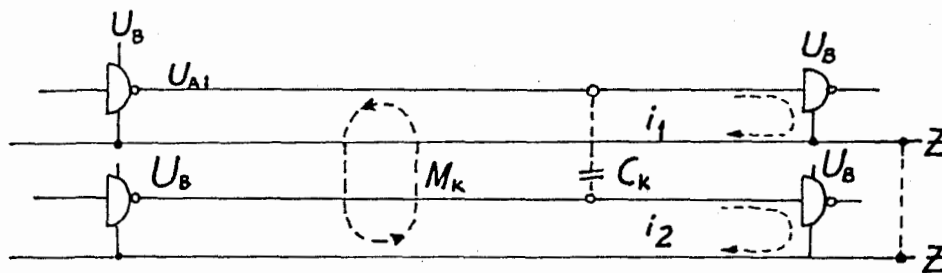


Figure 4-2.- Example of concerns for digital avionics.



C_K = CAPACITIVE CROSSTALK
 M_K = MUTUAL MAGNETIC COUPLING

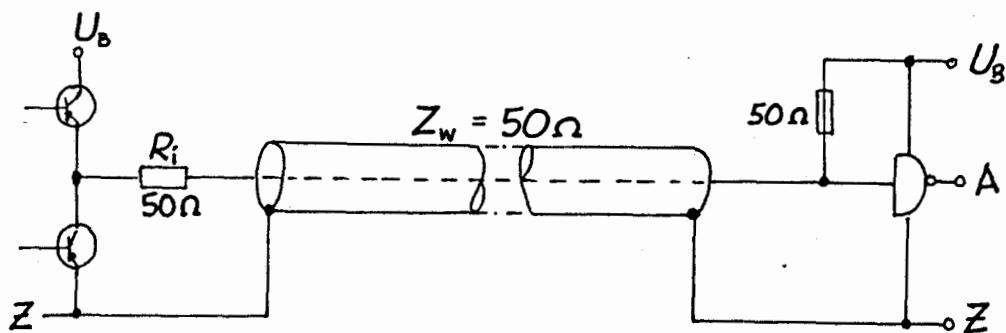


Figure 4-3.- Circuit coupling..

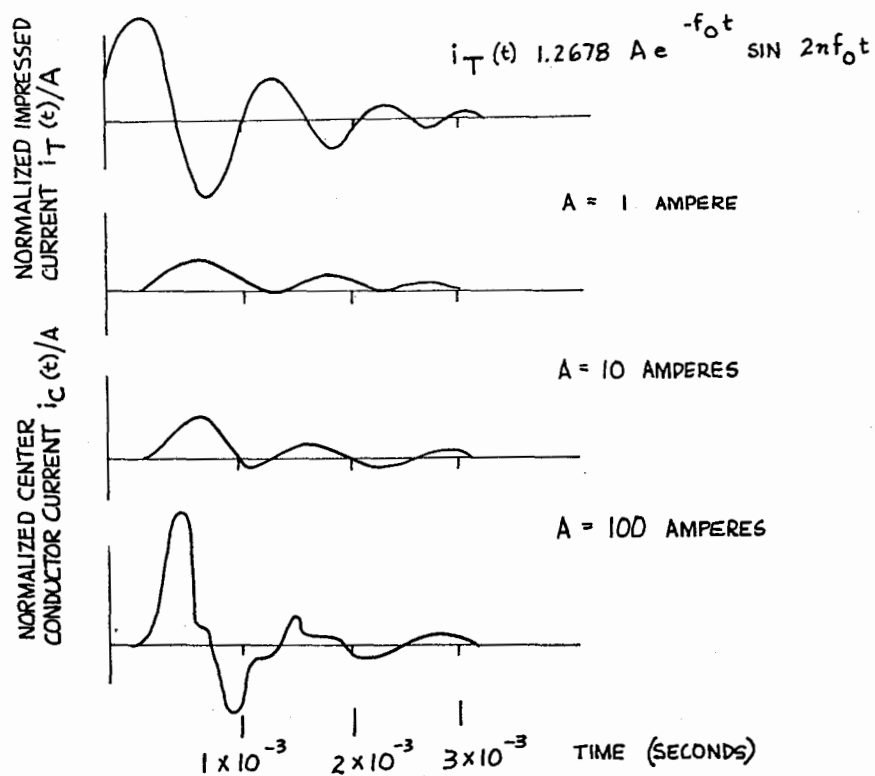


Figure 4-4.- Normalized center conductor current for a damped sine wave impressed current $f_0 = 1$ kHz.

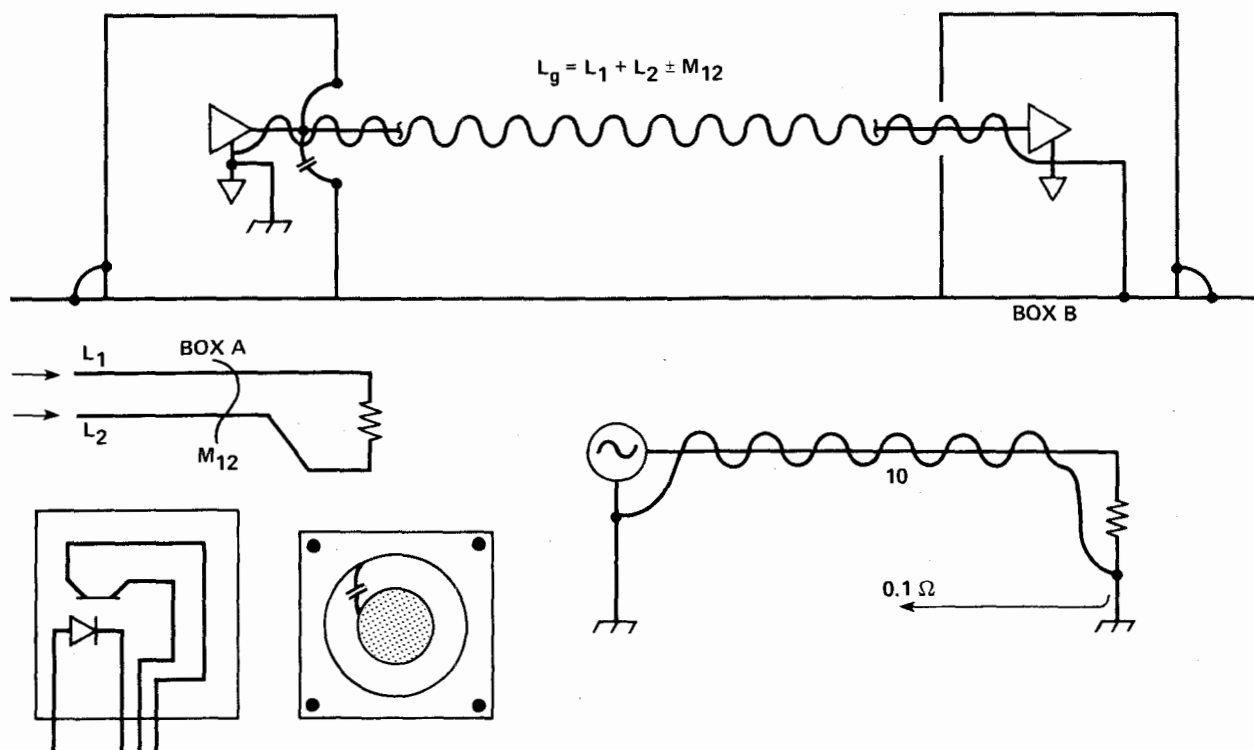
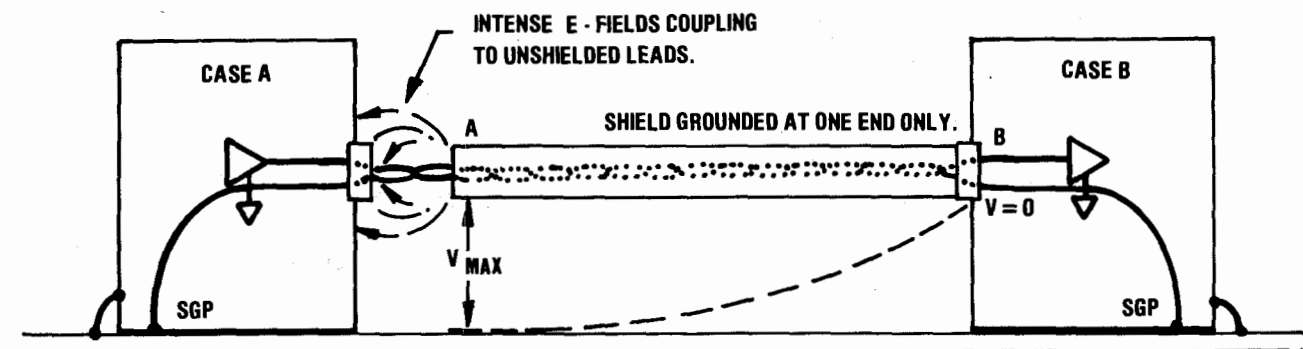


Figure 4-5.- Typical radiation penetration.



- WHEN SHIELDED CABLE AB EQUALS $\lambda/4$ OF EXTERNAL RADIATION THEN V AT B EQUALS ZERO BUT V AT A EQUALS MAXIMUM.
- SINCE CASE A IS GROUNDED TO FUSELAGE OF AIRCRAFT LARGE VOLTAGE EXIST BETWEEN UNGROUNDED SHIELD AND CASE.
- LARGE DIFFERENCE IN VOLTAGE CAUSES E-FIELDS THAT COUPLE TO UNSHIELDED PORTION OF CABLE.

Figure 4-6.- Radiation penetration into improperly terminated shielded cables.

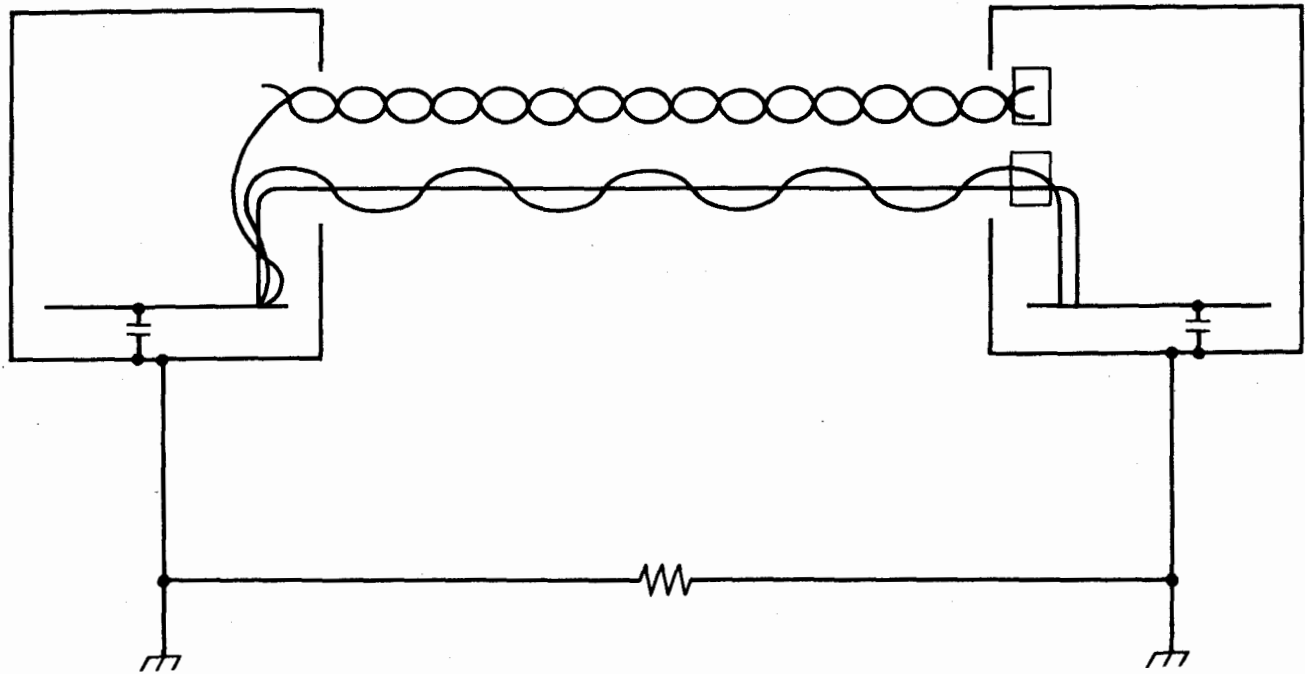


Figure 4-7.- Radiation penetration into shielded cables.

TRANSIENT UPSET HARDENING CRITERIA OF DIGITAL COMPUTER BASED SYSTEMS

Gerald M. Masson

Johns Hopkins University
Baltimore, Maryland

MR. RASCH: Dr. Gerry Masson is a professor of electrical engineering and computer science at Johns Hopkins University. Dr. Masson has been involved in the fault tolerance and computer reliability areas. He is directly involved in research for NASA Langley and the FAA Technical Center through the direct lightning strike program. I would like to introduce Dr. Gerry Masson.

DR. MASSON: I'm going to talk about a different level of the upset phenomena. The perspective I will be interested in is what is going on internal to this computer based black box once some type of transient phenomenon penetrates it. Basically let me set a scenario for discussion here.

I will be discussing a system that looks like this — a computer based device.

I have a microprocessor as the CPU unit. I have some program storage in RAM. I have some temporary storage in a random access memory device. I have some facilities for I/O. You may temporarily ignore the boxes on the bottom for my initial discussion. These devices are communicating across buses; they are sending signals back and forth, and that's the type of device I'm interested in.

For some of the work I'll be describing and some of the things we're interested in, I want to consider a system of this type. The programs I'll be doing experiments with are simple programs, generic programs, look-up table programs from which you're getting some input data.

The program will be manipulating data. The program might go to a look-up table for some data. And then it may put some data back out on the output line. It may get some data from the input, perform computations based on it, process the data, and put data back into memory.

I realize this doesn't cover the whole field of computer devices, but at least it provides me with the test setup for this discussion.

When you look at what a transient is, how a transient affects a computer device, you have to look at it at various levels. The level or the perspective you take probably depends upon what you know the most about.

Regarding this area, I come at the problem from the systems level. I think the problem is complicated enough that the solution will be an integration of the ideas at levels other than the one that I'll be talking about today.

But I think those levels are, first of all, the circuit level, and the analog signal level. You have transistors, and some of these chips today have a lot of them. Those transistors are characterized by various curves, and you can look at the transient fault at the level at which it disturbs the operation of this simple device.

You can go up to the gate level, as well. Maybe even to the register level or a combination of gates, to an arithmetic unit type of level.

Now you're talking about how the fault is characterized in terms of logic signals: 0's and 1's temporarily held at a certain level. You can go a level above that in terms of looking at the collections of gates as devices and looking at the signals they pass back and forth. And you have been talking about errors.

You can go a level above that, and you can look at the way the system functions from the black box point of view.

I consider an upset at the systems level to be a deviation of the performance that I have programmed the system for. In other words, I assume that I know something about what the system is supposed to do, and I'm interested in it at a functional level, in how performance has deviated from the desired performance.

TABLE 5-1.- ASSESSMENT OF
TRANSIENTS IN DIGITAL
SYSTEMS

CIRCUIT LEVEL

ANALOG SIGNALS

FAULT LEVEL

LOGIC SIGNALS

ERROR LEVEL

DIGITAL WORDS

UPSET LEVEL

FUNCTIONAL OPERATIONS

AN UPSET OF A DIGITAL
SYSTEM IS A PERFORMANCE
DEVIATION THAT IS BASED
ON OPERATIONAL KNOWLEDGE
OF THE DIGITAL SYSTEM'S
TASK.

My perspective to upsets is a systems level approach. And the question you have to ask is, what does a system do when it's not upset, when it's actually performing what you programmed it to do? Well, I like to think there are categories of performance. There are features of performance regarding the operation of the device; those features are the program flow.

The program flow, given a body of code and a system that will execute that code, is the sequence the code is performed, how the system accesses the memory, what instructions the system has, and how it will actually be used.

Finally, the idea of data context; a good example of that is the bounds on the variables the system is going to calculate for you.

If you try in an abstract way to describe the features of performance, you can put them into categories. I want to talk about upsets in a computer-based device relative to these features, and I'll probably concentrate more on the first category, the program flow, because I think it's the most interesting. And it's the most difficult to deal with.

If you look at these features of performance falling into categories and then expand on them, you can now talk in terms of these candidates. You can talk in terms of these features when the system is upset. When we're talking of program flow, what do we mean? We mean there is some invalid program flow. There is some sequence of instructions executed that were not intended to be executed.

TABLE 5-2.- FEATURE CATEGORIES

-
- PROGRAM FLOW
 - MEMORY ACCESS
 - INSTRUCTION REPERTOIRE
 - DATA CONTEXT
-

We can talk about an invalid op code address. We can talk about trying to fetch an instruction from an address wherein the instruction was not placed. We can talk about trying to access memory from a memory area that does not exist; or it exists, and you did not use it.

The details of the categories are not really important, but are used as examples for this talk. I just want to enumerate these categories of upsets. They deal with the features regarding the execution of the program, and we can characterize the upset in terms of these types of deviations.

Invalid op code is an interesting deviation, by the way, where the system will fetch something that isn't really an op code. That's interesting because you have an 8-bit microprocessor device that will give you 256 op codes. I think they let you use 248 of them; 8 of them are undefined.

And yet the system does something deterministic for those op codes. If it fetches a piece of data and tries to execute it, the system will do something with that op code. You have to know about this area to characterize the upset.

These are categories: invalid program flow to nonexistent memory; and those are ways, from a systems level, that describe the deviation in performance that a glitch can produce if it penetrates the device.

I'll now talk about the invalid program flow because I think it's the easiest area to give an example of. It's also the most difficult one. I'll show you some data which indicate how often we see it in our experiments.

TABLE 5-3

IPF (INVALID PROGRAM FLOW)	- IMPROPER SEQUENCE OF INSTRUCTIONS
IOA (INVALID OPCODE ADDRESS)	- FETCH OF AN INSTRUCTION FROM A NONINSTRUCTION ADDRESS
UNM (UNUSED MEMORY)	- MEMORY ACCESS TO AN EXISTENT BUT UNUSED MEMORY AREA
IRA (INVALID READ ADDRESS)	- READ ACCESS (FOR DATA) TO AN INSTRUCTION AREA, OR UNUSED OR NONEXISTENT MEMORY
IOC (INVALID OPCODE)	- FETCH OF AN ILLEGAL INSTRUCTION, OR AN INSTRUCTION NOT PART OF THE SUBSET USED IN THE SPECIFIC TASK SOFTWARE
IWA (INVALID WRITE ADDRESS)	- ATTEMPT TO WRITE INTO MEMORY NOT DESIGNATED AS ALTERABLE
NEM (NONEXISTENT MEMORY)	- ACCESS TO A LOCATION WITH NO MEMORY

Here is an example of what I mean by invalid program flow. We're talking here about an experiment and these are instructions for a Z-80, where at a certain point a fault is injected or the system is perturbed.

The first thing I want to point out is that from the point at which the system is perturbed, or the fault is injected, there is not necessarily an immediate response. But if an upset occurs and if it falls into the category of invalid program flow, I would like to show as an example that instead of the instructions being executed in the normal sequence, the next four instructions that are executed will fall into a special category.

Now, some interesting things can occur. That sequence of instructions could be valid. It could be another part of the program that the system has simply jumped to.

If you had put a logic analyzer onto the system at that time, you would see the system executing the code you had written. But the system has had an invalid program input.

Alternatively, that code could be an invalid code embedded in your valid code. It's actually written. You have written it. But it's invalid, and the system has found an embedded invalid loop and is executing it. It could eventually come out of that loop and begin executing the correct code again, or it could be caught forever in that loop, and unless you do a reset you're stuck in it.

Usually when the code is caught in an embedded loop, the system has crashed. The system is useless to you unless you physically intervene with a reset order. A popular way to get around this is to have a device called a watchdog timer, which is a device that will cause a reset if the system doesn't reset every so often.

We have seen examples in our lab where you find an invalid program loop that resets the timer. In effect, the watchdog timer is reset, and yet other than resetting the timer, the system is executing junk.

Take this example: this is the Z-80 in the read control line. What we see is the sequence of signals on the read control line corresponding to the execution of the instructions listed there. And this is a normal operation.

Here we have an injection of a 1- μ sec transient, and I want to indicate that this is the only injection. That fault is the physical perturbation. We literally seize this line, and hold it high, and that little downward spike is an artifact of the mechanism by which we seized the line. The injected fault is this perturbation right here. The remaining lines are the effects, the ramification, of that fault. The source is not dead. There is nothing now physically driving this line.

What this shows is that the source has died down, although there is an effect on the line. If I were to put a logic analyzer on that line and record what was going on, I think this would be the error level.

The code that should have been executed again is on the normal list, and that's the code that was executed relative to that transient-induced error on the line.

I think we have to know something about the system, how we can perturb a system and the ramifications of such a disturbance. From the systems level, we can do something about this case of invalid program flow.

In this case, we have only injected on one line. We can also inject on multiple lines, but usually one line is good enough, and the systems will respond to it. I mentioned that this code being executed could be valid or could be invalid. Here's an example of what I mean by that. This happens to be Intel 8085 code, loop L₀, that I wrote. That's what I wanted the system to perform for me.

These other two loops, L₁ and L₀, are embedded loops that will result from incorrect system operation because it's been glitched. It's executing the data associated with some of the instructions in the valid code. So I have two invalid loops. Now, if we go into the lab and we put in glitches like those in the previous slide, we can drive the system into the invalid loops, and it will stay there forever unless we reset it.

Invalid program flow is an example of systems level upset. We can do an invalid jump from, say, move immediate A to this NOP here. You can do an invalid jump from one part of the code to another part of the code.

But we can also, which is worse, find ourselves stuck from going from this valid loop to this invalid loop. We're stuck there, and the system has crashed.

And as far as the system is concerned, the microprocessor-based device, it's happy. It's executing code the way it thinks it should.

Again, for this example you can get around this with devices like a watchdog timer, but if you're not careful, the watchdog timer can also be reset, and still leave you in an invalid loop.

I want to talk a little bit about the experiments we do and what I think is important in experiments like this.

In effect, we have a single microprocessor-based device. We have looked at the Z-80 and the Intel 8085 and 8051. We're looking at the 8086 right now.

TABLE 5-4

Result	Addr	Data	L0 code	Li code	L2 code
L0	0000	00			
.	.	.			
.	.	.			
.	.	.			
L0	00C9	00			
L0	00CA	3E	MVI A,0C3H		
L1	00CB	C3		JMP 0D3H	
L0	00CC	D3	OUT 0		
L0	00CD	00			
L0	00CE	22	LXI H,0CFC3H		
L2	00CF	C3			JMP 0CFH
L0	00D0	CF			
L0	00D1	00	NOP		
L0	00D2	32	STA 0CBC3H		
L1	00D3	C3		JMP 0CBH	
L0	00D4	CB			
L0	00D5	00	NOP		
L0	00D6	C3	JMP 0CAH		
L0	00D7	CA			
L0	00D8	00			
L0	00D9	00			
.	.	.			
.	.	.			
.	.	.			
L0	00FE	00			
L0	00FF	C7			

Basically the devices we are looking at are like a printed circuit board. The way we do our analysis and the instrumentation complex that we set up looks something like that.

We have a program, and we have the system perform the program in what we call a normal run in which we record events. They're called micro events, on all the bus lines. We try to get as much information as we can about what the system did when it ran in the fault-free mode.

What we then do is take the same device and run it again, and this time we inject a fault and record the same data in a number of ways. But we can do a DMA into a computer device, which for us happens to be an 8085. We analyze it and, by replaying the information, try to determine the nature of the upset. Was the upset invalid program flow, invalid memory write, invalid memory read, or invalid op code?

I show this slide to characterize the upset; you have to have these normal data. I don't think that — although I have seen some people attempt to do it — you can just take this system and (on the basis of data that you record, or maybe even data that this system is recording for you) characterize the upset because the system itself is subject to the upset. It could be the recording mechanisms or the programs that are gathering the data for you that have been upset. And the upsets can be very subtle and devious.

There is the alternative of running two devices in parallel and recording everything in parallel with those two devices. We have chosen to go this route and have come up with what we consider to be a methodology.

This discussion understates the complexity of the instruments that we have. We have logic analyzers hanging all over the place. And the data I have shown you are based on about 2000 runs into which we injected various faults.

It's not simple. When you get in this business, you do a lot of recording of data and think you're learning all about upsets, and then you find out you're just screwing up. You're recording and you find the instruments are all out of sync. It's not trivial. You need a lot of micro event data, but you don't want so much information about what went on that the analysis becomes complex to the point that you can't do it.

There is an issue of too much data, and there is an issue of not enough. But this is the experimental approach that we take.

The other thing we used is the concept of the shell program. We take a generic program, and we identify a target. This example happens to be 9 bytes long. It can be longer. We shift the target within the program, but we inject at various points within the target in the shell. We try to have a robust enough collection of instructions and conditions in the shell that we're exercising the system. We're not seeing something because of a funny state that the system has been put into.

The issue also is when do you inject within the target area? There are well-behaved transients or nice transients which are nicely synchronized with a clock. We try to avoid that by moving the injection around so that we're not seeing some special case of a transient.

The nature of the shell program; we looked at two things. In our first series of experiments, we looked at our assembly language code. For the next series of experiments, we used a high-level language, PASCAL, and then with a compiler injected into the resulting assembly language, code what was produced.

Invalid program flow seems to be the predominant form that upsets tend to take, at least for the experiments we have seen.

We didn't want to be caught in some particular set of results that was unique to the assembly language code that we had written. So we thought if we went to a higher level language and took the assembly language code from that, we would not be caught up in that sort of thing. The experiments that we have been running have used either the assembly language or higher order language.

As I showed you with the example of the upset, we latch a pin either high or low. The duration can be for a single cycle of the machine, a microsecond or less.

We can also latch a pin or combination of pins for an entire instruction cycle of the machine or for multiple instruction cycles of the machine, and for something we call permanent where we simply seize the line and hold it for about 10 sec or so.

We inject into data lines, address lines, control lines, and the power supply. We inject a burst of noise into the power supply. And if you ask why, I guess

TABLE 5-5.- TEST METHODOLOGY EXPERIMENTAL CONDITIONS

FAULT TYPE	- LATCH (UP OR DOWN)
	- NOISE
FAULT DURATION	- SINGLE MACHINE CYCLE (~1 μ sec)
	- SINGLE INSTRUCTION CYCLE (~5 μ sec)
	- MULTI-INSTRUCTION (~100 μ sec)
	- PERMANENT (10 sec)
FAULT INJECTION INTO	- DATA LINES
	- ADDRESS LINES
	- CONTROL LINES
	- POWER SUPPLY
TARGET INSTRUCTIONS	- REPRESENTATIVE Z80 or 8085 INSTRUCTIONS

TABLE 5-6.- TEST METHODOLOGY COMPUTER PROGRAM ENVIRONMENT

FIRST SERIES OF EXPERIMENTS - ASSEMBLY LANGUAGE CODE

TARGET INSTRUCTIONS IMPLANTED AT A SINGLE TEST POINT IN PROGRAM

LARGE PROGRAM WITH TARGET INSTRUCTIONS AN INTEGRAL PART OF PROGRAM

SECOND SERIES OF EXPERIMENTS - HIGH LEVEL LANGUAGE (HLL) CODE

LARGE PROGRAM WITH TARGET INSTRUCTIONS AN INTEGRAL PART OF HLL PROGRAM

the answer is I want to see upsets. I don't quite know what else to do. The reason we do this set is that, if I were doing only a subset, someone could say it's just a special case. We try to have a robust enough set of injected faults that we're not seeing a peculiar response to one particular type.

We started doing this 9 months ago and we have seen about 2000 successful runs where we have had an upset. Sometimes you inject and you don't see an upset. You seize the line, and you're convinced that the systems should be clobbered by it, but upon analysis the normal run is about the same as the run where you have injected the faults. These are just ballpark figures. When we see an upset, about two-thirds of the time it's in the form of invalid program flow. One upset can fall into more than one category, but we see invalid program flow as a predominant category.

The numbers in parentheses next to the percentages correspond to the latency. For example, with the 8085 we see an average latency of about 6 μ sec. We inject the fault, record everything, and on the average of about 6 μ sec afterwards the upset begins to take shape.

One, two, and three, invalid program flow, invalid op code address, and invalid op code; those are the categories that tend to have the shortest latency, so

TABLE 5-7.- RESULTS OF EXPERIMENTATION

INVALID PROGRAM FLOW	63% (1)*
INVALID OPCODE ADDRESS	58% (2)*
UNUSED MEMORY	52% (5)**
INVALID READ ADDRESS	49% (6)**
INVALID OPCODE	37% (3)*
INVALID WRITE ADDRESS	20% (4)**
NONEXISTENT MEMORY	9% (7)***

they have the single asterisk. The double asterisk means that they seem to be grouped in the second upset set that we see in terms of time. The percentages indicate what we're starting to see as ballpark figures regarding the characterizations of the upsets.

I should also add that this is not a complete list of upsets. There are hybrids. There are things we see that we simply can't say that the system is definitely upset. In these cases we haven't been able to place it in one or more of the categories.

DR. AUCLAND: Dave Auckland, Syracuse Research Corporation. I was wondering how independent these results are to a particular piece of software.

DR. MASSON: This is the average for the higher level language and the assembly language. The numbers change a little bit. I don't claim if you do the same experiments, and you change your code and you go to a Motorola 6802 or something else, you'll see the same thing.

The point I want to make is that we see this invalid program flow as much as anything else. I think you can do something about the other categories, but I don't know what you can do about the invalid program fault.

As a matter of fact, this morning the discussion came up about the system not being able to change states. I can see how you can do something about invalid op code address, unused memory usage, invalid op code.

There are mechanisms you could build into the system to prevent that. But if you simply glitch the system and it jumps either to another point of valid code or to an invalid code, and we see that happening, I don't know what you're going to do, at least unless you have taken precautions.

I want to talk a little bit about some of the precautions you can take. But the point I want to emphasize is that the invalid program flow is what we see as much of as anything.

MR. SMITH: Hector Smith, Douglas. It would seem that by invalid program flow you mean a jump to a different place in the program executed. Some part of the program that wasn't supposed to execute?

DR. MASSON: Or jump to another valid part of the program, but you had no business going there from where you were.

MR. SMITH: It seems to me that if your program is large, with respect to the available memory addresses, there is a greater probability of jumping to a different part of the program. If your program is small, you have a greater probability of jumping to a new memory. Do you find that to be right?

DR. MASSON: Yes. If you fill up the memory space, then obviously you're going to start to eliminate categories like the nonexistent memory and things like that.

MR. SMITH: How do you eliminate the probability of that?

DR. MASSON: In the data here, the system had the ability to do any one of these.

MR. SMITH: Equal probable outcomes?

DR. MASSON: I wouldn't say that. The programs are about 3000 to 4000 bytes long, and the memory space is much bigger than that. So you really do have a lot of unused memory spaces you can go into. But you could put monitors on the bus lines to prevent the use of unused or nonexistent memory.

MR. SMITH: There was a great probability to go to the unused memory space and to stay within the program?

DR. MASSON: That's right. From my experience, upsets are observable. I think they are potentially controllable. I'm most concerned about the invalid program flow category.

I think you could do something about the other categories. I would like to show you some experiments regarding the results we have, and maybe a concept that we have, for considering deviations of program flow.

This concept is based around what we call a containment set. That is where the system is designed so that you are aware of all possible states that the system can go into. Now, those are valid states as well as invalid states. I'll denote my containment set as set L1 to LN, and that's simply a listing of all possible states.

TABLE 5-8.- CONTAINMENT SETS

-
- A FINITE SET OF MUTUALLY EXCLUSIVE FUNCTIONAL STATES
 - COVERS ALL POSSIBLE SYSTEM FUNCTIONS
 - INCLUDES:
 - VALID STATES
 - ERRONEOUS STATES

WE CAN DENOTE THE CONTAINMENT SET AS:

$$(L) = (L_1, L_2, \dots, L_N)$$

If you give me a large program, the containment set can also be large. And for the experiments that we have been doing, we deliberately build the containment set to be small.

MR. PEACOCK: Max Peacock, FAA. What is the order of L_N on the sets that you were working with?

DR. MASSON: We keep it simple from the analysis point of view -- in the range of about 10. We do this simply because the experiments that we work out, when we do the invalid program flow, we have to record sufficient data to figure out where we are.

I'll show you some experiments where it takes about 90 hr from a series of about 40,000 injections. To work out the results I have eight states; I'll show you the results of that.

But we could theoretically do the same set of experiments with N of any size. It's just that the analysis would take a long time.

What we're really looking for here is a sense of how well you can characterize a microprocessor-based device in terms of invalid program flows.

The system that we set up has a program, and basically the programs we execute are a sequence of loop programs in which, instead of getting some data for I/O devices, we're processing data on the basis of the input data, and it may stay in that loop for awhile. But then the input data will change, and it will jump to another loop until the input says you should change to another loop.

Embedded in those multiple loop program will be the valid loops, as well as the invalid loops.

A QUESTIONER: We used a similar technique to determine numbers of expected failures in systems, but we have had difficulty in applying it to software because we can't come up with a containment set for a program which is doing something other than checking itself.

Have you looked into that aspect of actually analyzing a program which is doing something other than an experimental?

DR. MASSON: I think that's the next step the research will take. We can now take a program written for the Intel 8085, and we have programs that analyze the code for that program.

It's a given that the system we were running on has some attributes to it to eliminate certain states that the system can go into. For example, Intel has things built into their devices that are internal test modes that are for use in-house, and you can glitch the device and put it into a mode like that. We have to have ways of knowing that the system is not doing things like that.

We're looking at taking an applications program on a system and putting that into another program that produces the containment set. But I'm not at the point where I could take any 8085 program and simply produce the containment sets. In that case the analysis that I have described here, the transition matrix, would fill this room if we wrote it out. There has to be some sort of a priori design with the containment set in mind.

Given the scenario that I'm working on here, we have these loop programs, and we can build the system such that the types of deviations of performance that we see are the fault of the category. If I'm in a certain loop program and I

TABLE 5-9.- CONTAINMENT SET FOR MICROPROCESSOR-BASED SYSTEMS

PROGRAM TYPES

- EXITING
- LOOPING

TAKE THE CONTAINMENT SET TO CONSIST OF ALL POSSIBLE LOOP PROGRAMS

- INCLUDES VALID LOOPS
 - INCLUDES ERRONEOUS LOOPS
-

inject my fault, I stay in the loop program, or I transition to another loop program. If I transition into an invalid loop program, unless I manually reset, we have a crash.

With that kind of characterization, I could then describe a transition matrix, where the transition matrix is such that I can talk about the probability of a transition taking place from state J to state I, given that a fault has occurred.

If I know the probability of where I am at some time period, K, and I have this transition matrix, T, I can come up with an assessment or probability of where I'm going to be if a transient occurs at time K plus 1.

What I want to show is that you can calculate to some extent the values that you need for T. I'm not saying it's simple, and I'm not saying you can go ahead and do it on any system that's submitted to you. There have to be some restraints on the way it's built. But I think this is a handle to developing the transition matrix.

If I know where I am, for example, at time 0 and I have K upsets, I can come up with a probabilistic definition of where I am at time K.

Now, some interesting things about the transition matrix in general. This particular transition matrix is one I made up to give you the idea.

There is one valid state and one invalid state. If you look at a system described by a transition matrix like this, if this system is in state 1 and I have a transient, the probability is about 0.75 that I'll stay in that state. And this transition matrix has a probability of 0.875 that I'll stay in the right state. You might think this system is somewhat more resilient to transient faults.

If you were to look at the same transition matrices, when the system is perturbed many times, this transition matrix turns into one in which you might as well flip a coin. You really have no idea of where you're going to go. Whereas this other one will turn into one in which you're more likely to stay in the correct state. This is just a hypothetical example. But it's the kind of phenomenon you will see if you can characterize the system with a transition matrix.

There is the opportunity to say things about the hardening, of the resilience of the system provided you can produce the matrix T. I won't go into all

TABLE 5-10.- CONTAINMENT SET TRANSITIONS

TRANSITION MATRIX:

$T = [p_{ij}]$, WHERE p_{ij} IS THE PROBABILITY OF A TRANSITION FROM STATE j TO STATE i , GIVEN THAT A FAULT HAS OCCURRED

$$L(K+1) = TL(K), \quad L(K) = \begin{bmatrix} p_1(k) \\ \vdots \\ p_n(k) \end{bmatrix}$$

$p_i(K)$ IS THE PROBABILITY OF BEING IN CONTAINMENT STATE $L_i \in \{L\}$ AFTER K UPSETS

AFTER K UPSETS,

$$L(K) = T^K L(0)$$

TABLE 5-11.- FAULT ANALYSIS AND SYSTEM VALIDATION

*SINGLE UPSET ENVIRONMENT

- P_{11} OF $T[p_{ij}]$ OF MAJOR CONCERN

*MULTIPLE UPSET ENVIRONMENT

- P_{11} OF T^K FOR LARGE K OF MAJOR CONCERN

*EXAMPLE

$$T^* = \begin{bmatrix} 3/4 & 15/16 \\ 1/4 & 1/16 \end{bmatrix}, \quad T^{**} = \begin{bmatrix} 7/8 & 1/8 \\ 1/8 & 7/8 \end{bmatrix}$$

$$\lim_{K \rightarrow \infty} (T^*)^K = \begin{bmatrix} 15/19 & 15/19 \\ 4/19 & 4/19 \end{bmatrix}, \quad \lim_{K \rightarrow \infty} (T^{**})^K = \begin{bmatrix} 1/2 & 1/2 \\ 1/2 & 1/2 \end{bmatrix}$$

ramifications, but these kinds of transition matrices have been studied for other phenomena. There is a lot of available theory that uses this.

If you can design the system to have a containment set that's finite and useful to you, you then start to become interested in the code. If you have the containment set for that system, you can produce a transition matrix. You then start to become interested in particular features of the code that might cause the transition matrix to change.

If you have a state in which the transient occurs, you would like to stay in that state, ideally in the same point in that state.

I think right now we can find and remove all the invalid loops in a system like the one I'm talking about. Unfortunately that is a less than elegant scheme.

We simply identify an invalid loop, change the code a little bit, and hope that it goes away. Then we analyze again to see if it has. There is no firm methodology for doing that.

But we can also look at the concept of what allows the system, when it's glitched, to change its path. What diverts the path? We're learning things about that so that we can build resilience into the system by removing the path diverters that cause these invalid jumps within the code.

Now, I want to show a transition matrix to you -- really two of them. It's for an 8085 system with eight states, and it's not in the probabilistic form. This is the very first step. It's noise injected for something less than a micro-second on the power supply.

TABLE 5-12.- PROGRAM PATH DIVERTERS

*HARDWARE	*SOFTWARE
- CLOCK STOP	- JUMP CATEGORY INSTRUCTIONS
- HALT	- CALL CATEGORY INSTRUCTIONS
- READY	- RETURN CATEGORY INSTRUCTIONS
- HOLD	(+ EFFECTS OF "UNDEFINED" INSTRUCTIONS)
- INTERRUPTS	

A PROGRAM STRUCTURAL ANALYSIS MUST BE MADE BASED ON PATH DIVERTERS

The system has eight states, and we know which eight states are there. The only response the system can have to an upset, a transient fault, is to do an invalid program flow.

We built it so that it can only do these invalid jumps. These are two runs, and each run consists of 5000 times putting the system into one state, and the rows correspond to the state, state 0 to state 7. We inject the fault at different windows within the code.

This particular program has about 1800 bytes of code. What I want to point out is that under two separate runs we're varying the point of injected noise.

There are things the system tends to do. It does not like to jump from any loops into states 4, 5, and 6, and it's consistent for two separate methods. These things take a long time for us to do because the analysis is done on a simple little microcomputer-based device. But the system likes to jump into states 0 and 1. For this particular set of experiments, at this particular noise level and pulse width, it likes to jump into loop 1 more than anything else. In 4769 times out of 5000 it stayed in loop 1 when the injected fault occurred. For the second run, in 4799 times out of 5000 it stayed in loop 1.

There is something there. It's not that we do two experiments and they are completely different. There is something that the system is tending to do. It likes to go to certain places, and doesn't like to go to other places.

TABLE 5-13

Noise level : 7.0 Pulse width : 2.0x1
 Prog. vers. : 6.1 No. exps /8 : 5000

	0	1	2	3	4	5	6	7
0 :	4737	118	45	53	9	6	3	30
1 :	78	4769	42	72	3	6	4	27
2 :	70	99	4714	68	6	6	9	29
3 :	84	112	33	4734	8	3	4	23
4 :	80	129	37	47	4672	7	2	27
5 :	158	45	43	45	8	4657	23	22
6 :	72	120	33	59	8	5	4670	34
7 :	58	109	43	66	9	5	5	4706

Noise level : 7.0 Pulse width : 2.0x1
 Prog. vers. : 6.1 No. exps /8 : 5000

	0	1	2	3	4	5	6	7
0 :	4769	122	33	40	5	8	0	24
1 :	81	4799	33	48	7	5	3	25
2 :	85	115	4698	59	5	5	4	30
3 :	73	120	25	4735	8	13	1	26
4 :	88	117	28	67	4658	5	4	34
5 :	179	42	28	65	8	4644	14	21
6 :	95	85	38	50	5	12	4690	26
7 :	92	108	34	46	5	8	8	4700

I wish I could say that the system likes to go to 0 and 1 because they are bigger than 4, 5, and 6, but that's not true. The system seems to put itself into a sensitive state, and it is ready to make a jump and it jumps.

Let me show you this same program, same system, different injected noise. It changes. This means that what I inject is important. In this case, the system tends to go to loop 0 more than it does to loop 1. It still does not like to go to 4, 5, and 6.

As we change what we inject, we can change the reaction of the system to it. It leads you to believe that maybe there is some way you could build the system making use of all its tendencies and sensitivities, so that only subsets would jump and the remainder would stay in a fault-free condition. And then perhaps by having most of the system in a fault-free condition, it could determine the faulted portion and cause the portion of the system that made the invalid jumps to recover.

We have seen this kind of data; unfortunately it takes us a long time to get it. We have a couple of system configurations from which some of the variants can be determined now. We have conducted some of the tests 20,000 times.

Obviously, if I take the same function and program it differently, the transition matrix will change. It's important to realize that if you change the code with this approach, you change the system's reaction to various faults. So

TABLE 5-14

Noise level : 5.6				Pulse width : 5.6x1				
Prog. vers. : 6.1				No. exps /8 : 5000				
	0	1	2	3	4	5	6	7
0 :	4700	161	27	61	2	8	2	40
1 :	153	4695	33	78	2	4	3	33
2 :	152	113	4628	66	2	8	3	29
3 :	141	134	34	4650	4	11	5	22
4 :	155	144	40	60	4555	6	6	35
5 :	214	81	46	60	8	4547	19	26
6 :	155	151	44	55	8	7	4547	34
7 :	144	132	33	70	7	7	4	4604

Noise level : 5.6				Pulse width : 5.6x1				
Prog. vers. : 6.1				No. exps /8 : 5000				
	0	1	2	3	4	5	6	7
0 :	4687	153	37	74	4	8	3	35
1 :	136	4688	36	77	9	11	9	35
2 :	160	132	4582	78	2	9	6	32
3 :	155	140	37	4609	12	11	5	32
4 :	136	170	40	48	4559	3	5	40
5 :	249	82	41	58	8	4513	16	34
6 :	157	130	29	63	8	11	4557	46
7 :	171	121	31	62	6	9	5	4596

doing a software patch on a program, or a system that you are confident is hardened, is going to have an effect on the hardened aspects of it. We can calculate these things. But, again, if you give me a block of code now and ask me to give you the transition matrix for it, maybe by the next meeting 3 yr from now I'll have it done.

I think you have to have a set of rules for the system you are interested in to follow. It can't be "anything goes."

Let me conclude by saying we think a concept that makes some sense relative to transient upsets is this transition matrix idea, particularly for the most predominant kind we see in our experiments, invalid program flow. It's coupled to the concept of the containment set. We think we can measure it in the laboratory.

What if I simply have a design that I haven't implemented, and I want to determine its resilience to various types of upsets. I don't know about that. The experimental stuff is messy enough. If you want to say that this is good and that's bad before you build it, that's going to be a hard one to approach.

I have a suitcase that has two microprocessor systems in it, and one is hardened to upsets, to invalid program flow, and the other is not. You can tell what state they are in by lights showing on LEDs. I glitched them both, and one

TABLE 5-15

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- CONTAINMENT SET AND TRANSITION MATRIX ANALYSIS PROVIDES A FRAMEWORK WITH WHICH TO ASSESS DESIGNS
 - MODIFICATION OF THE TRANSITION MATRIX BY HARDWARE AND SOFTWARE AUGMENTATIONS CAN PROVIDE TRANSIENT RESILIENCE
- THESE AUGMENTATIONS DEAL WITH PATH DIVERTERS
- REMOVAL OF ERRONEOUS ELEMENTS FROM THE CONTAINMENT SET PROVIDES TRANSIENT TOLERANCE
-

always stays in the same loops and program, and the other one will crash and the lights will freeze or go out.

I gave this talk at NASA Langley, and in order to demonstrate the concept I tilted the suitcase up on its side. There was a loose contact, I learned later. They taped that talk, and I've never seen that tape, but I hope they burn it. Because that demonstration didn't work.

But I want to conclude this. I can talk afterwards to people about how we have a system with only eight states and things like that. I also have a couple of publications with me.

There is this whole other subject called fault tolerant computing. And none of us working on that come to your conferences, and you don't come to ours. But I think we're going to get a solution to this problem by meetings like this where we get together. Maybe the next time we have one of these meetings there will be a couple of people in the fault tolerant computing area with approaches other than the ones that I have.

But I believe in addition to the transition matrix approach that I have talked about, there are systems level approaches that are valid, also, and might be of interest to you people who are faced with problems such as these.

MR. ISTWAN: Dale Istwan, Airline Pilots Association. I was wondering when you had a different sorting of faults with incorrect addressing, etc., if you could show how you might sort this thing out and what analysis you would use. Let's say that some statements were about to be executed by the processor where it was to write the result to RAM, and as a result of the fault or glitch on the address bus it ends up that the output was sent to ROM instead of going to RAM.

Compare that to a situation in which now you are going to intentionally read from a ROM address. But in this second case you have on the data bus a glitch that causes you to write out an op code and the address to follow. So the net effect is the same.

But what would normally follow in sequence would be entirely different because in the one case maybe a data point was going to be updated in RAM and injury created by trying to go to ROM is wasted effort, and it wasn't updated. Or in another case, where a read instruction that now became a write instruction, which normally would be followed by processing. How do you sort these two net effects out that are the same, but their location makes all the difference in the world as to what the consequences are?

DR. MASSON: You're saying that we're trying to characterize initially the form the upset took. But it's going to carry on, and it could get worse and could lead to a crash.

So you could, over time, see a number of different upsets because of the initial one, and we're gathering them all in and trying to say that for this injection we saw this number of upsets or these upsets.

MR. ISTWAN: In that instance you're not treating those two as a similar fault category, are you? Those are too different?

DR. MASSON: I think that's correct. I believe, from what you described, that we are not treating them as the same.

A QUESTIONER: Have you tried using a number of processors?

DR. MASSON: Yes, it's not that we have one 8085.

A QUESTIONER: Do you see differences?

DR. MASSON: No, not large variations. I'm glad it's not a large variation; that would disturb me. So it's characteristic to the processor itself.

A QUESTIONER: Do you think most of the solutions you're going to come up with are software solutions rather than hardware solutions that change the structure of the processor?

DR. MASSON: I would like a shot at designing my own processor eventually, to be resilient to transient faults. I think the way we approach this now is we're given this device, and we take what it's got, its internal test modes. We take everything. When I go to a Z80 I have to live with what they give me.

I have been thinking about going to something like the microprogrammable devices, the AMD, to build into it in the way it operates some of these resiliency ideas. Maybe eventually go to a "silicon foundry," I love that word, where you present them with a logic diagram and 10 sec later a chip comes out, and you plug it in and it works.

Going to a foundry like that with my crash-proof processing design and coming out with something other than an experiment — I need to know things about the way these processors work that the vendors won't tell me. I find out about internal test modes by discovering them, and they say, "oh, yes." I find out that these processors were originally supposed to use this op code, and they put all the hardware in there to do it, but for some reason they decided not to, and we learn things like that the hard way.

I think the experiments I work with would be more interesting if I didn't just stumble into things that later I find out I could have done something about a priori.

I also see, by the way, that you can monitor these upsets, the kinds of upsets that we're talking about, with very simple devices, combinational devices that you latch onto the bus. I can see, for example, in building the system to be resilient to upsets that you could have monitors that are sensitized to certain types of upsets.

Now, they have to know things about the program in the way that the system is going to execute it. But you can plug these things unobtrusively onto the bus. You can experimentally determine ahead of time how sensitive these monitors are to the upsets. You can calibrate them. And then you can expose the system you're interested in with these monitors attached to it.

The basis of the calibration, and the recorded data that these monitors give you, can give you a sense of how resilient the system you're interested in is to the upsets.

MR. SMITH: I think you have answered the question I had, and that was "do you see any differences between the 8085 and Z-80 to indicate that the chip design, or a different way of implementing the op code, would harden the system? Or is it programming?"

DR. MASSON: I can't come up with a definitive response to that. But I would like the chance to do it myself. There are things that I would do in the way they execute op codes . . .

There is another thing called stress. You can take the system you're interested in and push it, stress it, and then you inject the same kind of transient faults. Under these conditions, it more often will be glitched into an invalid program flow or one of these upset states.

The system can be stressed. So there is something about the way you write your program which causes a stress factor, and I don't understand it yet, but it exists. I think there is something in the way they are executing their op codes so that you can stress them in different ways, and maybe there is some way to undo the stress.

MR. TREACY: Jim Treacy, FAA. You're determining the fault by comparison with what a good program should do. Have you done any work to determine how difficult it is to detect that you had an interrupted program flow or some of the other faults?

DR. MASSON: You mean like a real time device that's going to give you a signal?

MR. TREACY: Yes.

DR. MASSON: I think that you can build a monitor that is simple relative to the complexity of the device that it's monitoring that can detect invalid program flow.

What it really has to know when you're executing an instruction at a certain point, is what valid places you can jump to are. It doesn't want to know anything about the kind of data you're putting out. It just wants to know you can go from point to point.

I think there is a good chance that a simple combinational circuit, a medium-scale integration-type device could be built that will simply tell you when you have invalid program flow or invalid memory read. It won't tell you what to do about it, but it would tell you that something should be done. And maybe you could get the indication soon enough to enable you to recover and not have to do a reset -- just roll back to a previous point and then go forward again.

I think we're looking at a simple mechanism, or device, to signal when an upset in a certain category has occurred. You can't have any disturbance of the

program so the monitor cannot really require that the system it's monitoring send it information. It has to "steal" it. I think there is a good chance we can build devices like that at least to expose the upsets.

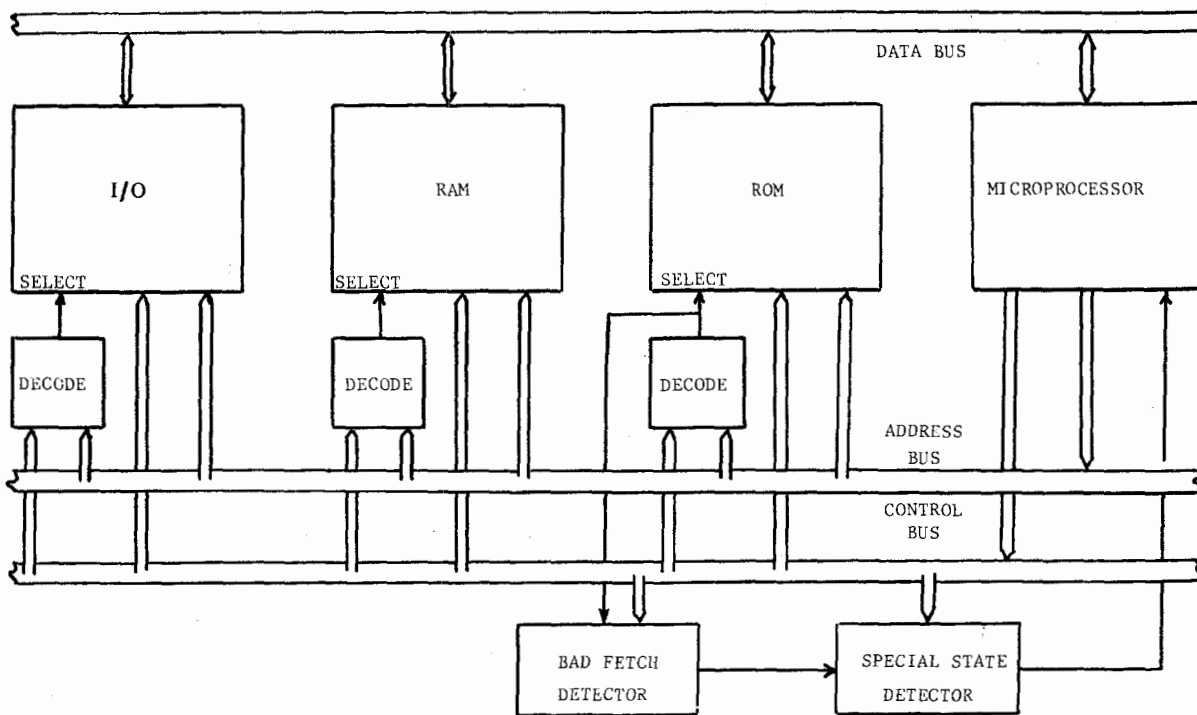


Figure 5-1.- Chip-bus layout.

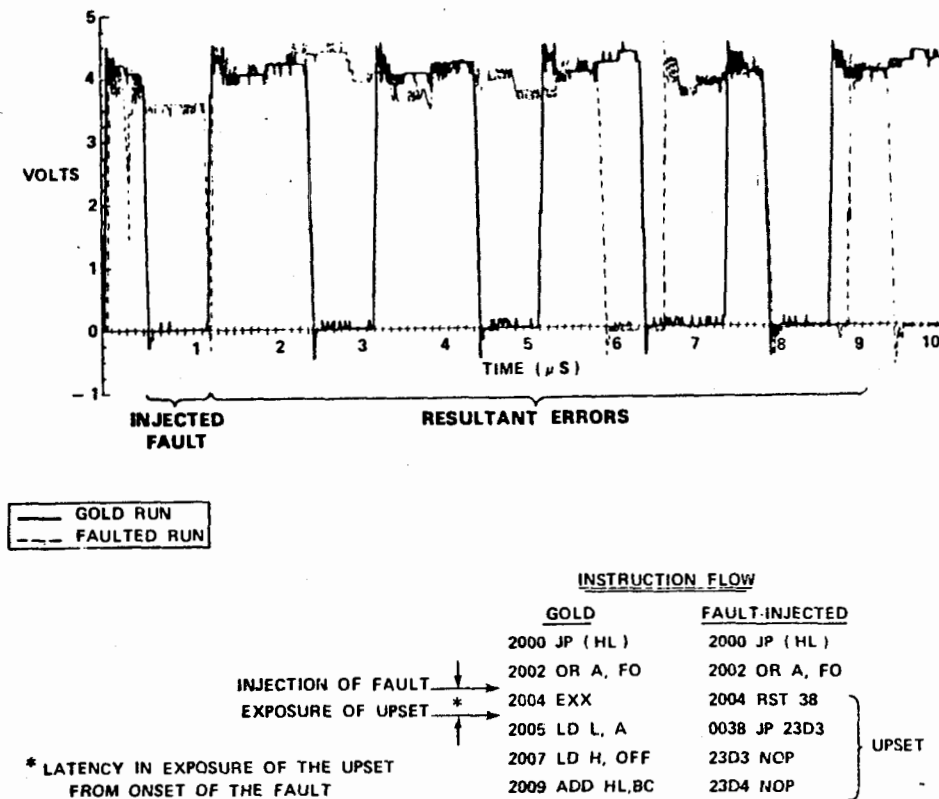


Figure 5-2.- Effect of transient injected on the "read" control line.

**EXPERIMENTAL
PROCEDURE**

**SERIES COMPARISON OF
GOLD & FAULTED RUNS**

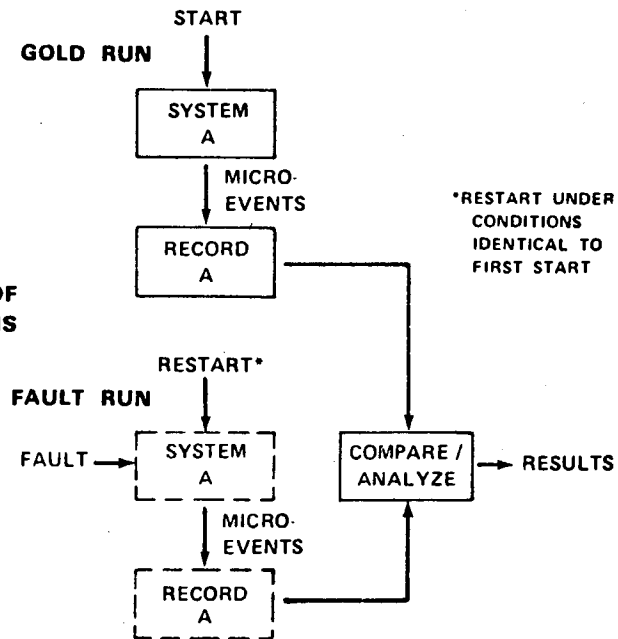


Figure 5-3.- A "gold run-fault run" approach to fault injection experimentation of a computer system.

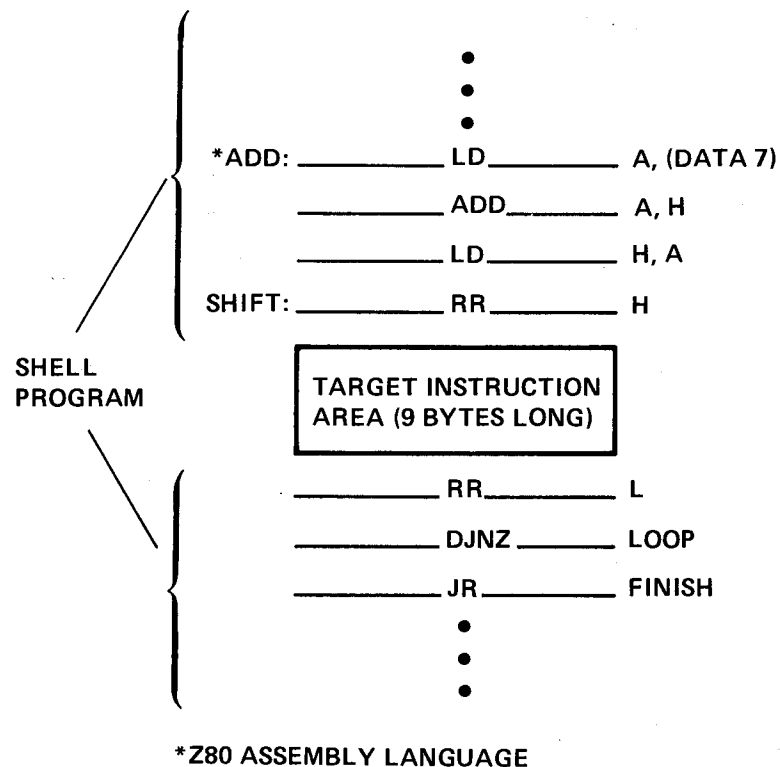


Figure 5-4.- Shell program concept.

EMI THREAT ENVIRONMENT — SUMMARY

Digital Failure Mechanisms, Coupling Paths, Noise Environment

Chris Kendall

Chris Kendall Consultants
Mariposa, California

MR. KENDALL: I would like to try to summarize where we have been today. Let's look at the underlying issue through all the presentations. That was the concern for transient effects: how we describe those effects, and how they are going to affect our definition of the problem, the design of the products, perhaps even our testing, as we just heard.

One of the things we have to be impressed with is that there are some unanswered questions, quite a few in fact, regarding what is a transient and what we do about it. Do we allow the system to perturbate in various classifications? Do we allow the transient to be a very fast rise time, on the order of 500 psec, with an amplitude of 1000 V. The width of that pulse would probably be 200 nsec. The question is how much energy is behind that transient? Could I just have a little capacitor or do I have Boulder Dam behind it? What do we know about the energy in transients?

I think that's another factor we may want to explore a little bit and see what can result. On power buses some years ago there was not a good correlation between some of the standards like MIL-STD-704 for transients on power lines; and MIL-E-6051, system integration spec for airplanes; and MIL-STD-461, the CS06, the so-called 10- μ sec, 1- μ sec rise time pulse. These transients are all voltage.

The problem with talking about voltage is that I can go just about anywhere in the airplane with a voltmeter and measure some significant voltage extremes or excursions, but that will not tell me one piece of information regarding the energy behind the transient.

So we have yet to deal with that problem. Just what is the energy behind these transients and how significant is it? Do we have to worry about our integrated chips and the so-called VLSI? What is the new one now? If we look at the junction real estate in these devices, it's extremely small, and we recognize that some of the transients can actually cause erosion of that junction area.

A phenomenon called current streaming has been documented over the years. It says that if a transient is fast enough in rise time as it goes through a junction area, it can actually erode the center of the junction area and cause permanent damage, even when the thermal calculations for the total area would indicate it wouldn't. Before the heat can dissipate to the edges of the traces it causes localized heating and possibly erosion. These concepts are far-reaching and raise serious issues as to the reliability of our products.

This morning I mentioned the possibility of picking up a chip and, without even knowing it, destroying the chip. There is only one thing worse than that, and that is picking up the chip and seriously degrading its performance. It would

appear to be all right, but it would fail prematurely when it was put into service.

These are things we still want to discuss and ponder. We need to come up with answers for (1) what is the real transient from these various sources, and (2) what is the energy level behind them.

This morning we talked about the threats, the way they come into the system, and some of the testing. We haven't talked about this a lot except for the presentation Keith was able to give us regarding the comparison of the two standards.

Even there, I think we pondered and considered that shopping list of testing that was discussed. Tremendous numbers of EMI tests exist, and the amount of time the product stays in EMI testing is substantial, depending upon the complexity of the design.

Yet most of those tests are not designed specifically for digital effects. Some of them could be useful, of course; for instance, RS-03, where we take a product and irradiate it with a certain level of intensity. I think one of the references was possibly as high as 100 V/m, a fairly strong signal. Much stronger than you would see from your CB radio, which tends to give you 10-20 V/m. It's not quite potent enough to cause baldness or any other perturbations to the body, thank goodness.

The radiation we're talking about is what we call nonionized radiation, as opposed to ionized radiation. We're dealing with radiation that is basically radio frequency in nature. This radiation level can vary quite a bit depending upon application. For instance, we mentioned an airplane flying on an approach to an airport and passing over an FM transmitting antenna. What would we expect to happen? We mentioned the possibility of dc rectification and/or modulation stripping of the rf signals as possible system responses to rf radiation.

The level of radiation that we would expect from narrowband radiation sources varies immensely, depending upon location. Some areas may be more critical than others. There is also the problem of what we call the rusty bolt situation where an antenna tower could actually corrode and rust, forming a diode detector that could remix some of the signals and retransmit new frequencies and new combinations.

In Los Angeles, there is a mountain called Mount Wilson. On Mount Wilson there are 1100 emitters in one square mile. I think it is the most amazing place that I have ever seen. It's fenced off. They oil the surrounding chain-link fence once a week just to prevent rusty bolt rf mixing conditions. If you take a Tripplett, turn it to the off position, and remove all the test leads, the meter remains pegged all the time you're in the area. So there is obvious concern for radiation.

I don't know about Burbank airport. I'm not sure you can approach it, as far as Mount Wilson is concerned. But there could be a concern as one approaches that area.

We know CW radiation is something we do have to concern ourselves with, from the design point of view. The problem in those areas, as you would guess, is the amount of mixing; it's phenomenal. We happened to put a repeater station up

there, and it was really an effort to pick a frequency that we could operate at. Just unreal, the amount of mixing that goes on.

So I think that this causes a little more concern about our digital avionics, and even the analog, the possibility of this upset to our circuits.

As we summarize and as we look at the various transient disturbances, one thing that digital systems tend to bring to mind is the possibility of a transient upset. We are concerned about the coupling mechanisms which are a function of speed, and the loop areas. The concerns that perhaps were acceptable for analog now become a challenge to digital.

Since we're summarizing, another thing I would like to spend a few minutes on is testing.

We were given a test list this morning, a rather comprehensive test list that would take a long time to perform if we did all the tests that were outlined. I think we should have some concern that most of the stress, in fact the only thing I could see of any consequence, may have been the referenced chattering relay test or relay transient test where we're dealing with a relay of undefined character. Even its age might affect the wave forms generated. Our concern is that it may have the fastest rise time of any device to threaten digital systems, and it is a potentially realistic threat. The rise time is typically faster than you would see in the CS06 or the 10- μ sec, 1- μ sec rise time test. Here we're dealing with a transient that is created by $L di/dt$, the inductance field collapsing at the rate of change of current. This inductive voltage transient that is generated usually has a rise time of anywhere from a few nanoseconds to a few hundred nanoseconds. The duration is fairly short, and it's repetitive, as shown, so that it has many make-break operations prior to physically breaking. As soon as it breaks it's ready to make contact again and start the sequence over.

We have also done a few experiments with this same type of relay. One of the things that's nice about it is if you fail it, you feel that you can do something about it. If you pass it, you feel very comfortable. So in a sense it becomes a test of a go-no-go situation with very little information as to what actual amplitude you may have failed at. If you failed the chattering relay test, for instance, you don't know how badly you failed it. Would you have failed the same test with a 1-V level? Or would you have failed the same thing at just under, say, the 600-V level indicated, maybe 595 V?

MR. VOGEL: Ray Vogel, Air Force Aeronautical Systems Division. The way to pass the test is to keep switching out relays until you finally find one that produces a spike that's not quite as bad as the other ones. That is how we find our contractors getting past that point. We don't have reproducibility. That's the problem. The standard is poorly defined.

MR. KENDALL: I think you're right, and I agree that that's probably the best thing to pursue. What kinds of tests could we develop that might be meaningful? One of the things I would like to suggest is the testing we do for commercial computers.

We found some time ago that transient phenomena are very disruptive to computers, and one of the things that disrupts them the most is the human body. There have been a lot of studies on the human body and a lot of special simulators built

for testing that supposedly represent the human body. One nice thing about them is that their wave forms are fairly precise. They have a set value of capacitance, a set source impedance, and usually have exacting transmission line layout techniques to ensure a very fast rise time phenomenon.

There are about three companies I can think of: one is a company called Experimental Physics Corporation which moved into Santa Clara recently. EXPX, they were called. Another is Andy Hish Associates, and a third is called Schraffner.

There are others, I'm sure. IBM in their main frame computers uses a rather interesting gadget called a "Zapper"; this device is aimed at stressing a computer from the possibility of human or furniture discharge. The wave forms are fairly precise. Typically they vary anywhere from 1 to 2 nsec to a maximum of 5 to 10 nsec.

The energy storage is generally in the range of 150 pF to 330 pF capacitor, with the worst ones going as high as 500 pF. In this case, the series resistance is a carbon resistor so you don't get reactive effect as you discharge, though it varies in impedance anywhere from 100 to 1500 ohms.

One of the most important things we have found from this type of testing, when you use this type of simulator to hit or discharge directly or indirectly, is that you get a very repeatable test. The wave form is that precise. The amount of energy is well controlled, which gives us a little less heartburn from the go-no-go situations of earlier years. You can change the amplitude at will and you can completely control the amplitude of discharge. Since you know the capacitor value, you have control of the energy being discharged, which is useful.

In these types of simulators, we found there are two failure mechanisms. The first and foremost failure mechanism is caused by the current, which is the one IBM simulates best by not using such a high voltage, but using a much smaller valve series resistor. In this situation the peak discharge current, again based on a 5-nsec rise time, is on the order of 80 A. When you discharge 80 A at 5 nsec, you have a rather strong magnetic phenomenon if you have not dressed your cables and terminated your shields correctly.

There is the other aspect of ESD phenomena, which is also important to test for and be concerned about. When you discharge the voltage fields at, say, human discharge levels (which are typically in the 10- to 15-kV range) you get an intense E-field radiation. This E-field can also be very disruptive to high-impedance circuits.

I'm not proposing that aircraft necessarily test to these levels. Some reasonable levels should be determined based on environmental studies of the vehicle itself.

These types of tests do help you pinpoint the source of entry into a system, for instance, indirect testing on the I/O cables. If you lay a cable similar to the chattering relay setup and replace it with an EXPX or Hish or Schraffner tester, where the wave forms are known to give indirect discharges, you can find the exact amplitude of failure. You can also determine how one compares to another.

We have done this on numerous computers. In fact, one of the classics I was involved with was a computer in Berne, Switzerland, a few months ago. They built the computer room over the train tracks. The train station takes a lot of room, so they felt it would be wise to put the computer room above the tracks.

These are electric trains. As the train comes in, it drops the pantograph, which is the mechanism from which it receives power. When that pantograph drops off the train, a blue showering arc occurs, which is rather obvious. The noise is a very large bang. When this happened, the computer decided it was time to take a nap.

Unfortunately, these are very expensive computers, and the customer wasn't happy with that kind of napping situation. We used the induced test I just mentioned, and tested the various cables in the system. What we found was rather surprising. We found that the major source of the problem was a power line sense cable. This cable was designed primarily to sense the power in the computer and feed it back to a special minicomputer to keep track of the large mainframe computer.

This cable was foil-wrapped. As it entered the computer it was supposed to be grounded. But the way they build these foil-wrapped cables is to metallize one side, but the other side is just polyester film. When they wrapped the cable, the polyester film was on the outside aimed outside the surface of the cable. Then when they were told to ground the cable at the port of entry, they removed the insulation, wrapped a braid around the polyester portion of the shield, and grounded it.

Well, that's great for polyester, I suppose, but it wasn't very good for the cable performance. So we had to invert the shield and ground the shield out, and that solved 90% of the problem. A very simple, very small cable caused that many headaches. This machine has 28 cables, and it was just one cable that caused 90% of the problem. It shows you how sensitive computers can be to ESD upset.

We have since gone in and experimented by improperly grounding other cables. No matter what cable we ungrounded, the problem came back. So every one had to be properly dressed.

It is kind of scary, really, when you consider the possibilities of aging and the possibility of corrosion on those surfaces. What would happen in a few years? We don't know the answers but they are interesting concerns when you consider that any one of those cables could have caused the problem.

It was the induced technique that helped us find the problem. We had used the chattering relay concept, but using the ESD type of simulator we found that in most cases all of the cables could take up to 25,000 V and not be disturbed. This one cable took 500 V and went bad. In this case it was a drastic, obvious change in performance and therefore it was easy to find the weak link.

Another thing we have found with ESD testing, over the years, is that people try to solve the problem in many different ways. In one case there was a requirement for withstanding a direct discharge so the manufacturer made the cabinet entirely of plastic. It wouldn't discharge. You could hit it all day

long, and there was no way you could draw an arc because there was nothing conductive. It passed the first test but when they got into the actual operation, it failed the second, the human, interaction.

Probably one of the first users of this computer was a person who had a metal desk top. The plastic computer was on the desk top and probably the first week of operation someone discharged to the desk top. The radiating field from the desk top completely wiped out the computer. The transient responded to the broad spectrum radiation of the metal table top.

Another concern is how to approach the problem. We recommend that an indirect test be conducted to make sure that this type of weakness is not missed and that it's discovered early and fixed, especially where there is no metallic surface to the computer.

So that gives us two possible tests. The third test is the direct discharge itself; making sure that the system would take and stand a direct discharge. The levels it should be at would have to be worked out. After all, we have to know what the probability of such a threat is, where it might occur, and how to best guard against it.

Do you shield the cable? Do you worry about back shells or that the shield has a coaxial termination; or do you use the 6-in. trick we heard about already? Do you build a filter pin or doghouse to the avionics box to improve it? That may help. But there are other questions - such as added weight and reliability questions. The single-point failure now exists. If I put a capacitor off the data bus to chassis ground and a transient comes by and causes a direct short, we have a failure; a single-point failure. This is a grave concern. In space vehicles this simply would not be allowed. You must not have a single-point failure, which means you must have two capacitors in series to use such protection. These are things that we're going to have to ponder here, too, I suspect.

Our last presenter did an excellent job telling us about the hopes that software may be a solution to help reduce the threats of transient phenomena.

Of course, that still does not answer the problem of direct radiation, because that would be more continuous. But it would answer transient disturbances, unless the transient rate got very fast. Then I suspect that would add further concerns.

If we had a transient occurring at 400-kHz rates, then perhaps that's more of a challenge than one operating at a 1-Hz rate. Those are some areas that we want to be concerned about. The next few days I think we would like to ponder some of these subjects in a little more depth.

With your good help, I think we have covered the outline of what we wanted to do and some of the objectives we hoped to extract from this workshop. I would like to think that we will now go into some of these areas in a little more depth. We should look at some of the threat mechanisms more analytically and look at some of the coupling systems with more numbers assigned to the variables. The test methodology also deserves more scrutiny so we can see whether we have some additional areas of concern.

ANALYZING THREATS — ANALYTICAL TOOLS

Chris Kendall

Chris Kendall Consultants
Mariposa, California

MR. RASCH: We're now ready to start our second day. I want to announce, by the way, the International Aerospace and Ground Conference on Lightning Static Electricity. It will be hosted by the NICG (which consists of the FAA, NASA, Army, Navy, Air Force, and NOAA) in Forth Worth, June 21 through June 23, 1983. We already have about a hundred abstracts, so we're expecting a hundred good papers.

I have a flier on the conference that I'm going to put here on the table. If you don't have a copy, pick up one.

Now I think we're ready to start with our first speaker, Chris Kendall.

MR. KENDALL: This morning we're going to go over analysis methodologies. We'll show where analysis exists today, what we can do with it, maybe even show you some of the ways it operates, to give us a little better feel of what we can accomplish in this area. First let's see if there are any questions, or areas of interest, before we get too far into the subject.

MR. KEUHL: I'm Greg Keuhl, Ozark Airlines. I have a question for Gerry Masson. Would you expand on your presentation of yesterday? Please describe the nature of the pulse that was used to cause a failure or upset the program flow of the digital system you were testing. Secondly, were particular lines more susceptible to upset? Finally, what program flow would you expect to see if the CPU was buried in a larger system?

DR. MASSON: Regarding the kinds of pulses; we latch lines, high or low, single lines and multiple lines, that is, accessible lines from the CPU. So this would be a control bus, the address bus, and the data bus.

The minimum amount of time that we have been latching lines is about one-half of a microsecond. We do that because of the cycle time of the CPU unit, which is longer than that.

Now, as to the shortest duration that can produce a program flow upset, I wouldn't want to guess at that right now. My feeling would be that we could go down to significantly shorter pulses.

MR. KEUHL: Relative to cycle times?

DR. MASSON: Yes. As far as what lines produce it, we see invalid program flow from injections on any single bus line as well as short pulses of noise on the power supply.

The pulses of noise are about the same length also. We have short as well as long pulses. And they all produce invalid program flows.

As far as a "buried unit" — by that I mean a CPU unit within a larger system. If the transients penetrate the system, I believe they can produce an equivalent effect on program flow that I have seen in the CPU only.

Should we expose the entire system to radiation, I feel we'd definitely see invalid program flow as one of the mechanisms by which the upset shows itself.

MR. SMITH: I'm Hector Smith, Douglas. What if you move the program to some other range?

DR. MASSON. Yes. We move the program around. And when you do that, then you're changing the address feeds. So there's no safe area or there's no particular dangerous area. I think it has something to do with the program being in a certain area, and the jumps aren't always that large; it tends to remain within the original program area.

It's as if you were to change all the bits on the address bus. Then you might be able to produce such a difference between where you want to go and where you are going, that you leave the program area, or region of memory. I think the jumps are more subtle than that. They're more bumps than jumps. But we do see the large jumps in memory location as well.

MR. KENDALL: Thank you. Any other questions? Okay. One of our concerns when we look at external threats, and how they might propagate into a given unit (either through the cabling or through the power line, or directly through radiation into the cabinet or case) is deciding how we're going to do the analysis. Should we do it in time domain, or in frequency domain, as we have discussed earlier?

The approach I'd like to share with you is the one dealing with frequency domain. Our first concern is to take the threat of, say, a transient of a given wave form characteristic; convert it into frequency domain using Fourier transformations; and then, in frequency domain, look at the various coupling mechanisms. That will give us a net frequency domain profile coupled into a given device, a logic gate, or something of that nature.

Then if we desire, we can retransform or inverse-transform that frequency domain information back into time domain data, depending on how well we have maintained the phase information.

For first order approximations, the easiest technique is simply to integrate the area under the curve. That will give us a "worst case," meaning that in some cases there will be lower conditions, or lower responses. At least, however, it would give us a "worst case" peak level introduced into that gate.

I think it's useful to do this, because in the process of going through these steps, we will also get information about what we might do to fix the problem. For instance, for a particular braided cable used for a particular data bus (say 429), we can determine if the shielding of the cable will be adequate. We do a frequency domain transfer function from the surface-induced current on the outside of the sheath to the voltage induced across an internal twisted pair.

If we find it's not adequate, then we can ask, "What can we do to this transfer function to improve it?" By looking at the parameters that affect the transfer function, we can get some insight.

For example, if we take a braided cable, which I alluded to yesterday, and simply wrap it with an aluminized polyester film, the shielding improvement about 10 MHz can exceed 40 dB, or a hundred-to-one improvement, just by that simple technique. So if we find the predominant threats to a cable are in the higher frequency region, perhaps there is an alternative if we are relying on shielding as the answer.

On the other hand, if we find that the braided cable is not sufficient to do the job in the high frequency, perhaps we can recognize that we can compensate for the lack of high-frequency protection by building filtering into the input connector of the unit being tested.

The amount of filtering, and the nature of that filtering, as far as its high-frequency characteristics are concerned, can be determined through that analysis process, at least on a "worst case" basis. And that's very helpful information.

I think we can gain benefits from this process as we go through the steps, even though it's a little detailed. But we're going to try to keep it simple.

First, let's see how we might go through the process of transferring a given threat from time domain to frequency domain.

Let's assume the threat is a pulse generated by static voltage buildup. We could also look at lightning. It's not too important. The process is what's important.

There are two techniques for doing this — the Fourier integral method and the Fourier series method. The Fourier series method is easier to manipulate, to some extent, especially if we make some assumptions. The assumption I'm going to make if I'm not going to be concerned with the exact amplitude at any given harmonic.

Now, since we're dealing with a unipulse, or a single pulse, or an infrequent pulse, we don't really have a repetitive situation. But I'm going to make it repetitive so you can see how you might manipulate the data. I'm going to give it a very slow repetition rate — 1 Hz.

Suppose I want to convert this to terms that are used by DO 160, in terms of decibel microvolts per megahertz bandwidth. I simply make the assumption that the pulse is coherent (not incoherent) broadbandwise, which means there is phasal relationship between one pulse and another. And if I do make that assumption, then I know that as I change bandwidth, I also change the amplitude.

For instance, let's assume that I take a measurement at 1 MHz, and at 1 MHz I use a bandwidth that's 1 Hz (not very practical, but possible). Suppose I had a slice of information with a 1-Hz bandwidth, at 1 MHz, and I asked that the amplitude would be if it were a 10-Hz slice, if it's coherent broadband. The fact that I multiply the bandwidth by a factor of 10 would mean that I also multiply the amplitude by a factor of 10. Therefore, there's a direct linear relationship between the bandwidth and the measured peak envelope.

Extrapolating that further to 1 MHz, what if we make a measurement at 1 MHz, with a 1-MHz bandwidth, 500 kHz on either side of 1 MHz, assuming constant amplitude with frequency noise distribution? Then we would add linearly, meaning that we would increase the amplitude by 1 million times because we've gone from 1 Hz to 1 MHz.

Now, in a practical situation, that isn't the way you make measurements for DO 160; some of the measurements start as low as 150 kHz. Let's take 150 kHz. At 150 kHz, the broadband data are required to be reported in terms of per megahertz bandwidth. Have you ever tried to tune a receiver with a 1-MHz bandwidth to 100 or 150 kHz? It's rather difficult because what does it mean to have negative bandwidths?

We recognize that isn't what's going to happen. What we also recognize is that the measurement will not be performed with a receiver with 1-MHz bandwidth. It will be performed with a 1-kHz, or possibly 10-kHz bandwidth. We assume that the data are linear from 150 kHz to 1 MHz. Obviously, that wouldn't happen in reality, but it's at least a basis from which we can compare data.

They didn't have to pick 1 MHz. They could have picked 1 kHz, and some emission specifications have. They used 1 kHz as the reference bandwidth. But we have to understand how they were manipulating the data, so we can use these data as a way of extrapolating information that we need to use, too.

When we're looking at the threat in terms of what might happen to a logic device, we're going to see that broadband data up to 1 MHz is not going to be very meaningful to us. We're only going to be looking at the data, say, from 1 to 30 or 1 to 60 MHz. We're really not too interested in the lower-frequency profile, because of the tremendous low-frequency coupling losses.

As we get into the high frequency region where the cable coupling losses are small and the cable transfer impedance allows a lot of voltage to be induced into the twisted pair, it becomes a more meaningful situation.

Let's start with the pulse itself. The attached figure gives typical assumptions of what the threat might look like. Remember, though, that these assumptions do not have universal acceptance. But let's look at a representative pulse (fig. 7-1).

Typically the voltage level rises very fast and then decays, usually with an exponential type of decay. Electrostatic discharge amplitudes vary from virtually no voltage to as high as 300,000 V. If you're in a helicopter, descending rapidly over dry, white snow, you could build up an ESD discharge as high as 300,000 V. But we won't pick the worst one. We'll just pick a 10,000-V threat.

Now, we can do the Fourier transform on an exponential wave form, but, for purposes of argument, it's just as simple to do it as a triangular wave form. It's that simple. The amount of information loss is not that significant, for what we're after. There is a slight difference, and if you want to be a little more accurate, that would be fine, too.

Now, with this wave form, there are two pieces of information I'm interested in. The pulse width, which I'll call d , is at the 50% point of the wave form. If

there's a disproportionate amount of rise to fall time, you could use one half of the fall time.

The rise time, t_r , is extremely important. We now have the rise time, we have d , and we have the amplitude of 10,000 V called out. So the only thing we need now is the periodicity, and we said we're going to use a 1-Hz rate. If this was really periodic, what I would see is a harmonic at every 1 Hz. So there would be a lot of harmonics in this window.

Once I know these four pieces of information (the amplitude, the pulse width, the rise time, and the repetition frequency) I have sufficient information to identify the loci of maximums in the frequency domain. I'll just give these to you rather than deriving them. (There are many good references, the ITT Handbook of Engineering, and many other articles dealing with this type of transformation.)

A triangular pulse will have the type of profile in frequency domain as shown. The only concern I have in identifying the resultant profile is to know what the fundamental frequency is.

Recognizing, then, f_1 is simply $1/\pi(d + t_r)$. And f_2 is simply $1/\pi t_r$.

Those are the two break points in the spectrum of loci maximums of the harmonic distribution. All we have to do is determine the amplitudes. And the amplitude is really straightforward, too.

I like to call the amplitude C_n and it is equal to $2A(d + t_r)/T$.

The fundamental amplitude at the fundamental frequency is $C_n = 72 \text{ dB}\mu\text{V/Hz}$. That's important, because if the pulse waveform was a trapezoid of 50%, like a switching power supply might have, or in a rectification of 400-Hz power, in a bridge rectifier, where we're on almost as much as we're off, the amplitude in the frequency domain is precisely equal to the amplitude in time domain at the fundamental amplitude.

You could argue that point, and I've had a few do that successfully, saying, "Really, it isn't exactly. If you use a little more rigorous analysis, it's just a tad higher." And that's probably true. But it's so insignificant in decibel terms, which are logarithmic expressions of the amplitude, it doesn't mean much.

So we'll make the basic assumption that in a 50% duty cycle, the amplitude in time domain equals the amplitude in frequency domain.

Now, you see if $d + t_r$ is at 50% amplitude, this would equal $t/2$. So you would have one-half of the original amplitude — so you have $2A(d + t_r)/T$. Therefore, if this relationship of $(d + t_r)T$ is equal to 2 on the bottom, the twos divide out, leaving the fundamental amplitude in frequency domain equal to the time domain amplitude. However, if I come down here to 1 Hz, which is my assumed fundamental frequency, what is this amplitude? Now, in this situation, $d + t_r$ is quite a bit less than 50% duty cycle. Let's assume that this is about 200 nsec at the halfway point. Now, with this information and a calculator we can virtually do the transformation. What this will tell us is that $d + t_r$ is 202 nsec.

So we have $(2 \times 10,000 \times 202 \times 10^{-9})/1$ which equals the amplitude at f_0 .

That would, of course, be expressed in terms of actual volts. So we have 404×10^{-5} V/Hz. We want to add that. Actually, this could be classified as a narrow-band signal, if you had a receiver with a bandwidth much less than 1 Hz. And you would see each harmonic in turn under this assumption.

Now, converting this to decibels — and the way they do that is 20 times the log of the ratio of microvolts, divided by 1 μ V. In this case, that would give me 4.04×10^3 μ V, divided by 1, that I'm taking the log of.

In that situation, we have the 20 log of 2 or 6 dB; 20 log of 4 is 12 dB and 10^3 is 60 dB, so that gives me 72 dB, decibel microvolts per hertz, as the level at the fundamental frequency.

That's not a very strong signal. As you can see, it's basically no more than about 4 mV. So 4 mV can't do any damage, can it? But that's per hertz bandwidth. If your analog circuit, or whatever circuit you're looking at, had a very small bandwidth, it wouldn't do very much damage.

Let's determine the bandwidth response of our devices. If you have an "enable" signal, that's the world's worst type of signal for transient upset because it's sitting there saying, "hit me." Some people do with transient effects, and once it gets hit, it latches, and that's the end of it. It's back into a reset mode or an enable mode, or something.

In that situation you have to be cautious. One of the requirements that a lot of people will place on the signal is that it shall not respond to transients of a certain duration, typically a millisecond, or maybe 10 μ sec, or whatever the criterion happens to be.

It says that a transient of less than 10 μ sec must not latch this enable signal, which simply means that it has to be filtered in such a way with an RC or an LC circuit that it will not respond to any transients that are less than 10 μ sec in duration.

Now we have the 72-dB μ V-Hz level. That is all we need to define the spectrum. It remains 72 until the frequency of f_1 is obtained. That's approximately equal to 300 MHz divided by the pulse width in nanoseconds. Since we're dealing with 200 nsec, it's $300/200$, which gives us approximately 1.5 MHz, which is the f_1 frequency.

The f_2 frequency is arrived at the same way. It's approximately 300 MHz divided by the rise time in nanoseconds. In this case, we've assumed 2. So, $300/2$ is 150 MHz wide. The f_2 frequency is 150 MHz for this example.

Someone yesterday was asking how the waveform parameters affect the threat. It's kind of fun to look at these numbers, now, and ask that question.

What would happen if the rise time was not 2 nsec, but 20 nsec? What would happen to f_2 ? It would not be 150 MHz, but simply 15 MHz. That's a significant difference.

If indeed it was not 2 nsec, but was 200 nsec, now we're talking about 1.5 MHz — which is a significant difference in the threat.

The rise time makes a very important difference to the threat. An excellent paper on this subject was presented at the symposium, by Ed Black who is on my staff. The point he made was that the test that you perform on a digital device only has to be with a pulse rise time that just exceeds the functional bandwidth of the logic that you're using.

Let's assume you're using T^2L . T^2L is approximately 30 MHz. If that's the case, then you want to make sure that the transient stress at least exceeds the 30-MHz useful bandwidth. You would therefore use a pulse tester that had a rise time of approximately 10 nsec or faster. If the threat rise time exceeded the test rise time for any fast rise time threat (like ESD or P-static), the threat would be properly tested for.

Now the amplitude of the threat is another part of the issue, as long as the stress is as fast as the bandwidth of the logic you're dealing with.

With this information derived, we now know the profile, simply 72 dB/Hz out to f_1 , which is 1.5 MHz, then dropping in a linear fashion with frequency down to f_2 (-20 dB is a linear drop in frequency), which is 150 MHz.

So the threat has plenty of energy, plenty of threatening power, in this particular example from the ESD phenomenon, out to a frequency of 150 MHz — what we have defined as the useful bandwidth of the threat. And that's the problem, which is pretty scary, and also pretty real.

Let's assume this is indeed our envelope. Our next step is to identify the transfer function.

There are two parts to this transfer function. This signal could be discharged directly into the logic, which is probably not likely; it could be coupled into the logic through capacitive or inductive coupling; or it could be irradiated into the wire, because of radiation due to the P-static or ESD phenomenon.

Either way, there's going to be a transfer function. Let's look at these transfer functions now. But first, let's compute the amplitude of f_2 , since it's dropping at a 20 dB rate. The way we compute this amplitude is to take the amplitude at f_1 minus 20 times the log of the ratio of f_2 , divided by f_1 . That gives us the amplitude at f_2 . The amplitude at f_2 is simply equal to the amplitude computation after f_2 , it's 40 times the log ratio of whatever the frequency is above f_2 , to f_2 .

That being the case, f_1 , we know, is at 1.5, and f_2 is at 150, and the difference in the two is what? A hundred to one. Correct?

Twenty times the log of 100 is simply 40 dB. I now subtract 40 dB from 72 dB, giving me 32 dB μ V/Hz bandwidth at the f_2 frequency.

Basically we're trying to get the amplitude distribution in terms of frequency domain. This, of course, is only the loci of maximums. I'm not bothering with precise amplitudes.

If you made the actual measurements, there would be a curvature although some of the amplitudes would not come to the curve. If you did the whole spectral

analysis, the harmonics would follow this loci of maximums. Now let's look at how those data can be transferred.

First let's consider the case of crosstalk. In the case of crosstalk, let's draw a typical circuit, a cable, and a box. We'll use a standard ARINC connector, and we will have a cable going to one particular box. We may also have another cable coming in, being routed for a distance, and then leaving. This would be to some other set of equipment.

We now have a situation in which the two cables are in parallel for a certain prescribed distance, and have a certain amount of separation distance. They also have a certain source load impedance. There are two types of source load impedance we're concerned about: (1) the pin to pin, but more importantly, (2) the pin to ground — the common mode effect which is often ignored, but generally is the greatest of all threats.

In this situation, there are two types of coupling, capacitive and inductive. The amount of capacitive and inductive coupling, and how it flows is precisely dependent upon the physical parameters of cable length, diameter, separation distance, height above ground, etc. (fig. 7-2).

We will not be getting into the actual equation here (it's a far more complicated situation than the other). There is an excellent source where you can look it up. But let's look at a typical result. When we look at the capacitive coupling situation, we find some very interesting transfer functions. In this case, let's look at the transfer function that relates to the voltage in the inner circuit; common mode, in relationship to frequency.

Let's look at capacitive coupling first. Here's our original threat and we're going to plot it, recognizing that some very important information has to be added — the length of the coupling and the height above ground. All of the profiles follow a very distinct pattern, and that's what I want to plot.

I'm going to do this in general terms. If we look at capacitive coupling for a certain set of geometry, we're going to find that the coupling does this (assuming electrically short conditions, by the way).

Now, look at this profile. We see a slope increase in coupling, meaning that we're getting more and more voltage induced for a certain amount of current flow or voltage in the culprit circuit to the victim circuit.

This is the relationship for a fixed amount of voltage in the culprit circuit. In the victim circuit, the coupling is getting more and more enhanced. Typically, this range varies, but the most significant thing is that this maximum point where it becomes independent of frequency is typically in the 5-MHz region. If the cables are widely separated, this is not true. We're talking of distances in cabling, say, from a foot down to maybe a micro-inch in separation.

In this range, the maximum is typically in the 5-MHz range. The coupling becomes independent of the frequency.

When the coupling is independent of the frequency, the question becomes just how many decibels down is this from the original signal that was available.

That depends again on the source load impedances and the geometry. Typically, for very close to reasonably separated cables, this variation depends on length and source load impedance. For unshielded cables typically this amplitude drop from the original varies from 0 to -20 dB, with the average (if there is such a thing) being between 6 and 12 dB. This means that whatever was in the victim circuit, half to one-fourth of the voltage is coupled into the victim circuit from the culprit circuit. These are typical numbers.

If we use cable shielding, this can be improved. Shielding is obviously a solution. One of the ways we can reduce crosstalk is to shield the cables.

A rule of thumb used by computer manufacturers was that if the two cable groups were totally unshielded, they must be separated by at least a foot. If one of the two were shielded, then they would have to be separated by 4 in. If they were both shielded, at least a 2-in. separation must be maintained. That's for commercial equipment. We're not talking about something as highly critical as the aircraft.

For that rule of thumb, there's some minimum and reasonable cable separations involved. It doesn't mean that you must maintain 2 in. if the parallel run is only 2 in.

We recognize, therefore, that the capacitive coupling gets worse with frequency. The slope of the disturbance spectrum is important here. This slope is 20 dB per frequency decade. If I go from 1 MHz to 10 MHz, there's a difference of 10. Therefore I would get 20 dB greater coupling at 10 MHz than I would have at 1 MHz.

DR. MASSON: Gerald Masson, Johns Hopkins. What's the physical effect? What physical phenomenon is causing the independent frequency situation?

MR. KENDALL: It is the stray capacitance shunting each end, so the equation is nothing but a simple capacitive (or voltage) dividing network at high frequency. Initially, you have the actual resistors in the circuit, and eventually the common mode stray capacitance of the circuits at each end. The PC board inside a box at one end, and the PC board laminate over the box forming a capacitor. That capacitor is in shunt with the terminating resistance. The reactive impedance of the stray capacitance eventually eliminates the resistor as part of the circuit. Therefore, it becomes independent of frequency.

Now, what would happen to this transfer function if it becomes electrically long? (Assuming that the cables are electrically short.) Some excellent models have been developed.

We find that the frequency would be further perturbed by the electrical length of the cables, and there would be two electrical lengths. Let's assume for a moment they were both the same. If these were the same distances and electrical lengths, the coupling would be perturbed further by the electrical length or standing wave effect of the cables. If you've got two cables, they would be perturbed twice, and you would get adding and subtracting of these out-of-phase lengths.

It gets still more complicated. But even there, the peaks still come up to the curve, and that's significant. Since we're not looking for the exact lengths, let's just ignore it, for practical purposes.

If these cables were electrically long, you would get this crescendo effect of the coupling mechanisms.

Any other questions?

MR. SMITH: Hector Smith, Douglas. Do you run across a situation in which the wire is going to a strong resonance, and actually builds up energy above the source?

MR. KENDALL: Yes, but it depends on the source load impedance, because these cables really form transmission lines to the fuselage of the airplane. They won't actually be equal everywhere.

In a real situation, the cable goes through a bulkhead.

MR. SMITH: What I'm trying to bring out, there are cases . . .

MR. KENDALL: Yes. You can get an effect like the Q of a circuit which will determine the gain of that particular situation. But most of the circuits are not necessarily high Q , so you get gain, but it's not a significant gain. A 6 dB gain, or something like that, might be typical.

Hector is saying that it's possible you might even exceed this coupling and that's why I've used 0 to 20. It might actually be +6 because of the effect of the cable having a resonant Q effect. Therefore, you can get gain equal to the Q resonance of the circuits. Good point.

Yes?

MR. ECKLAND: Eckland, from Boeing. What would the curve look like at PC board levels maybe equal with the ground plane? Is there any variation, or is electrically short still going to be too long?

MR. KENDALL: The real question is what would happen if the geometries were smaller, like the PC board, as opposed to long cable harnesses? This frequency, this point where it becomes maximum, is determined by the electrical parameters -- or the physical parameters, if the distance is a few inches as compared to a few feet or a few meters.

Therefore, if we had a PC board coupling problem, the general slope is the same. It happens at a much higher frequency. So when this becomes maximum, instead of maybe 1 MHz, it's now 10 MHz; you have a variation according to the length.

The shorter the length, the higher the frequency before you reach maximum. But once you do reach maximum, it's still usually in that 0- to 20-dB number.

The ground plane is significant. If you add a ground plane to a PC board, the coupling is dropped significantly. If you have guard traces, you can do lots of things on PC boards to reduce this effect. You can do lots of things to the cable to reduce the effect, also.

Recognizing we have this transfer function, and recognizing our original threat, I'd like to superimpose the curves. I'm going to make some assumptions and see what happens. I think you'll be amazed to see what's going to happen.

I'm going to add the ESD spectrum curve to the crosstalk curve. In the ESD curve, we had a situation in which we stayed at 0 slope from virtually 1 Hz to 1.5 MHz. In the transfer function during that same region, we assumed the peak to occur at 5 MHz; during that exact same region, we had a 20 dB slope.

Now, if I add 0 slope and -20 I get -20. Therefore, my net induced voltage into the load in the region of 0 to 1.5 MHz is this -20 dB slope. From 1.5 MHz to 150 MHz, I have a -20 dB slope from ESD.

The crosstalk from 1.5 to 5 is still increasing at 20. So I end up with a net 0 dB change.

At 5 MHz, I have 0 slope for the crosstalk, and I have a -20 for the amplitude reduction, giving me net -20. That's going to continue until I reach the break point in frequency, which is 150 MHz. At that point, my crosstalk still remains at 0, but my slope is dropping off at a 40 dB rate.

That's very significant. It shows that in the low-frequency regions, I do not have a very good transfer of information. But between 2 to 5 MHz, I get a peak transfer of interference, and then it begins to roll off according to the rise time of the threat.

Typically, if you did look at this envelope, you would observe a damped sinusoidal response effect. It may not be critically damped, although it could be. But this usually creates ringing in your circuit, because you suppress at the low end, reach a maximum, and then you suppress again. This almost always is typical of a damped ringing pulse.

The important thing is where the greatest transfer occurs is also where the greatest threat to the logic occurs. In this region the logic is really going to respond.

Then at 1.5 MHz, where I had 72 dB $\mu\text{V}/\text{Hz}$, I now have 62 dB $\mu\text{V}/\text{Hz}$. I'm 10 dB lower, because of the crosstalk. So that at this frequency, 62 dB $\mu\text{V}/\text{Hz}$ got induced.

Let's assume I'm integrating from 1 to 5 MHz, and 62 dB $\mu\text{V}/\text{Hz}$ was the level. First of all, I have to convert from hertz to megahertz, and I have to convert from megahertz to 5 MHz. When you're integrating, if it's coherent noise, we're looking for the difference between the narrow-band level and the broadband level from the ESD curve.

From the ESD curve the amplitudes are per hertz. So the actual broadband level is going to equal 20 times the log of the bandwidth of the receiver, divided by the pulse repetition rate of the signal, which is 1 Hz.

Therefore, I want to know what happens from 1 to 5 MHz, a 4 MHz difference. All I really have to do is put in 4 MHz and divide by 1 Hz. That is the factor I add to this number to get the total effect. This is nothing more than 4×10^6 , and 20 times the log of 4×10^6 is simply 120 dB, and 4 is simply 12 dB, so it's 132 dB.

Add that to my 62, and I get 194 dB, or approximately 200 V induced into the circuit. My threat was 10,000 V. I got 200 V induced. This is a very good way to look at the phenomena.

I got 200 V simply from 1 to 5 MHz. If I integrate beyond, I'm going to pick up a little more threat. It won't be as great because it's decreasing, but it's still going to be additive. After here, it becomes insignificant to integrate. But I should integrate this region.

I have at least a 200-V threat caused by the capacitive crosstalk between two cables, one being hit by 10,000 V.

That's rather significant. What does it normally take to disrupt the circuit? One volt. In a logic gate, we have typically 1 V of dc noise immunity, and now I'm 200 times higher.

What does it take to damage a circuit? Usually around 50 V. If I sustain an electrostatic discharge (ESD) hit, and I have no cable shielding and no other protection, I could destroy most integrated circuits (ICs).

Fortunately, we usually do shield. Typical braided cable shields, in this frequency range, would yield anywhere from a high of 70 dB to a low of 20 or 30 dB, unless you've grounded and shielded only one end (fig. 7-3).

If you shield the cable and ground the shield at one end, the shielding achieved at $\lambda/4$ is 0. If your shielded cable is grounded at only one end, that cable better be electrically short for the threat you're dealing with. Otherwise, you're going to have a very serious problem.

You will see the full 200 V. This is well substantiated by a recent paper showing that if you hit a box with 10,000 V, as I've indicated here, you will see 600 V induced into the circuit. This occurs even when the cable is fully shielded with no lead exposure, but the shield is only ground referenced at one box.

We're computing 200 V mathematically. So I think our numbers are conservative, and quite typical of what you could expect.

We now see how this happens. We see that the threat is not in the range of 10 kHz, or 1 kHz. The major threat is actually in the 1 to 5 MHz range in this particular example, or 1 to 150 MHz if I'd completed the integration. To complete the analysis would probably raise the induced voltage another 200 V; therefore, our total threat would be around 400 V. This is in the case of crosstalk, which is one of the major threats to a system.

The next major threat is radiation. What would be the radiation crosstalk? This requires another analysis. First of all, we've only looked at the voltage waveform; we must convert the voltage existing on the wire into its equivalent E-field that will emanate from the lead. Then we look at the second wire as a receiver, and if it is a true receiver of some consequence, and it's impinged on by a homogeneous E-field, what will be the voltage coupled into the circuit? We have two more efforts that we have to go through.

The first effort is predicting the radiation field. There are some excellent models. I like to look at the simple model to obtain a first order approximation.

In this situation, we're interested in taking the voltage on a given wire. This wire is going to have some impedance to its return. I'm interested in the common mode effect to ground. So, therefore, I want to know what is the terminating impedance of a logic gate at the far end?

Let's take the 429 bus for a moment. I believe 429 is a differential signal, a two-shielded twisted pair, transformer-coupled, or something like that? At least 1553 is.

I'm not interested in the voltage that's going to appear pin to pin on that differential pair. I am interested in the voltage that's going to appear between one or both of those wires and ground, because that's what's going to radiate -- the voltage that's allowed between each pair and the chassis of the fuselage of the airplane, if there is one.

If there isn't one, it will have even more radiation. So the fuselage can actually help a little bit.

I'm interested in the common mode impedance. Typically, that's high because you have purposely made it high, with the hopes that you could help the system by eliminating impedance to ground and avoid possible ground loop currents.

Well, that's a marvelous argument, providing you don't get to 5 MHz. At 5 MHz, there has to be current flow because of the stray capacitance. And that loop is closed whether you want it to be closed or not. We'll get into that as time permits, and show how that happens.

Let's now look at the common mode effect. The impedance is high, and we'll assume that this is the driven impedance. So we have an antenna effect. The first area of concern will be the electrical length of that wire. That represents the first frequency of major radiation.

What I like to do is use some of the following terms. The attached drawing shows a typical example (fig. 7-4).

If I put an antenna 1 m from that wire, and I tune this antenna, or I measure the E-field, at the $\lambda/4$ frequency or multiples thereafter, $3\lambda/4$, $5\lambda/4$, $7\lambda/4$, the field would be three times lower than the voltage on the wire. You can derive that mathematically. We have measured this in the lab, and it seems to be a pretty good average.

Let's look at 1.5 MHz. I'm not too interested in numbers below that. We know the voltage amplitude was 72 dB $\mu\text{V}/\text{Hz}$. Now we're going to subtract 34, because that's going to be the E-field at resonance, 1 m from the lead.

We now have another correction. The Air Force manual for looking at antennas says that if you want to know the antenna factor or the gain of an antenna at a frequency other than its resonant frequency, you should subtract 20 dB per frequency decade, from frequencies below the resonant frequency of the antenna, or 10 dB if you're dealing with power gain. We could use that same model here. But we've been in the lab, and found that 20 dB is a little too generous, and 10 dB is a little too much the other way.

Since we're looking for a "worst case" effect, I'm going to recommend to you -10 times the log of the frequency of resonance, f_3 divided by f_x , the frequency of interest to us.

This is saying that the wire is not at resonance, and you have to correct radiation at frequencies less than the resonant length of that wire segment.

The next term that I offer for consideration is the number of elements that can radiate. This is especially useful in terms of data cables where you have more than one conductor to the radiation profile. There I'm going to recommend that you use $10 \log n$. But n is a total number of conductors, not necessarily carrying the same digital data, but all carrying the digital data generated from the same clock reference.

That would be what you're trying to use if you're trying to predict radiation from logic. Now, since we're not, we're interested only in pulse phenomena, so we're not going to use this factor. But I throw that in for consideration if you were using this for other purposes.

There is another correction we could use, but it's not too meaningful. That is, what happens at distances other than 1 m of separation? I'm going to make this measurement at 10 m, or 100 m. Well, then I would have to have a distance correction, because all I have done so far is predict the amplitude at 1 m away from the wire segment. Then from 10 m away, I'd have to use the model of a linear dropoff for distance. That's your "worst case" dropoff rate of E-field radiation. Use a $1/R$ model for that purpose. But we don't have to do that here, because we are measuring at 1 m. If you're closer than 1 m, then it's an added factor.

So now we'll simply sum the numbers on the drawing. In this case, we have 1.5 MHz. We started off with a 72 dB level. We subtract 34 dB. Now we have to ask how long the cable is, so we can correct for the cable length, which is the ratio of f_3/f_x .

Yesterday we used some examples. There were 20, 50, and 100 ft cables. Let's pick a 30 ft cable, and convert to meters. Let's just call it 10 m.

If the cable is 10 m, we would like to know what the f_3 frequency is. The f_3 frequency from the calculations is the speed of light, 3×10^8 m/sec divided by four times the cable length — because I'm looking for the $\lambda/4$ frequency. That being the case, we would have about 0.75×10^7 MHz.

We want to take that number and use that as our f_3 frequency in this calculation. That would be our frequency. If that's the case, we are looking at 1.5 MHz. Since we're looking at 1.5 MHz, and we're not above 7.5 MHz, we do have to use this correction. Ten times the log difference of 7.5 to 1.5 is approximately 5. So 10 times the log of 5 is about -7 dB.

Now we say that the amplitude is 72 minus 34 minus 7, or 72 minus 41. And that gives 31. Thirty-one decibels microvolts per meter, because that's the conversion that this gave me, per meter, per hertz bandwidth.

Now we want to know what damage that can do. We've got that level. We will first want to convert it to megahertz. To do that, you have to add 120 to 31.

So, if I want to take that same frequency and convert it, this will be 151 dB $\mu\text{V}/\text{m MHz}$, for those who are interested in per megahertz bandwidth. You simply add the 120. That's the radiating field.

Now, looking at that for a moment, the 1.5 MHz is the first break frequency, and the next break frequency is 150 MHz. Let's convert it for the two break frequencies. We also have to do it for the one in between. That being the case, 1.5 to 7.5, in that region, we were dropping at a linear rate of 20 dB, and again we got the 5 to 1, so it would be about 14 dB lower. That would be 58 dB.

What we have is 58 minus 34, or 24 dB. Then at 150 MHz, we're dropping from 7.5 dB to 75 dB. That would drop 20 dB and 75 dB down to 50 dB or another 6 dB drop. So it would be 26 dB lower than 58 dB, which would be 32 dB minus 34 dB, and 0. We get a minus number, -2 dB μV . So now we have the profile of the radiation.

Next question. If we are radiating (which we are) how does that couple into a wire? What does that transfer function look like? If we look at it in those terms, what we have is the reverse of this. We have a wire, or a cable, sitting between two boxes, with connectors, and we are now radiating an E-field at these wires.

We have to assume the E-field is homogeneous. There have been some special models for inhomogeneous fields, and they're fun, too. If you're interested in their study, I recommend Albert Smith's book on E-field coupling into transmission lines, published by Wiley Interscience a few years ago. Albert Smith is with IBM, and he's done some excellent models for this type of situation. I suggest you read that reference.

In that situation, the E-field coupling into the transmission line takes on something that looks very close to capacitive and inductive coupling. If I look at the transfer function, frequency versus amplitude, it's getting a linear relationship until it reaches the frequency of the receiver's cable wire segment length. Then it drops off at $3\lambda/4$, and so forth (fig. 7-5).

We're not interested in the exact frequencies, so we're just going to put a line labeled loci of maximums on the next figure, and it will look like capacitive coupling. It's going to have the same profile, -20 dB slope; it reaches its first maximum transfer at $\lambda/4$ of the receiver's wire segment, then $3\lambda/4$, and so forth.

What will that transfer function look like? Again, there is an awful lot to this model, and I'm not going to put exact numbers to it. But let me give you some typical numbers.

This is the actual field intensity right at the wire segment. That being the case, these numbers vary, depending upon whether the cable is shielded or unshielded. If the cable is unshielded, the numbers are typically anywhere from 0 to -20, almost like capacitive coupling. If the cable is shielded, the amount of stress to that cable, at its resonant frequency length, is going to be between 0 and -20 dB, down, depending on its common mode impedances. If you put in a filter capacitor between the pin and the chassis right at the connector input, the internal induced amplitude is going to be very small, because

the capacitor is going to shunt that voltage and not allow it to develop internally.

If you shielded the cable, the shield then adds another transfer function, to further reduce the threat to the actual signal inside.

Assuming you have done none of those things, then you're in the 0 to 20, with the average being about 10 dB down. That means that whatever these levels are, we're only going to be 10 dB lower in the threat.

Now, we can add these together, but first we must pick the receiving cable length. Now, we can pick 10 m again, and therefore all the break points occur at the exact same frequency. That makes it very simple, but it's not very illustrative.

So let's pick a 1-m cable length. If a 10-m cable length reached its $\lambda/4$ frequency at 7.5 MHz, a 1-m cable is going to reach its $\lambda/4$ frequency at 75 MHz. So we now have the radiating E-field established. It got transferred from the radiated emission spectrum.

Then we're going to have this cable-induced transfer function. What we want to do is sum those curves together. As the end result, without putting a lot of detail into it, this is going to be as shown in the figure labeled "Radiation induced voltage from ESD source into 15-m cable" (fig. 7-6).

This curve is what the total spectrum induced into the logic gate would look like. This assumes a radiating field in which we had a 10-m cable radiating and a 15-m cable receiving.

Now, I haven't put a lot of numbers on this example, but let's assume in this range it's 10 dB down, and, therefore, we started off at 7.5 MHz; we have 24 dB. We add 120, and that gives us 144 dB, radiating. We lost 10, so we end up at 134 dB $\mu\text{V}/\text{MHz}$ induced into the circuit, integrating over a 4-MHz band and increasing that by 12. This gives us 134, which is 5 V induced times 4, which is 20 V induced. The actual peak voltage would be approximately 20 V induced.

You will notice something interesting. The 20 V induced is lower than what was induced by crosstalk. You might expect that because the wires are 1 m apart. They're not a few inches apart, which may have been the original assumption.

The fact is that 20 V is still significantly higher than the 1-V noise margin of the logic gate. But it's not enough to damage the device. It may be, if I finish the integration all the way through.

So here we have a situation. A radiated transient field is 1 m away from an I/O cable, unshielded, with a potential threat of 20 to maybe 50 V if the cable was unshielded.

If you shielded the cable in this range with, say, 20 dB of shielding, you reduce the 20-50 V down to 2-5 V. This is still enough to upset logic, even if the cable was shielded, depending upon the quality of the shield.

I used 20 dB for a braid. If I had a foil-wrapped cable, it would drop by a factor of 100 and bring it down to 0.02 V. This is very acceptable, provided I didn't blow it at the terminations that I had good quality shield termination at each end.

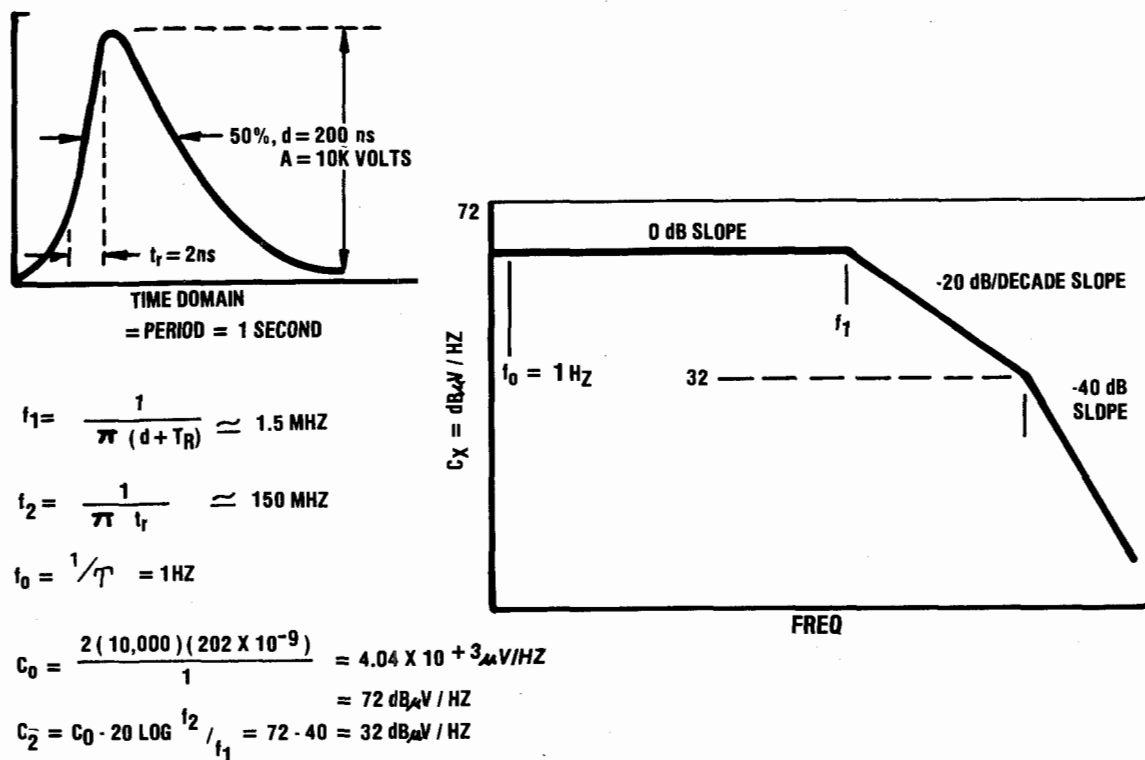


Figure 7-1.- Frequency spectrum of an electrostatic discharge transient.

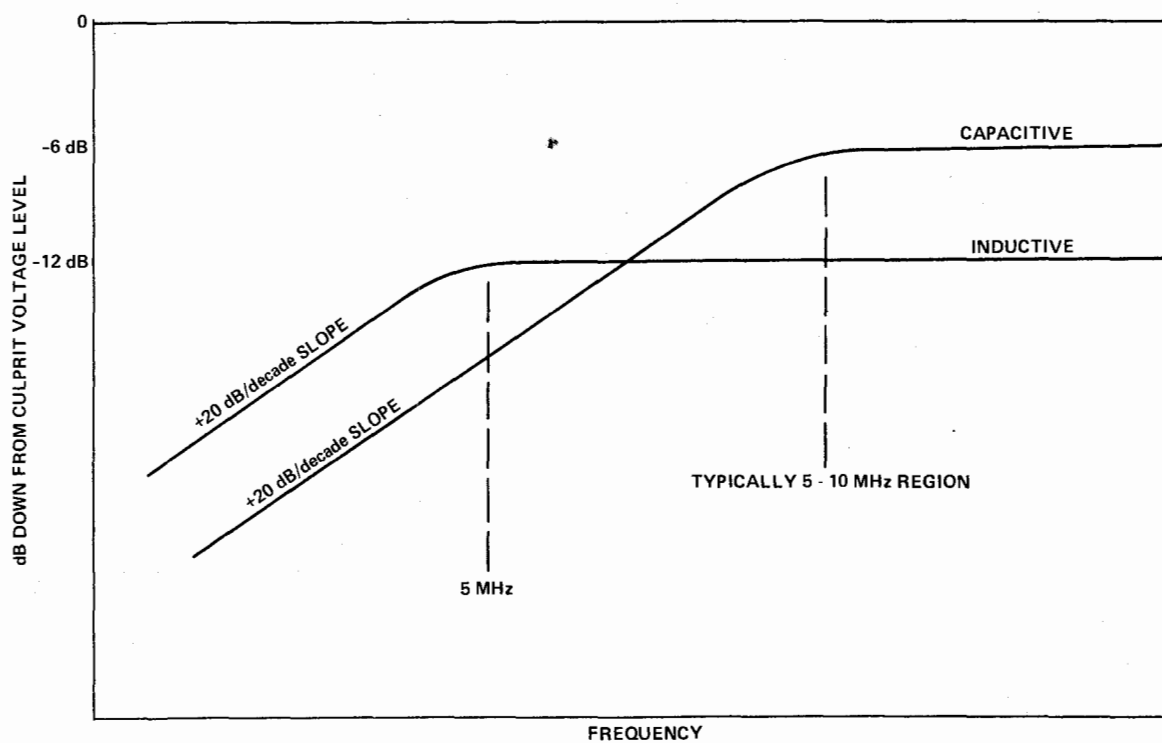


Figure 7-2.- Typical transfer function curves due to cable crosstalk.

E - FIELD

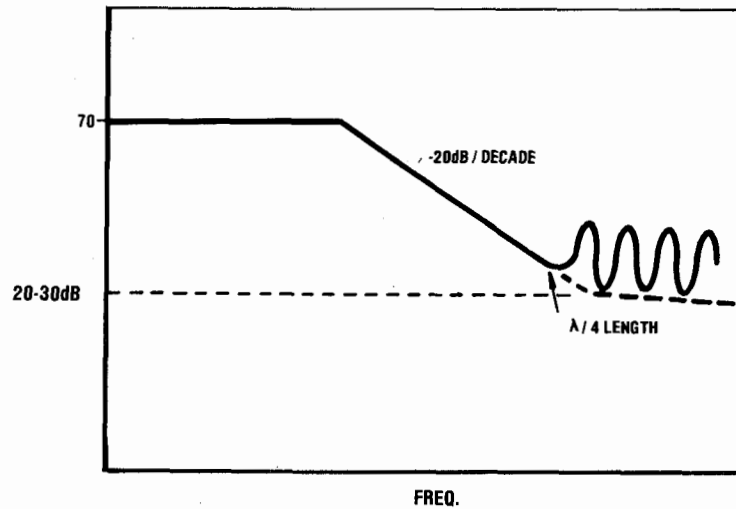
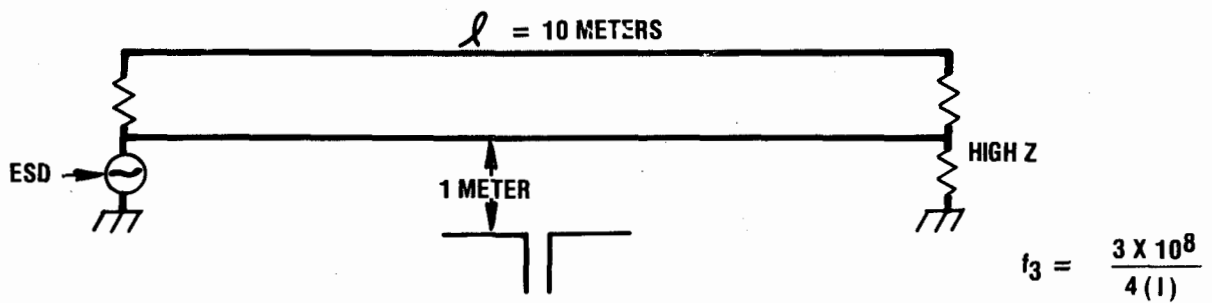


Figure 7-3.- Typical braided cable shielding effectiveness.



FREQ	Cn	T. F.	ANTENNA EFFECT	# OF LEADS	SUM	
$f_1 = 1.5 \text{ MHZ}$	72	-34	-7	0	31	151
$f_3 = 7.5 \text{ MHZ}$	58	-34	0	0	24	144
$f_2 = 150 \text{ MHZ}$	32	-34	0	0	-2	118
					dB μ V / M / HZ	
					dB μ V / M / MHZ	

Figure 7-4.- Radiation spectrum of an ESD transient from 1 m long lead.

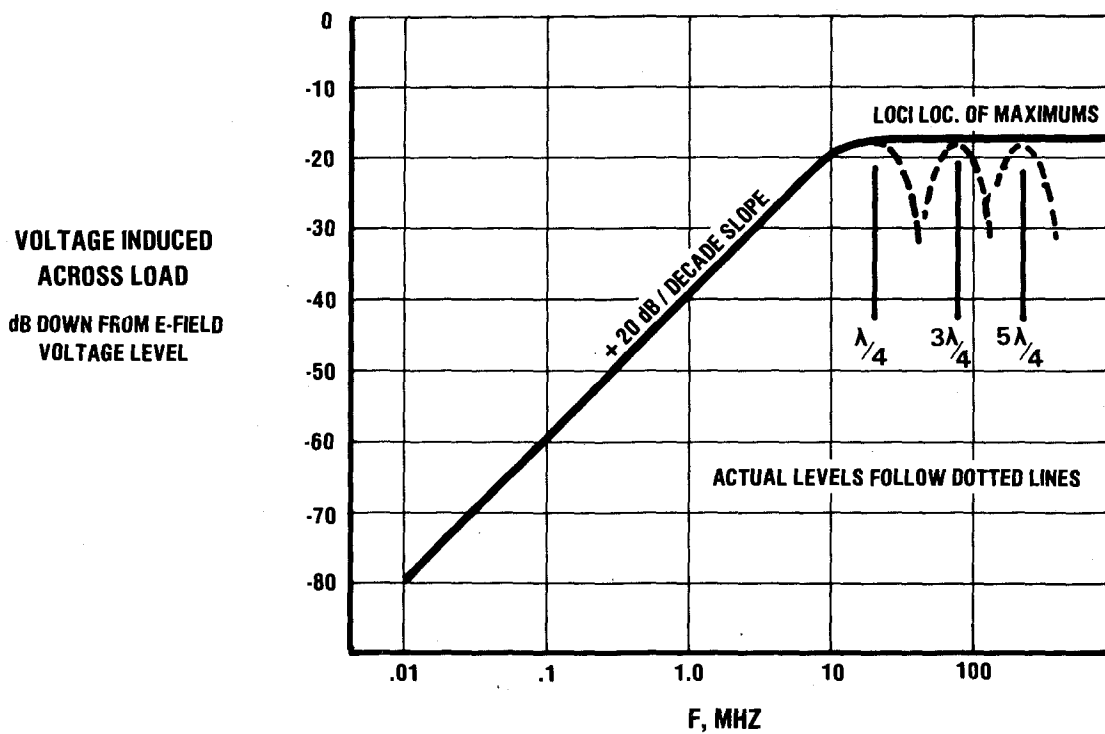


Figure 7-5.- Voltage induced into a wire due to electromagnetic radiation.

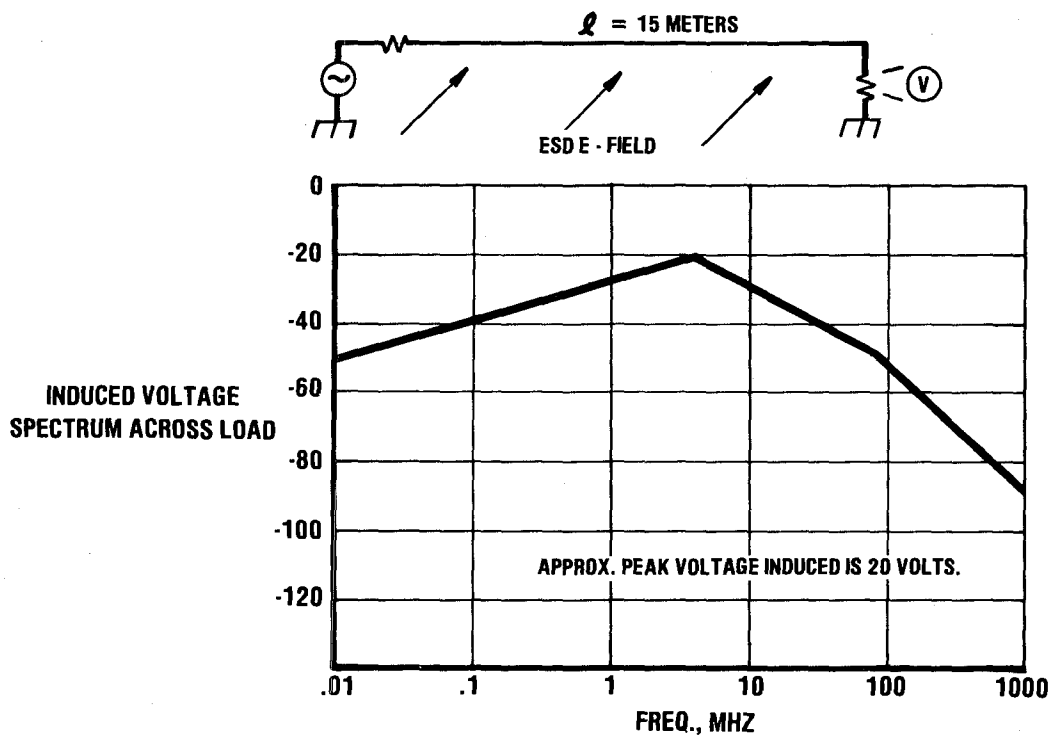


Figure 7-6.- Radiation induced voltage from ESD source into 15 m cable.

WIRE BRAID TERMINATION EFFECT

A Discussion on the Effects of Wire Braid Termination on Avionics Systems

Keith M. Kalanquin

The Boeing Company
Seattle, Washington

MR. KALANQUIN: Nick asked me if I'd tell some of you what DER stands for. DER stands for "Designated Engineering Representative." It means that I'm empowered to sign an 8110 form and recommend to the FAA approval of the equipment, or the equipment installation, in a particular area. And within the Boeing Company, there are a great number of DERs.

The area for which I've been given responsibility is EMI and induced lightning. There are DERs for every aspect of airplane safety certification.

I was given this task about a year ago; I'm still coming up to speed on all of my responsibilities.

This demonstration I have here is one we take into our project areas and staff areas, to show some of the problems with the shields and shield grounds.

I spent more than 10 yr on the 747 program. During that time, you become very aware of the turnover in personnel in your project groups and your staff groups. I suppose that you within the FAA who have spent a long period of time in the same location have noticed the same trend.

In the EMC area, Boeing is not much different from other companies. You operate your EMC activity with a minimum number of people. In order to assure that you've got control of your airplane and your installation from an EMC standpoint, you really need to enlist the aid of your responsible project and staff people, and get them aware of EMI concerns. They might not understand it all, but at least they know who to come talk to when they feel they might be getting into trouble.

The demonstration - I'm only going to hit a few of the highlights - vividly shows what can happen. The purpose of the demonstration is to show circuit susceptibility problems of shields grounded on both ends, what the cause of that susceptibility is, and some of the circuit parameters that you need to look at to determine whether you can minimize a problem, or whether you are into a problem in the first place.

The demonstration basically covers the low-frequency area, up to 100 kc or thereabouts. You may believe that doesn't involve the digital avionics you're concerned about, but that may not be true.

The board I've set up here (fig. 8-1) has three wire bundles on it. They're typical lengths you find in an airplane. I have them arranged so I can tie them all together or separate them. I have 100-, 50-, and 10-ft runs, and you can find these runs at various places in the airplane. On the 747, it wasn't uncommon to see 160 ft of wire between one component and another.

I have an amplifier here that is a basic differential input amplifier using a 741 op. amp with no suppression control on the input, no bandwidth limiting, just a straight differential input. I have a switchable ground on the input, so I can put it into an unbalanced mode. The amplifier will be unbalanced for most of this demonstration.

The load box on the other end can be varied from 0 up to 10K. For this demonstration, I'm going to leave it set on 1K.

My wire bundle has three bundles in it: a twisted shielded pair, a twisted pair, and a source wire, or a single conductor. The amplifier and load will be connected to this twisted shielded pair in the configuration that you see here, with the shield grounded only at this point, which is the same point as this reference ground to my amplifier.

My noise source is a standard 747 lamp dimmer (fig. 8-2) used on the flight deck for panel light dimming. The lamp dimmers we have on the 767 and 747 (the generation following these) are basically the same type of lamp dimmer using SCR control. This dimmer is connected into my 100-ft run, and I have a No. 81 lamp on the far end of the circuit. That lamp draws just about 1 A, so I'm subjecting that bundle to about 100-A ft per coupling.

If I turn the dimmer up to maximum, I get a fairly clean induced waveform. If I bring it back down to maximum noise, I see a peaking signal. For a structure return circuit, the peaks are about 10 V, or 20 V peak to peak.

By the way, I'd like to introduce our technician, John Bishop, from our laboratory. Whenever we go out to work on an airplane problem, John is generally our first choice of a person to accompany us.

To show you the type of hum we can hear in a structure return circuit, I'm going to make this temporarily a structure return circuit (fig. 8-3). Now I'll ask John to turn on the inverter. There — that's what it generates. Now, if any of you have been on an airplane that has 400 Hz power as a source, you've probably heard that type of a hum on a headset. The amplitude is about 10 V peak to peak.

If I lift my structure return and go to a twisted shielded circuit, the circuit will become absolutely quiet. I do that by removing the ground at A. It's down now to better than 60 dB.

A QUESTIONER: What did you do with the one . . . ?

MR. KALANQUIN: I removed this ground so that my circuit is running on this twisted shielded pair, with the circuit grounded only at this location, and the shield grounded here. The important thing when you've got a twisted pair circuit like this with an unbalanced input (fig. 8-4) is that this circuit ground and shield ground have to be at the same location.

The airplane wiring always has a red wire and a blue wire for a twisted pair. We always use the red wire for the high side of the circuit and the blue wire for the low side of the circuit. So I invariably talk about the wires by color.

The voltage induced into the red wire and the blue wire will be identical. It will also, in this instance, be identical to the voltage induced into the shield.

If you made a plot of induced voltage versus distance along the wire, you would see a voltage gradient that looked like this, for any one of those three wires.

I've plotted this for the other coupling sources, but I'm going to stay with the 100-ft coupling.

The reason this is important is that if you make an equivalent circuit (fig. 8-5), you can represent the source wire as a primary; the red wire, the blue wire, and the shield as secondary windings of a transformer.

If you put your dots on there for polarity, you will see that the far end of the circuit has the same voltage on it. And if you look from the shield to the blue wire, or from the shield to the red wire, that voltage potential will always be the same; even though, if you were to look from the shield to the other end of the shield, you would see an induced voltage.

Now, when you ground the shield on both ends (fig. 8-6) for a digital circuit, or for a circuit which requires RF protection, you may get yourself into problems. Once you do that, your shield voltage gradient will come up to a peak and then decay to zero. This area is the IZ drop for the shield (when you ground a shield on both ends, you cause a current flow). That current drops across the resistance of the shield. In this area you have the induced voltage minus the IZ drop.

Now I'll show you what happens when we do that -- by putting a shield ground here at this location. My shield is continuous across all of these joints, and is open-circuited here. When point A is grounded, you immediately cause a hum level that is a function of line impedance and coupled length.

If you take the same equivalent circuit (fig. 8-7), the induced voltage in your shield flows around this loop here, where these two resistors represent the shield resistance and its reference to ground (labeled S). If you look from that point to the red wire or the blue wire, you will see an induced voltage that's equivalent to half the induced voltage.

If you trace this circuit around, you can draw a small equivalent circuit that looks like this where the shield voltage, between the blue wire and the shield across that wire-to-shield capacitance, flows around that loop.

This loop from the shield to the red wire across the wire-to-shield capacitance and then to the blue wire gives you a current flow across the line impedance, and that's what gives you a problem.

Now, you may say that's a low-frequency problem. It is. It can involve any circuit on the airplane. If you plot the response due to that ground with frequency, for a particular load impedance where V_{RS} equals the open-circuit induced voltage, you end up with a capacitor resistive voltage division. Here's that plot (fig. 8-8).

This upward slope is a straight function of the decreasing wire-to-shield capacitance reactance for a fixed line-to-line load.

In this area the shield current that is flowing causes a canceling magnetic field. And that starts to become important in the 2 to 4 kHz range, depending on impedance, and the curve flattens out.

When you get up in the neighborhood of 20 to 30 kHz, the canceling magnetic field due to the shield current is the limiting factor, and you fall off on a standard 6 dB slope until you get up to between 100 kc and 1 Mc. Then the other effects Chris was talking about really take over.

The thing that's important is that if you look in the area between 4 and 40 kHz and are using a standard twisted shielded pair, single-point ground unbalanced, circuit with the shield grounded on only one end, then that shield configuration is good for better than 60 dB, to these low-frequency magnetic fields. Once you put the ground on the far end, you've lost anywhere from 20 to 40 dB of isolation.

Now, on the 747 airplane that problem was not significant. On the 767 and 757, you who are getting into putting in new equipment are seeing a lot of equipment that is using switch regulator power supplies for weight saving and other efficiencies. Those things operate in this 10 to 40 kHz frequency range. You can see those harmonics all the way up.

My demonstration here will not generate a level high enough to get you into logic thresholds once I get to a twisted shielded pair with the shield grounded on both ends. But the effect certainly does take place on the airplane. If you've got a long enough run, you have to make sure of your line length and impedance level.

Here is a typical configuration (fig. 8-9) of an installation where maybe you've got a low-frequency circuit. You initially had it installed as a single-point shield ground, but it goes out to, for example, the engine, and you need to provide some lightning protection, so you ground your shield on both ends out there. That causes a degrading effect, and I can't quite show that here, but I can show this (fig. 8-10) where I have a little longer coupling. This, for example, is a shield that may be put on that circuit for lightning protection. I can get that configuration by taking this shield and grounding it to that point. When it's turned on, you see, it gets louder. It did get much worse. That's an item we have to really watch. Every time we ground a shield for lightning, I get concerned, because I end up with a capacitive load out here to ground, and anything I induce into this circuit drains directly across the wire-to-shield capacitance.

A QUESTIONER: Is there a connection between the two shields?

MR. KALANQUIN: No. No connection.

A QUESTIONER: Could you simulate doing that?

MR. KALANQUIN: Yes. What would happen is that it would essentially go down to the level before. Let's turn it on. It essentially goes back to the level where the two are tied together here.

The circuit design parameters (Table 8-1) that are important to this problem are shown here. Wire length is fixed, and generally there's not a thing you can do about that. You've got to put one component in one area of the airplane, and the other component in another area of the airplane. You generally have little choice about your wire-to-shield capacitance. It's generally fixed by wire type. The only thing you can do to reduce wire capacitance, generally, is increase the wire spacing by using thicker insulation.

TABLE 8-1.- CIRCUIT PARAMETERS OR DESIGN
IMPORTANT TO PROBLEM

-
- WIRE LENGTH (FIXED BY INSTALLATION REQUIREMENTS)
 - WIRE TO SHIELD CAPACITANCE (FIXED BY WIRE TYPE)
 - LINE TO LINE IMPEDANCE
 - AMPLIFIER INPUT DESIGN
 - UNBALANCED
 - BALANCED
- DIFFERENTIAL INPUT
TRANSFORMER COUPLED
-

You need to look at your line-to-line impedance. I've showed you a line impedance of 1 k ohm. If you reduce that to a lower impedance, you get much less effect.

You need to look at your amplifier input design. If it's unbalanced, you're into this problem. If you're balanced, you've got to know whether you've got a differential input or a transformer coupled input.

One of the things I found in this area is that it's very difficult to go ask about and get correct wire-to-shield capacitance (fig. 8-11). You ask, "What is your wire-to-wire capacitance?" and the value they'll generally give you is this value.

That is not the value that is important to this problem, because it's a parallel series sum of this whole network. The value you really want to know is this, the actual value of C_{RS} or C_{BS} .

In the airplane, the wiring we use on the airplane generally has these values. Twenty-gauge wire is about 10 pF/ft, going down to 7.7 for 24 gauge. The wire-to-shield capacitance runs from about 60 pF down to about 47 for those gauges.

For purposes of calculation, I've used 10 pF/ft coupling, wire to wire, and either 50 or 60 pF wire-to-shield capacitance.

This is a plot (fig. 8-12) that shows the reduction in induced voltage as a function of the line-to-line impedance over the wire-to-shield capacitance, impedance. If you had the low value, you would be down to where you don't have to worry about it.

Fortunately, on the airplane, most of the time your line impedances are generally less than 500 ohms and you can avoid the problem. But you have to make sure of circuit requirements. You can help correct this problem by making the circuit a differential input (fig. 8-13). And a differential input is really quite good, but it still has a common mode susceptibility problem.

If I turn this up, there's still a little bit of hum in it. But it's down, on the order of 60 dB, which is generally quite good. Right now, with a

differential input, all of the induced voltage (it's all induced common mode) exists from A or B to ground. It's at a location where you do not care about it.

But if I put a ground out here at C and I'm going to put a ground at C (center tap), I can cause a shift of most of that induced voltage to the other end. It depends on the impedance at each end, how much you shift over to the amplifier end. The hum comes up a little.

Now, I'm going to put a short right across the amplifier input (D&E), and I'll show you that you are still in trouble. It may go down a little bit, but basically you've still got the problem. I've not found a differential amplifier that is the equal to a transformer-coupled input. They do have a common mode problem.

If this was a digital circuit and this wiring was coupled to an inductive source or spikes of some sort and you have a ground reference at the far end (such as at C), you can see those transients on this end (amplifier) of the circuit, in a magnitude greater than the logic thresholds. I've seen that level anywhere from 5 to 20 V. It's enough to clobber the word at that time. Fortunately, all of the digital logic that we use in the airplane on these interconnect wires is on a continual update, so the loss of one word is not really a problem.

MR. NELSON: Lauren Nelson. What's the advantage for not grounding that in the center, as we see it?

MR. KALANQUIN: I would recommend grounding that location, too. It doesn't cure this problem. It helps it a bit, but it doesn't cure it.

MR. NELSON: Okay. I was wondering if there was any advantage to it.

MR. KALANQUIN: I've got it grounded right now, ties together there. There is an advantage, because in the RF range, it makes this section of the shield as efficient as you can make it. If you change this, with this ungrounded here, the shield is just there for low-frequency electric field protection.

If you put a ground on it there, you're not only getting your low-frequency electric field protection, but you're getting your RF protection.

You might have caused some degradation to this magnetic field coupling problem, where it couples across the wire-to-shield capacitance, but that's an item that you've got to look at on each circuit, and make sure that that degradation does not create your problem.

MR. NELSON: Well, that was your long run, was it not? The 100-ft . . .

MR. KALANQUIN: Yes, it is.

MR. NELSON: That's why I was wondering what about the grounding.

MR. KALANQUIN: But you know there are certain circuits on the airplane that you are incapable of grounding, such as your engine vibration. The engine vibration transducer is a piezoelectric crystal and very high impedance. And if you were to put any ground on that shield, other than at the signal conditioner, the circuit units become very susceptible to this low-frequency magnetic field problem.

Generally, when I've given this lecture in the project areas, I've coupled the source wires to these other areas, and showed them the effect there, but the thing I really like to show the people in the project area is the degradation that you do get into in this low-frequency area. Rather than having 60 or 70 dB of isolation to the low-frequency magnetic field that a twisted pair can provide, a shield grounded on both ends (depending on circuit impedance) can reduce that isolation to about 35 dB. You've got to make sure you can tolerate that.

MR. ISTWAN: Dale Istwan, Airline Pilots Association. Earlier, when you talked about a twisted pair being grounded on one end, did you try using a shield at the opposite end, a capacitive coupler on the ground, to see the effects of harmonic content? In other words, instead of making a dc ground on the both ends, having an ac ground on one end and a dc on the other?

MR. KALANQUIN: Well, that's just a perturbation of this problem. Maybe I can find a shield where it's ungrounded. In order to make that efficient, if you're going to put a capacitor out here to ground this, and be effective, you're going to have to use a capacitor that's probably about 0.01 to 0.1 μ F.

It may move this up a little in frequency, but it's still going to cause a degradation, because you're still allowing shield current to flow, and the shield in this area will not have the same voltage gradient as the wire.

MR. ISTWAN: I was just wondering if there was some capacitive reactance, as a function of length, and the capacitance of the cable used, that would optimize the low frequency from the standpoint of the twisted pair, grounded at one end, and still provide the benefit of the higher harmonic reduction of the double grounding at the other end.

MR. KALANQUIN: In order to do that, you're adding a component in the aircraft wiring someplace, and you're having to provide an installation, packaging, and some means to mount that package at some odd location in the airplane. That's not really good practice.

You're better off to redesign your input, to get away from the unbalanced input. Go to a differential input with adequate bypassing and bandwidth limiting. I'm not particularly in favor of components like that in remote locations of the airplane. You get into environmental problems, depending on where you put it, and you also get into maintenance problems. I would rather try to solve the problem by good circuit design. The unbalanced circuits basically occur in circuits in which you try to feed more than one user, or you try to send one user more than one signal.

The flight interplane audio system is a good example of an unbalanced system. I know that's not the digital scheme you're talking about — but it's an example. You run all those audios with one common. And in order to do that, you end up in an unbalanced configuration. I would never recommend that type of a scheme in a digital circuit. You need to keep your circuits balanced, and you need to know what your impedance levels are.

This has been an effective demonstration to the project people within Boeing. I've given it about three times over the past 10 yr, and I've gone into it in more detail with them. The last time I gave this was about 3 yr ago to both the 757 and 767 projects. Some of the people did not realize the common mode problem with differential input amplifiers.

I've been having somewhat of a running commentary with an equipment manufacturer because I want them to assure me that when we put shielded wire on the system, we do not have a low-frequency magnetic field problem and that we don't get into a susceptibility problem, regardless of shield ground configuration — whether the shield is there or not.

The fellow told me, "Well, that doesn't make any difference. I can run your 400 A ft on 10 ft of wire using 40 A or I can run it using 4 A on 100 ft of wire and get the same results."

And I said, "No, you can't. Try it. You'll find you'll get entirely different results if you don't have the right circuit."

MR. KALANQUIN: Would any of you want to look at this waveform and demonstration after Chris finishes, before lunch? If you do, I'll leave it set up.

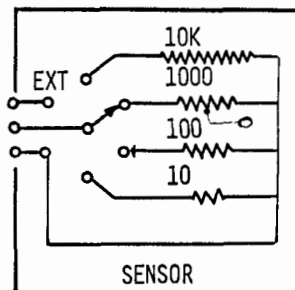
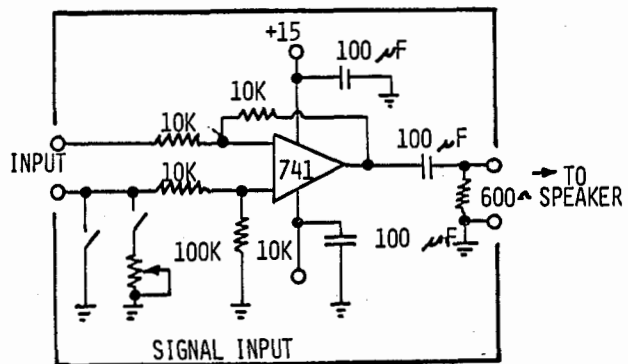
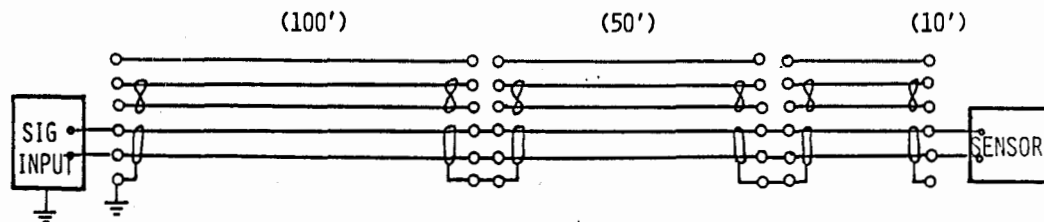


Figure 8-1.- Electrical sketch - test setup.

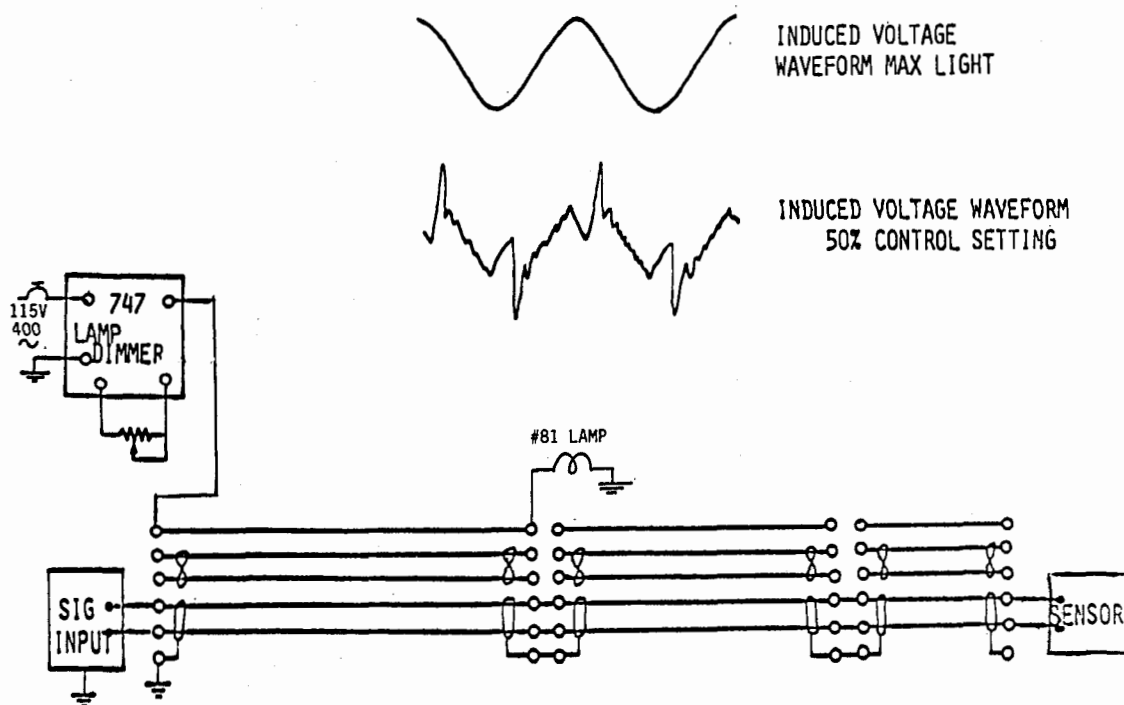


Figure 8-2.- Electrical sketch - interference source.

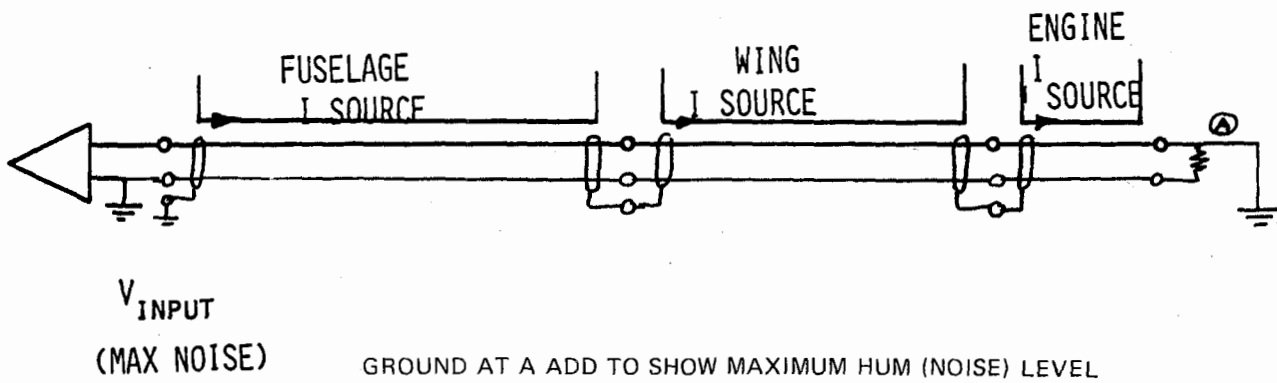


Figure 8-3.- Induced voltage — reference circuit.

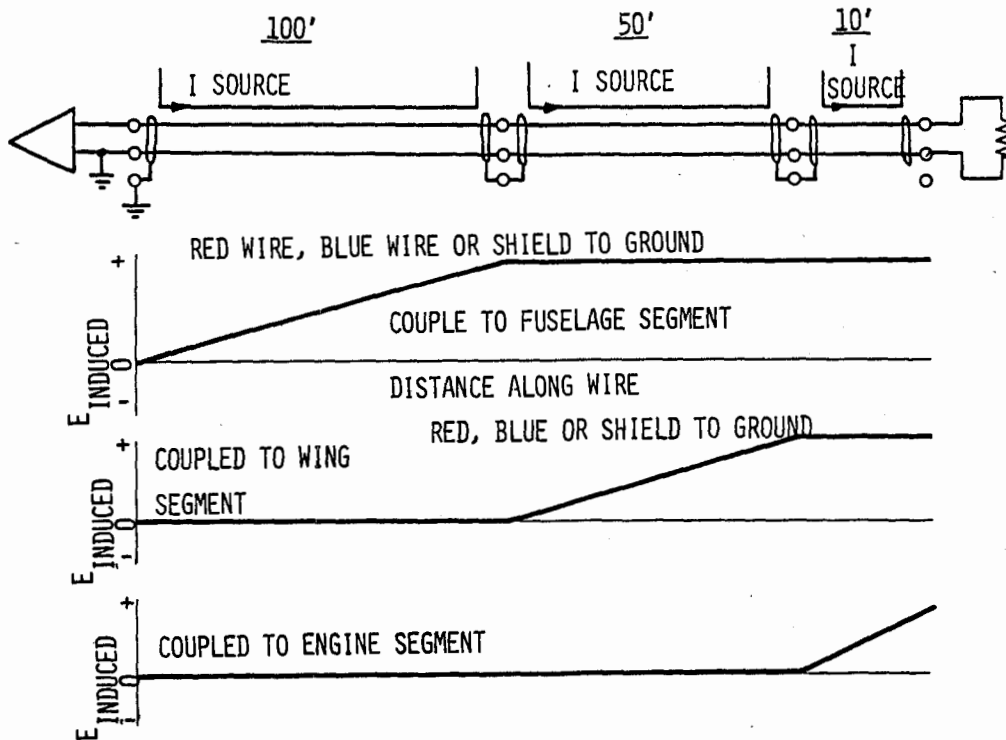


Figure 8-4.- Induced voltage single point circuit and shield ground.

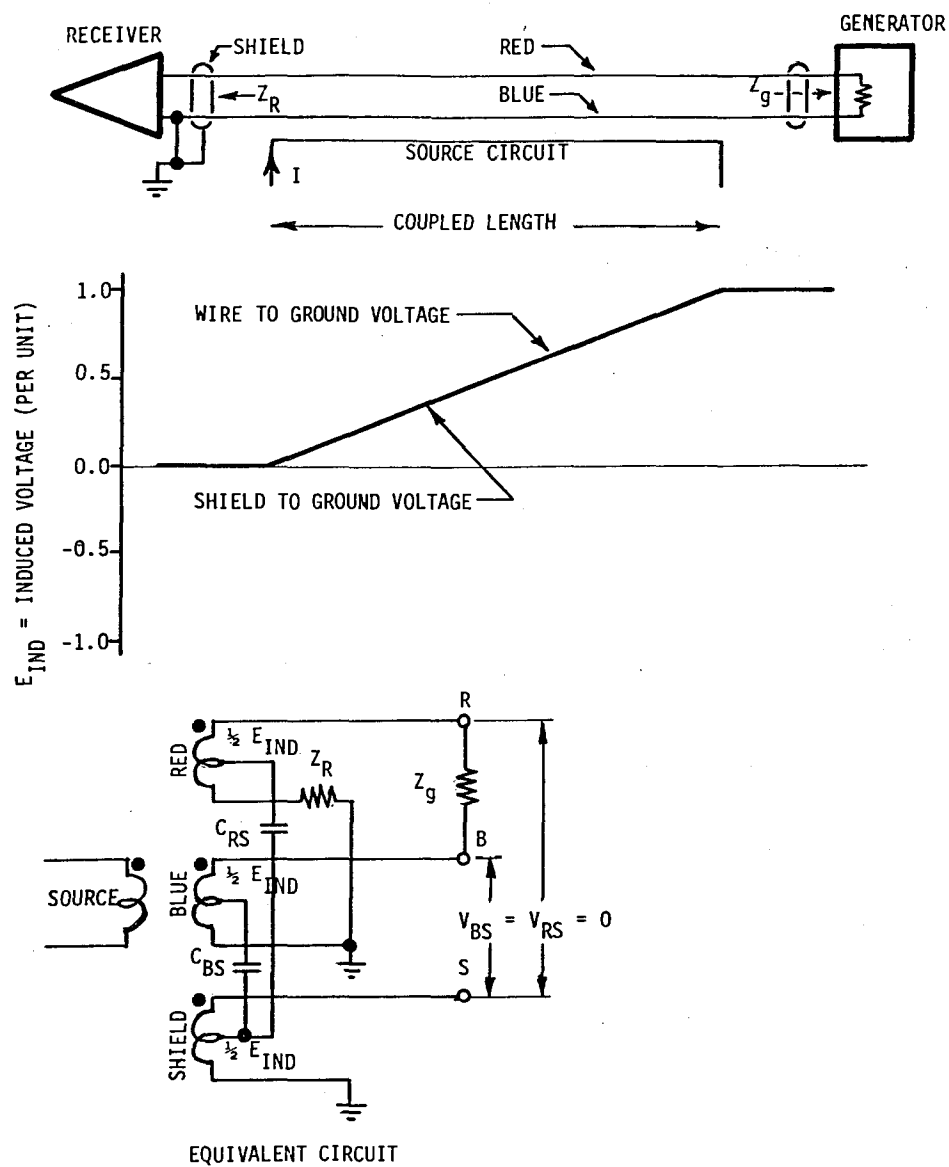


Figure 8-5.- Single point circuit and shield ground at same location.

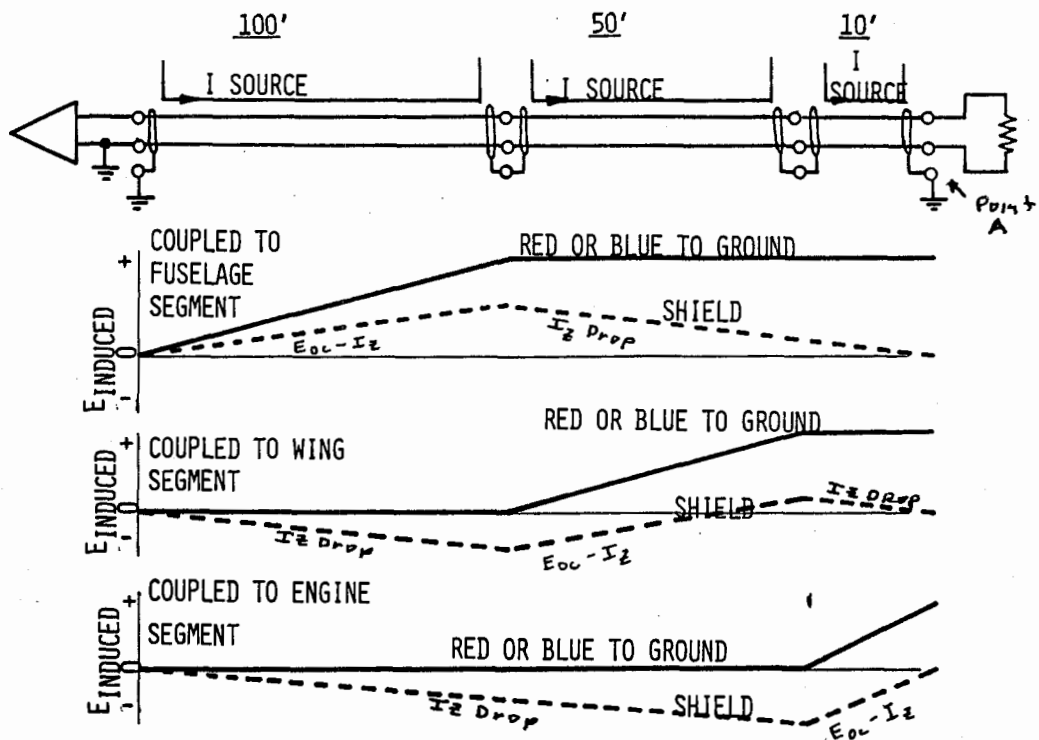


Figure 8-6.- Induced voltage — single point circuit ground — dual shield ground.

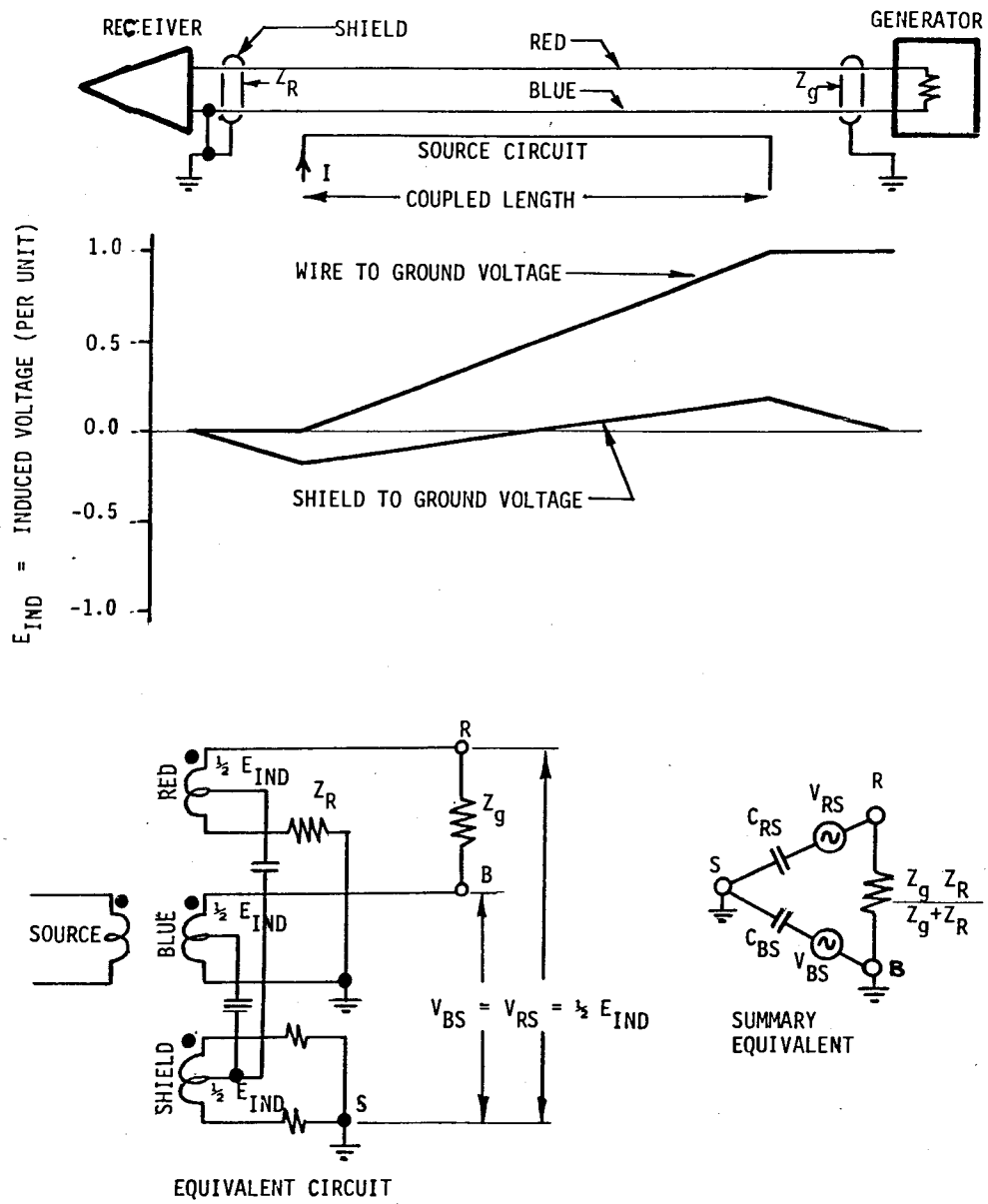


Figure 8-7.- Shield grounded at both ends.

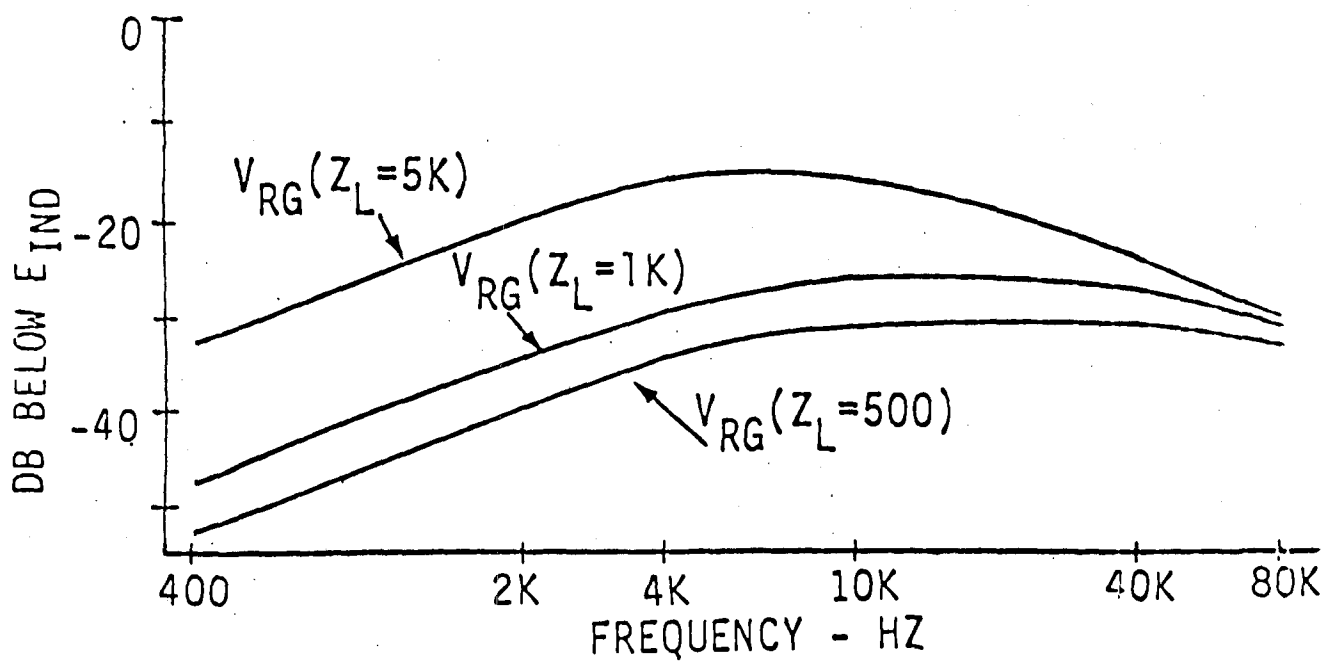


Figure 8-8.- Induced voltage — line to line.

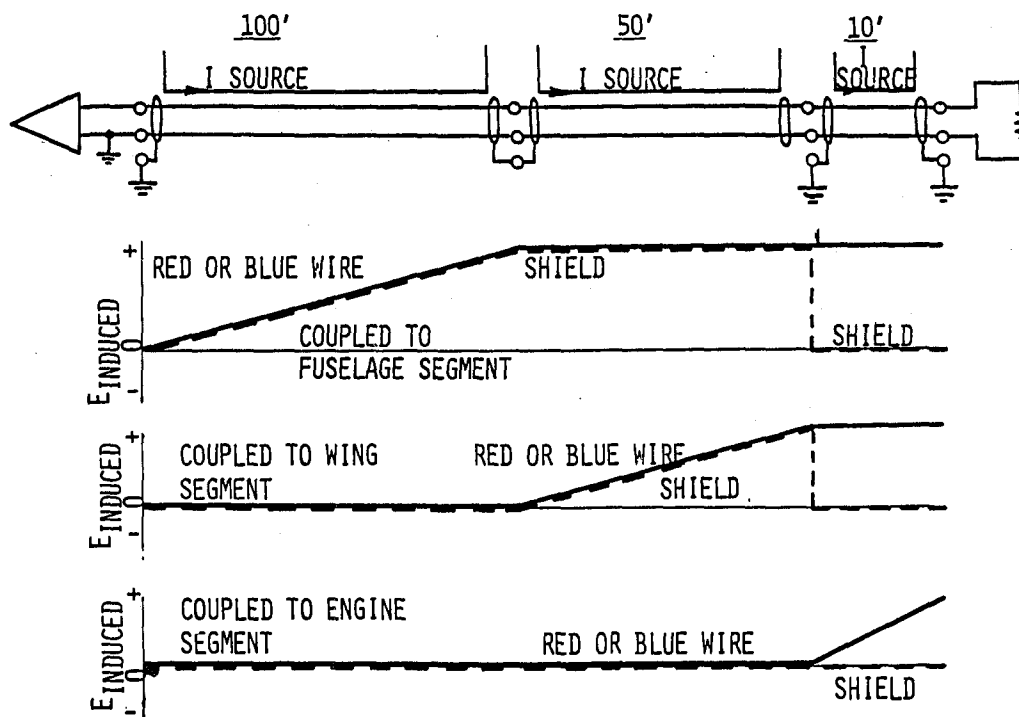


Figure 8-9.- Induced voltage — single point ground circuit and shield with dual grounded shield on engine.

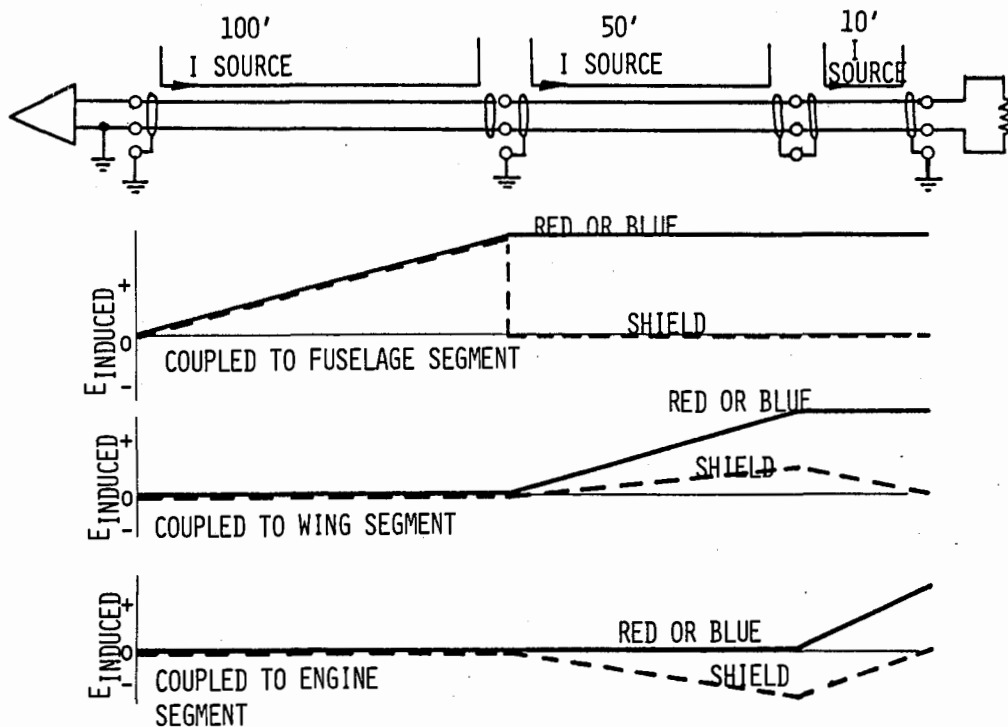
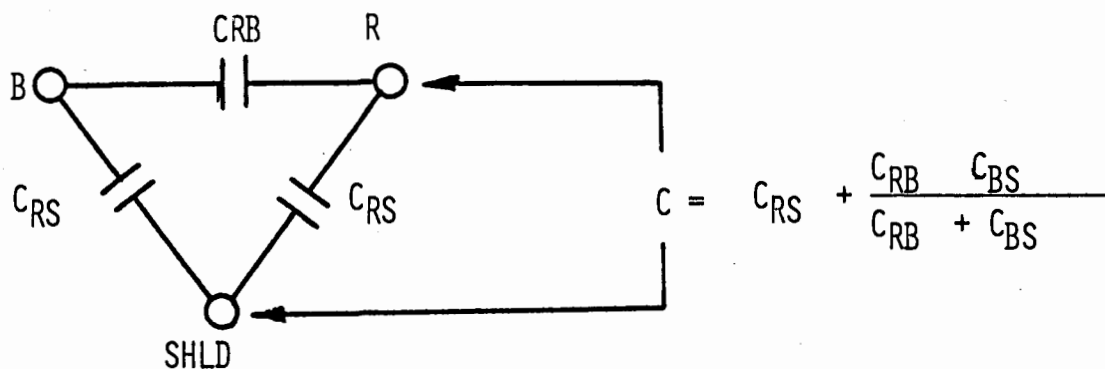


Figure 8-10.- Induced voltage — single point ground shielded circuit with shield dual grounded on wing.



BMS 13-51 TW - PR SHLD

20 GAGE

22

24

C_{RB}

10.8 PF/FT

8

7.7

C_{RS} ≈ C_{BS}

60.2 PF/FT

52

47.3

Figure 8-11.- Wire to shield capacitance.

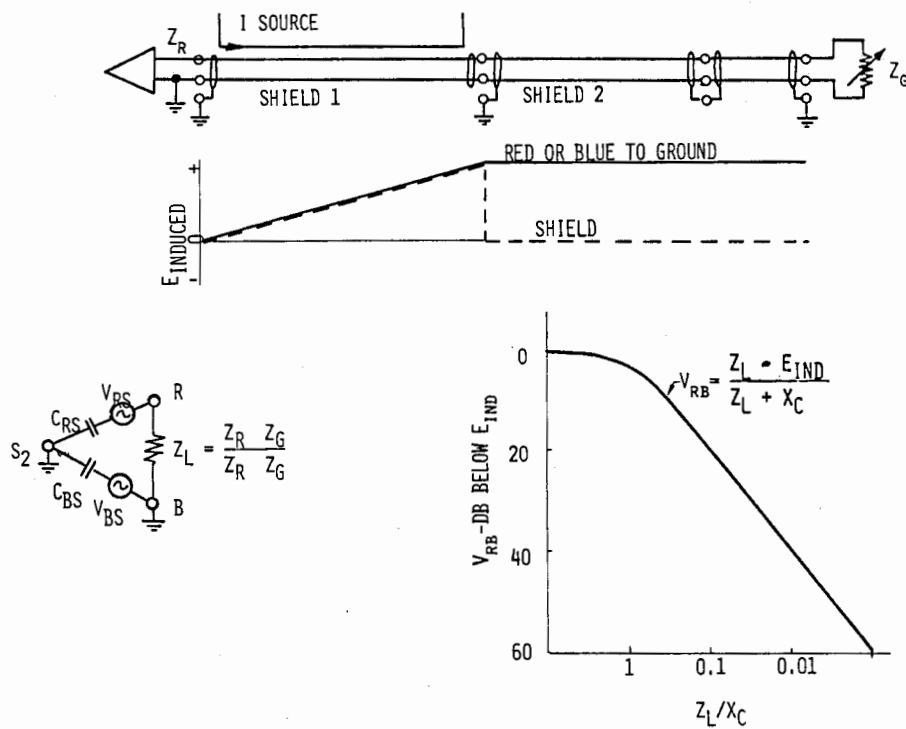


Figure 8-12.- Effect of lower line to line impedance.

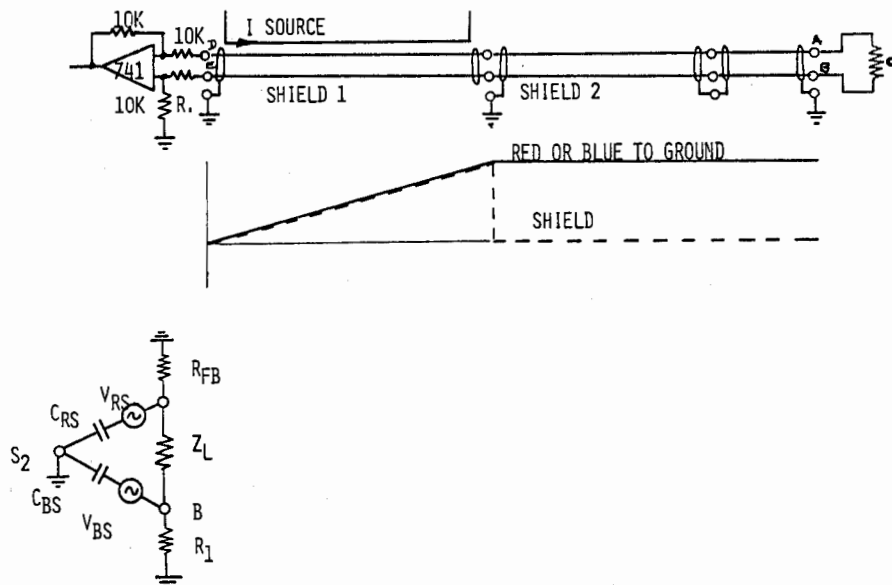


Figure 8-13.- Effect of differential input using op-amp with good common-mode rejection.

DESIGNING TO MEET THE AIRCRAFT GENERATED EMI THREAT

Chris Kendall

Chris Kendall Consultants
Mariposa, California

MR. KENDALL: Thank you, Keith.

I think that perhaps better than any, this last demonstration should make you concerned about cable shielding techniques on aircraft. It shows that if you are not careful, you can create some serious low-frequency problems, especially related to analog circuitry.

You might explore different solutions and different parameters than those presented, and have some different answers. But I'd like to go ahead and follow the concept of what is used today, in light of what the threats are to digital equipment and also look at the consequences of different cabling techniques in the high-frequency region.

We've had the opportunity to do this extensively, and it's kind of fun. I wish I'd had a chance to bring my experiments with me.

Consider the fast-rise-time transient from the chattering relay test that was discussed earlier. We can measure carefully the voltage induced into various cables due to the chattering relay, where the grounds are changed in a similar fashion, as described by Keith.

What you will find is that if we do use a shielded cable, as soon as that cable reaches its electrical length, two things have to occur. First, with the shield terminated to chassis at one end only, the cable's shielding efficiency goes to 0 at $\lambda/4$.

This has been demonstrated by numerous authors, such as Henry Ott, Bell Laboratories in his book titled "Noise Reduction Techniques in Electronic Systems." It's excellent in dealing with this subject matter.

The problem is that if a cable is grounded at one end during a high-frequency exposure, the shield, because of the standing wave effect (which is not a problem in the low frequency) becomes totally useless.

We recognize that the cable has zero shielding above a certain frequency. That means that the shield is worthless as far as high-frequency transient protection for those frequencies that are able to still cause circuit upset. That's a very important conclusion (fig. 9-1).

There are exceptions. For instance, the twist rate on the cable makes a significant difference. A Boeing study in 1956 showed that if you twist a cable at six twists per foot, the approximate reduction is 49 dB, at 400 Hz compared to a 2-in. loop circuit.

If, on the other hand, you twisted it 18 lays per foot, the difference went to -79 dB, over a 30-dB difference in performance.

If that's the case, then one of the possible solutions is to pay closer attention to the type of cabling we use in the aircraft. For instance, if we suspect a low-frequency problem with digital, by increasing the number of twists per foot, perhaps we can get over 30 dB of added protection. That's significant. That's in the low frequency, the area we're talking about right now.

On the other hand, if we can pick up 30 dB in the twisting ratio, which can add significant benefits, can we do anything for its high-frequency protection?

The question of the capacitor being added to the circuit was a real one. What happens if . . .? Those are wonderful games to play.

The most significant factor is the length of the cable. If the length of the cable is fairly short, the value of the capacitor can be very small. If, on the other hand, the cable is very long, the capacitor has to be a little larger to be effective. The key ingredient is the $\lambda/4$ length. At the $\lambda/4$ length, the shielding would have to be 0, theoretically.

But let's look at this problem as it relates to the entire system, not just the cable. Let's take a two-box system, typical of what we might see on an aircraft. Let me draw the circuit reference inside the first box, with perhaps a ground reference, through the printed circuit board, and then another ground reference to chassis inside the box. (See the attached drawing.)

Here we have a daughter board, or even a mother board. A logic device resides on that board and, therefore, ultimately, its power distribution back to chassis. It has a reference to its own case. This is not uncommon. We expect this in most systems.

On the opposite end, a second box that also may receive its own power has a similar situation, with a lead coming in. Again, it would have a reference ground, and probably ultimately a chassis reference to its case. So now we have the classic two-box problem. During the exposure of fast rise time transient from this morning, we realize that if the cable bundle is still totally unshielded, we're looking at anywhere from 10 to 200 V induced into that cable, in the critical frequency range of 1-4 or 1-5 MHz, or greater, possibly, depending on how well we can add, or integrate, thereafter.

The first problem when we're dealing with cabinet shielding is that we must not violate Faraday's Cage law. Now, a Faraday Cage used to shield the product, which we all tend to use, consists of some type of metal cage, usually solid aluminum, around the entire electronics. One of the basic principles Faraday demonstrated, by getting into his cage and allowing himself to be hit by lightning (he had more guts than I do), was during that exposure, the currents would remain on the outside and not penetrate the sheath, or cage.

The same thing is true when we build an aluminum box. The current flows to the outside, because of skin effect, which is very pronounced even at relatively low frequencies, even in the 30 and 40 kHz range.

If you violate that Faraday Cage by having the audacity to put a wire inside that doesn't ground at its port of entry, you will violate the shielding integrity of that box at high frequencies. For example, take a simple shielded room. Run a wire through an open port in that room, leave about 2 ft inside and 2 ft

outside, and see if you can pick up an FM radio station. You'd be amazed how well you can.

In fact, that's an excellent test of a shielded enclosure. Tune to a strong FM station, go inside your shielded room, close the door, and you should hear nothing. Then put a little wire, 2 ft on the inside and the outside, and I bet you'll hear a lot. Because you have violated the Faraday principle of shielding, which says that any inlet or exit to the shielded room must be terminated to chassis at its port of entry, or within an electrically short distance of the port of entry, so that the wire does not allow an appreciable difference in impedance or voltage across that section as it enters the room.

Now let's take a situation where cables are routed from the inside of the unit in this case, that are now at this point of exit, and have an opportunity to act like antennae for the RF inside and the RF outside.

How can we prevent these cables from acting like antennae? One way is to shunt the wire to chassis ground. I like to dc-ground it to chassis. It works very well. Unfortunately, when you insist on bringing 115 V, 400 Hz, into a box, it poses a little problem for the box when you short it out at the port of entry, with a direct dc shunt to chassis.

So, then, how are we going to solve the problem? The only other solution is to provide some type of filter action, either in the form of a capacitor ground or an LC to ground. We have to stop or shunt ac-wise that lead to protect the shielding integrity of the case.

This is done during a lot of EMC tests including DO 160 testing. I'm sure that you have seen where the power lines coming to the shielded room have gone through line filters on the room as they enter, usually rather substantial filters. For instance, some are rated at 100 dB at as low as 14 kHz. That means there's probably over 90 μ F of capacitance in that filter between each ac power lead and the chassis of the room.

How is it placed? Simply from each 115-V, 400-Hz line to the chassis of the room. Now, that creates other problems that we don't want to ignore in the low-frequency situation. But you have to shunt it; otherwise, the shielding is going to be lost.

We discussed this morning that if you don't shield a box, you're in trouble. You're going to crash the digital logic. So we have to provide some type of shunt. Let's assume it's a capacitor. The value of the capacitor can be determined through tests or perhaps some analysis.

Now, the problem with the shunting effect from a digital logic design point of view is that the capacitor tends to impede the speed and rise time of the digital transfer itself. If we're dealing with 30-MHz effective logic bandwidth, then the capacitor to ground cannot be very large.

If you run through the analysis, I contend that you cannot effectively take high-speed data transfer and capacitively shunt it in this way, and solve the entire problem. You'll destroy the quality of the signal.

This problem is going to get a whole lot worse before it gets better. Digital speeds are on the increase, not on the decrease. We want to transfer more information, not less, between these boxes.

So the capacitive solution here for the signals, whether it be on the signal or on the shield, creates a problem if we follow the logic that we want to use circuit techniques to solve this problem. What we're really saying is we want to use line-to-ground filter techniques to solve the problem, because that is the only solution. You must terminate this energy to ground, or you'll violate the shielding integrity of the box.

That means you're forced into some type of common mode line-to-ground capacitance as a solution, possibly augmented by a balun, or a common mode choke that we talked about earlier. It's the only possible solution, if you're going to use unshielded cable. And if you use a shielded cable and ground it at one end, it is unshielded, for all intents and purposes, after it reaches its $\lambda/4$ length.

See the problem? We were told this morning that we cannot ground shields at both ends because of the inductive coupling — at least with the assumptions used — and now I'm telling you that if you put a shield and ground it at one end, you don't have a shield, at $\lambda/4$. Both statements are fact, not conjecture.

So what do we do? We've got to solve this problem or we're not going to have digital avionic systems. Well, I think we have to look at some of the alternatives. We cannot rely on one solution.

We need to consider filter elements, even though there are questions of vibration. I'm sure they can be solved. They've been solved on the F-18 in the form of filter pins at the entry — or by strip-line technology, where the flex print itself is made to be a filter between the input connector and the mother board, by using something called a miconfilter.

But something has to happen. Somewhere, we have to add filtering and cable shielding. We realize that an external lead is an antenna to the box, and therefore either we have to shunt the leads to chassis or we have to shield the leads.

If we choose to shield the cable, we have to terminate the shield at both ends ac-wise. There's no exception. Otherwise, at $\lambda/4$ the shield will not exist. That's the dilemma!

There was some concern about what happens if you use capacitors. Is the capacitor a further violation of the low frequency? It's a function of the value of the capacitor, the common mode source impedances of the circuit, the number of twists per foot of the cable used, as well as the proximity of the culprit wire to the victim wire.

In the case of typical airborne cable harnesses, the culprit wires and victim wires are extremely close together, a fraction of an inch. In reality, we would have to use rules that would not allow spacing that close.

First, I'd like to ask the commercial computer companies how they solve this problem. After all, they're dealing with a building. They wire computers over

the entire length of a building using much more electrical footage than we normally see in an air vehicle. And they have a lot of 60-Hz potential threats from the 60-Hz power distribution.

Fortunately, the return of the 60 Hz is through a wire that's close to the high side. They don't use automotive-type wiring, where the return is brought through the fuselage of an automobile (or an aircraft).

Perhaps if we go to the entirely composite airplane, we will run return wires for the power distribution, and this problem will be diminished. That's one of the problems -- you force a loop to exist because you terminate your phase neutral wire in an air vehicle to the fuselage. Therefore, you have left a net loop area for the flow of current.

Now, in multiphase Y-connected systems, it's not quite as bad, because most of the power currents tend to be on the other phases, and not necessarily through phase neutral. But still, phase neutral carries current, and the loop unbalance continues.

In dc systems, the problem is still real; 28 V carried back through the fuselage, unbalancing the loop area of the 28 V power circuit, generate large magnetic fields that can couple to other aircraft cables.

There are some exceptions. For instance, look at the S3A aircraft. In that type of airplane, the requirement that was levied on the aircraft was that the return currents for 400 Hz had to be through a wire trusted with the high sides, adding weight to the aircraft, but eliminating the loop problem mentioned this morning, because there you had no unbalance of the power distribution. It was solved by the return wire being in close to the high side; the loop area of the culprit circuit was diminished, and the magnetic field simply did not exist.

The same wiring is used in space vehicles. Weight is at a premium, yet the returns are not allowed to be through the fuselage in most cases.

So there are solutions. We have to weigh these solutions in terms of the benefits to the overall system. If we want digital electronics, we're going to have to solve some of the other problems, and marry these into a totally integrated program.

The other possible answer, as I mentioned, is the shielding. So let's look at shielding again. We have many choices as to how we transmit the signal. We could transmit the signal through a twisted pair, along with several other digital signals, each with its own return, and then gross shield the whole bundle. We could send the signals through individual twisted shielded pairs. We could send the signals through individual coaxes, if single-ended circuitry was used.

I like to think about coaxial cables, only because I draw the analogy to an IBM 3038 processor that uses high speed, up to 2 megabits of I/O data. They use individual cables for each data signal sent from an IBM 3038, and they transmit from one connector to another over distances up to 1000 ft.

Why the coaxial cable instead of a plain twisted shielded pair? Does the coax buy us anything? Absolutely, and the reasons are interesting. They take us back to the basic rules of physics dealing with grounding.

We mentioned earlier that single-point grounding doesn't exist. It's a little play on words. If I create a point in space, how many wires can you terminate to a point? Not very many, unless the wires are dimensionally small. That's because a point is a dimensionless location in space.

Well, I'm being a little facetious. We didn't really mean a point; we meant some finite area, like a horseshoe-shaped ground bus or a round widget, or something that we can bolt to the chassis. This ground object selected has finite dimensions so that the current flowing across this object selected as ground, times the impedance of the object, results in a small change in voltage. As long as the induced voltage is below the threshold of upset of the circuits we're referencing, the ground is acceptable.

Already we're not talking about a dimensionless location in space. We're talking of a finite, dimensioned area. In digital systems we'd like to designate this dimensioned area as the mother board of the interconnect of the system. Let that whole mother board ground plane be the central ground reference, and connect that to the chassis.

Now, the daughter boards will then come in reference to this ground plane. This ground plane, as long as it meets the criteria just mentioned, would become your central reference.

The problem is if I do that in box number one, and I also carry it out in box number two, I have violated the principles of single-reference grounding.

How do I solve this reference problem? There are two parts to the reference problem. There's the low-frequency reference problem and the high-frequency reference problem.

Let's first look at the low-frequency problem, and consider the case of a single-ended circuit. Again, let's use the twisted pair cable as shown in the attached diagram (fig. 9-2). This means that the digital return is twisted — with the digital high side. We allow this load in unit No. 2 to tie to the chassis also.

Now I have two possible paths of the return flow of current. Let's assume you're a little electron, and you have been forced to flow from unit No. 1 to unit No. 2, and now you're forced to make a decision. You get to unit No. 2, and you have to decide in which path to flow. Dc-wise, the aluminum ground plane has much lower impedance than a No. 22 gauge wire. And the rule of thumb about current flow is it takes the path of least resistance.

I'd like to change that slightly to say it takes the path of least impedance.

Let's take a look. We want to know where this electron is going to flow. If the ground plane has 0.1 ohm, and the twisted pair return has, say, 10 ohms, it's obvious we're going to have most of the current flowing in the 0.1-ohm path. An excessive loop area will result, which is not good, especially in present-day aircraft.

How are we going to prevent that from happening? It turns out that if we calculate the reactance (or the impedance) of the circuit, it is equal to the self-inductance of the first lead, plus the self-inductance of the return lead,

plus or minus the mutual inductance between them. So we have an L_1 , an L_2 , and an M_{12} , the mutual inductance between the pair.

Now, the total circuit impedance the current flow in is simply going to be $L_1 + L_2 \pm M_{12}$. When is it plus, and when is it minus? Fortunately, we find that as current flows the way you would normally expect current to flow, down one wire, across the load, and back on the return wire, it takes on the negative sign. In other words, the impedance, the inductance of that circuit, is less than the sum of the self-inductance of both conductors.

On the other hand, if we have a ground loop current, which will tend to make current flow in the same direction on both leads, it takes on the plus sign. And we have more inductance than the summation of the self-inductance of both leads.

In the higher frequency regions, the coaxial cable becomes a common mode choke. And it's the best kind. It's not lumped, so cross-coupling is minimum. It's distributed. The longer the cable becomes, the greater the mutual inductance becomes per linear foot, and the greater the common mode rejection becomes.

So what we're looking at is transmission lines. What separates a simple circuit from a transmission line is the factor of mutual inductance between adjacent twisted pair conductors.

Now, you might tell yourself: If that's the case, what I really should do is find what cable configuration gives me the highest amount of mutual inductance. Therefore, I could use the cable as my circuit isolator to isolate box No. 1 from box No. 2.

The answer is coax. It has the highest amount of mutual inductance between the center conductor and the braid of any cable configuration.

Now, I don't want to say what a company does, and why they make decisions. However, it's interesting to note that IBM, over the many years they've been making computers, have never deviated from the coaxial cable as their form of transmission line. They didn't go to differential circuits. They cost too much. That means you need two transistors, where you need only one for single ending.

Now, how does IBM ground the cable? At one end? Absolutely not. They ground it at both ends, and for extremely good reasons. They have to, because if they don't, they'll violate the shielding integrity of the box.

If I allow the coax to stop 2 in. before unit No. 1 and terminate into a twisted pair, and allow the twisted pair to continue inside the box, I have violated Faraday's principle of shielding — just the same as if I had violated the shielding of a shielded room by letting an unfiltered lead route 2 ft inside the room. The shielding has been compromised.

We cannot afford that luxury. That shield has to terminate at the port of entry and there are no exceptions. IBM used to have a rule of thumb not to terminate coax shields at their port of entry. They said: "We don't need to terminate this shield at the port of entry. We violate so-called single-reference grounding." And they had a very exotic test to make sure that there

was only one connection between logic ground and chassis ground in their computers. This was the way it was for many years.

You talk to some of the IBM service people about this technique, and they'll tell you exactly how the test was done — very detailed procedures. But they found out something. The computer kept getting hits, unexplained failures, and transient disturbances of the data. They found that some of this was caused by people taking a cart of magnetic tapes, and slightly nicking the computer with the cart. Bang! The machine collapsed; the power even turned off because even that was monitored by logic circuitry.

Let's look at what IBM went through to protect the computer against fast rise time transient phenomena.

They first decided that they would add a gross shield to the coaxial bundle. So they took the 32 coaxial cables that represent one cable, and they gross shielded it. It was a marvelous solution. With the shield grounded at both ends, the individual circuits still remained floating. But, they found out another interesting fact by doing so. They added weight to the cables, and over \$2.00 per linear foot to its cost.

IBM, like many other companies, tries to use cost reduction programs. So they launched an extensive study into this problem. They modified their standard serpent connector, which was plastic, to allow the coaxial cables to come in and terminate into individual pins for both the shield and the center conductor. They found that when they plated this connector with a conductive finish, so that each of the individual coax cable shield was grounded to chassis at its port of entry at both ends, they could raise the immunity by over 40 dB to transient phenomena. Further, they didn't need to add an outer gross shield.

Because of the length of the cable already, they had extremely good noise immunity built in. Forty-decibel improvement to transients is excellent.

How about radiating emissions? Is there any benefit there? They found the same thing was true. They didn't have to gross shield a cable to contain the RF to meet FCC and German standards, and other international regulatory requirements on radiation.

Now, these are significant solutions. We're talking about a company that's been around a long time, that has built many systems. And I'm talking about hundreds of feet of distribution of data cable, where the grounds are grounded at both ends.

So you might ask how we can prove that this is good or bad, from a susceptibility point of view.

Well, I ran an experiment. I took the so-called chattering relay test that we've been talking about for the last day or two, and I wrapped it around the cable. I first ungrounded one end of the coaxial cable so it would float and would be taken through a connector pin. We ran the chattering relay tests. As you probably can quite well imagine, we completely bombed the computer. We had a clocks-off situation; we had data interrupts; we had all types of classic failure mechanisms.

So then we said, "Okay, let's ground it the way this cable should be grounded." Then we grounded the cable, and we again performed the chattering relay tests. No hits whatsoever after 3 hr of chattering relay exposure.

Then we removed the chattering relay and replaced it with an ESD simulator, since the chattering relay only generated 600 V. We hit it with 10,000 V to see what happened.

Failure after failure occurred, as low as 100V using the ESD simulator. But as soon as we grounded the shield at both ends, we didn't even fail 25,000 V static discharges directly to the coax itself.

The same type of results using shielded ribbon cables was reported in a paper presented in a symposium (1981 IEEE Symposium on EMC, Boulder, Colorado, p. 281, "Shielded Flat Cables for EMI and ESD Reduction," by Charlotte M. Palmgren, 3M Corp.).

Here we have a very serious problem. We've got to protect against a threat that we never had to worry about with analog circuits, namely, extremely fast rise time, very narrow pulses. We also have to do it so that we don't suffer problems with low-frequency coupling between power and digital cables. It's not going to be easy, but we've got to look at both problems.

I propose the following: Consider coax as your first choice. Consider single-ended. It's the least expensive, and the most proven digital transmission method. If you want to use differential circuits, that's fine. But we found this morning from Keith's demonstration that even at 400 Hz, from the inverters — and their harmonics — even differential circuits cannot be relied on. When a differential amplifier was used, you still heard the hum. Can you imagine how much more difficult it would be to maintain that digital isolation at frequencies as high as 10 to 100 MHz? It's nearly impossible.

Tektronix publishes a Tek-Scope paper all the time, I guess monthly or so, in which they talked about differential amplifiers used with their high-performance oscilloscopes. In one of their issues, they made a plot of the common mode rejection of their high performance differential amplifier plug-ins. The amount of common mode rejection as a function of frequency was scary. By the time one got to 10 MHz, 90% of the common mode protection had diminished. By the time you were near 100 MHz, the differential amplifier didn't operate any better than the single-ended amplifier. So we have to recognize that differential devices are only one answer to this equation, and questionable at that.

Another isolation technique is optic isolators. Using an optic isolator to break up ground loops sounds like a good answer on the surface until one sees how they're implemented.

We've seen a lot of optic isolators on PC boards, where the leads that come into the light-emitting diode, and the leads that leave the transmitter, go through the same connector. So we put an optic isolator in to protect our circuits against high-speed transients, only to find that the transient energy couples around the isolator because of the crosstalk in the connector and cable harness that we chose.

The inputs and outputs have to be in parallel, when only one connector exists for the PC board, and the leads are generally bundled and tied together, maximizing crosstalk.

This isn't going to work. If we're going to use these devices, we have to use good RF layout practices, and recognize that crosstalk around them is a very serious threat to their isolation capabilities.

We took a light-emitting diode apart and put a piece of opaque paper between the light-emitting diode and the base of the transistor. We hooked it to a function generator, and at low frequencies, we applied the proper signal to turn the diode on. It didn't turn on because there was no light transfer.

Then we slowly increased the frequency. To our amazement, as soon as we got around 1 MHz, we could turn that transistor on. Why? Because of the capacitance between the diode and the base of the transistor. There was enough leakage capacitance so that the transistor would turn on.

So there is a high-frequency limitation using optic isolators. Some are better than others; some have greater distances between the diode and the base, so that the capacitance is lowered intentionally. Nonetheless, if we're not wiped out by this stray capacitance, the lead capacitance generally limits the amount of isolation that can be achieved. It's not a good long-term solution.

So we're really getting down to the bottom line on solutions. What we're beginning to see evolve is the need to use shielded cables in a high-frequency sense, the way the RF industry has used them for years, successfully. Coaxial cables have been with us a long time, haven't they? And they are grounded at both ends. And they don't seem to have quite the problems we have alluded to, partly because we do try to separate them from other cables by a few inches, and partly because of their built-in rejection qualities.

A digital circuit has similar characteristics to RF circuits. If we send the digital signal from point A to B, the 1 V of dc noise immunity is significant. It takes a lot to induce 1 V into a digital cable, in the low frequencies, as demonstrated by Keith. And to do so, the cables must be extremely close together.

Perhaps we can follow rules of keeping the digital cable separated from power by some minimum distance, so that the long parallel runs are not allowed, and couple this with good quality coaxial cables. If we have a ground loop problem, allow a very simple solution; namely, the capacitor termination between the shield and chassis ground at the point of cable entry.

That problem is not so difficult if we look at how people are doing it in present-day computers. Most of them are building a very simple PC board, and the connector is mounted on the PC board. This can be beefed up by using a strong metal support for vibration. It's been used now extensively on Navy programs for the big shock test, the big boot test that Hughes has, and I guess others, and has survived very nicely.

The coax connector is mounted to the inner ground plane. The pins come through the connector. The shield pin that comes through is immediately terminated through a capacitor to the second ground plane that's on the outside. Therefore, you have a capacitor between the shield pin, or the two ground planes.

Now the outer or second ground plane is mounted directly to chassis ground. This technique terminates the coax shield at the port of cable entry to chassis ground via the capacitor.

This method is extremely effective, even controlling transients generated by the chattering relay. A really good way to evaluate this problem is to use something broadband of that nature. So there are simple techniques for putting these capacitors in.

The capacitors solve some other problems that we probably didn't think about. By properly selecting a capacitor, we can do quite a bit to control an EMP threat. When you're doing pin-to-ground stresses for EMP, capacitors to chassis are a simple solution. By controlling precipitation static and ESD static threats, you can do a lot of good toward solving EMP situations.

It also helps in lightning, but you have to be careful in the voltage rating of the capacitors. Typically, I recommend 0.001 μ F capacitors, with a 2000 V rating for this termination. They're not very large, by the way, and they can be very effective in terminating cable shields. If one cable is much longer than others, then perhaps a little larger value would be in order.

We have to integrate the low frequency into the high-frequency solutions, or we're not going to have successful digital avionics.

I'd be glad to answer any questions for the last minute we've got here.

A QUESTIONER: What's the full name of that symposium?

MR. KENDALL: The symposium is the IEEE EMC International Symposium, held in Boulder, Colorado. The proceedings can be obtained from the IEEE and reference the 1981 International Symposium on EMC.

DR. MASSON: Are you recommending that dc power ground couple to chassis in your box?

MR. KENDALL: Yes. We'll get into why you want to do that, if we have more time later.

DR. MASSON: Can you do that to all your boxes in the system?

MR. KENDALL: Yes, but then you must isolate signals between the boxes. Right?

DR. MASSON: Must isolate the signal?

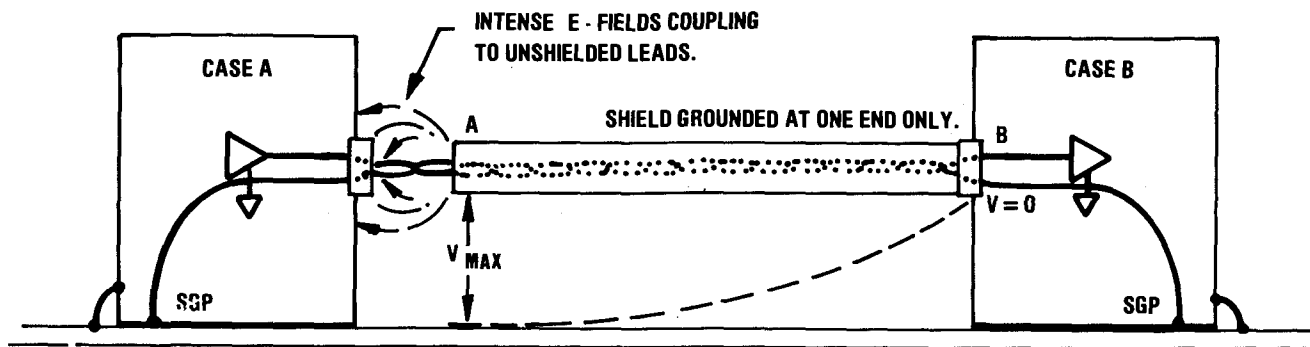
MR. KENDALL: Yes. They have to be isolated. The question is, how do you isolate? I content that the coax is the answer.

MR. MOOREHEAD: Most of our input to it, we use the same high frequency type of shielding for the analog-type input?

MR. KENDALL: No. For analog, of course, you have to recognize the problems properly presented this morning, which means the capacitor termination is absolutely necessary for the shield.

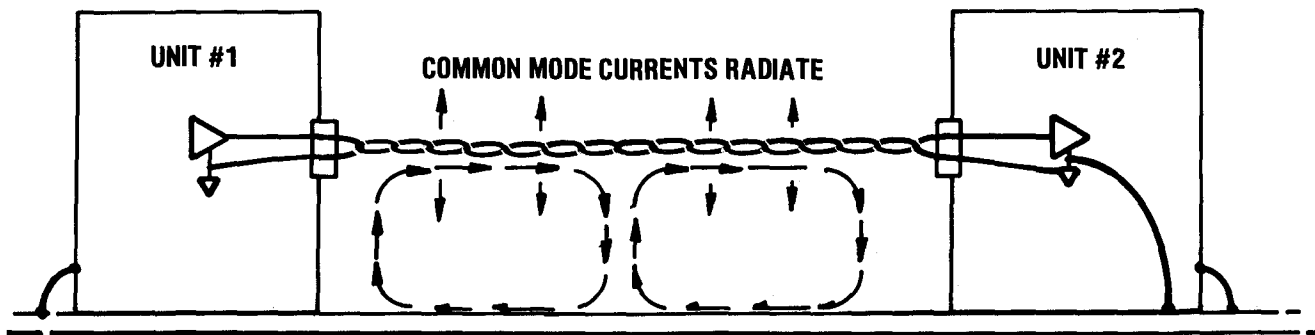
Let's assume you don't ground the shield of the analog, and you allow it to enter, for some reason, inside the box, and terminate. Then high-frequency

interference on that analog shield, which may not disturb the analog circuit at all, can wipe out the digital signal performance. So you cannot allow an analog shield to enter a box which contains digital circuits. The standing waves are just as prevalent on the analog sheath as they are on the digital, and therefore they both have to be stripped - terminated, if you will - before entering a box. Otherwise, you violate Faraday's Cage law.



- WHEN SHIELDED CABLE AB EQUALS $\lambda/4$ OF EXTERNAL RADIATION THEN V AT B EQUALS ZERO BUT V AT A EQUALS MAXIMUM.
- SINCE CASE A IS GROUNDED TO FUSELAGE OF AIRCRAFT LARGE VOLTAGE EXIST BETWEEN UNGROUNDED SHIELD AND CASE.
- LARGE DIFFERENCE IN VOLTAGE CAUSES E-FIELDS THAT COUPLE TO UNSHIELDED PORTION OF CABLE.

Figure 9-1.- Radiation penetration into improperly terminated shielded cables.



NOTES:

- ① PIN TO PIN CURRENTS (NORMAL MODE) DO NOT RADIATE
- ② PIN TO GROUND (CHASSIS) (COMMON MODE) CAUSES MOST RADIATION

Figure 9-2.- Radiation from twisted pair cable.

FULL LEVEL LIGHTNING AIRCRAFT SYSTEM HARDENING (FLLASH) PROGRAM

Naval Air Systems Command Study for the Development of Computer Models
to Model the Interaction between the Aircraft and the Lightning Channel

David Auckland

Syracuse Research Corporation
Syracuse, New York

MR. RASCH: Our next talk will be by Dr. Auckland. It's going to be on the Full Level Lightning Aircraft System Hardening Program, which is called FLLASH. This is a Naval Air Systems Command study for the development of computer models, and to study the interaction between the aircraft lightning channel and the aircraft itself.

Dr. Auckland received his Bachelor's of Electrical Engineering degree from the University of Washington, Seattle, and his Master's and Ph.D. in Electrical Engineering from the University of Syracuse in New York.

For the last 3 yr, he's been with the Syracuse Research Corporation, in Syracuse, where he's presently employed as a senior research engineer. His major area of research has dealt with developing computer models in the lightning study and NEMP fields. With this, I'll turn the meeting over to Dave.

DR. AUCKLAND: I'd like to acknowledge my gratitude to Nick Rasch and the FAA for giving me the opportunity to talk today about some of the things that I've been working on for the last couple of years.

Basically, I'd like to talk about three things. First, I'd like to briefly outline the Full Level Lightning Aircraft System Hardening Program (FLLASH) directed by John Birken of the Naval Air Systems Command. I'll give a brief overview of that program, as far as the testing and test methodologies are concerned.

Second, I'll discuss the computer models that the Syracuse Research Corporation has been developing for predicting bulk current levels and surface current levels and surface current density responses on actual aircraft and models of the aircraft. I'll discuss the transfer function approach to the coupling problem, and some of the contributions we've made in that approach, which is not a new approach, but some of the modeling techniques may be interesting to some people.

And third, I'd like to say something about user-oriented computer-aided design, and applications of this type of modeling to cable bundle layout considerations and point of entry redesign, as far as joint seams, panels, and avionics box protection are concerned.

Let me start with an outline of the FLLASH Program organization. NavAir is the test manager, and this chart gives a block diagram of all the participants. Electromagnetic Applications in Denver and Albuquerque acted as the test integrator. They actually performed most of the measurements, with LTRI as a

FLLASH PROGRAM

FULL LEVEL LIGHTNING AIRCRAFT SYSTEM HARDENING
(J. BIRKEN, N.A.S.C.)

COMPUTER MODELS

TRANSFER FUNCTION APPROACH TO COUPLING PROBLEM

C.A.D. (USER-ORIENTED)

CABLE BUNDLE LAYOUT

P.O.E. REDESIGN

AVIONICS BOX PROTECTION

consultant designing the corona/ring attachment used in the high level portion of the test.

The Naval Weapons Evaluation Facility, Naval Air Test Center, and Naval Surface Weapons Center were involved. And of course McDonnell Douglas was consulting during the F-18 testing, and Grumman during the F-14 testing.

And the bottom lines, Sandia National Laboratory, Air Force Flight Dynamics Laboratory, TRW; there were quite a few people and organizations involved in the test.

The two aircraft tested, which are both completed now, are the F-14 and the F-18. The F-14 was tested in the April, May, June time period, and the F-18 has just been completed at the end of this summer.

The FLLASH Program consisted of four major types of tests. A low-level CW injection test was performed first, which consisted of an amplifier injecting a CW current into the nose of the aircraft, the ground return being coaxial cable, the outside jacket of which was used as the conductor.

AIRCRAFT TESTED

- F-14 -- COMPLETED
- F-18 -- JULY-AUGUST 1982

TESTS PERFORMED/PLANNED

- CW CURRENT INJECTION
- AFFDL LOW LEVEL, FAST RIST TIME
- NSWC -- WHITE OAKS SKIN CURRENT INJECTION TEST (SCIT)
- SANDIA HIGH LEVEL TEST

The CW current was injected into a likely attachment point on the nose of the aircraft, which could be a pitot boom, if there's one there, or a bulk-head station. Then the current would be taken off a wing tip or somewhere by

the tail, some likely direct strike current path, and returned to ground via the coax cables which were supported more or less concentrically about the aircraft by a wood frame structure.

Sweeping the current from 10 kHz to about 13 MHz, we would measure the ratio of individual wire current measured inside the aircraft to the current being injected into the aircraft, which changes as frequency changes, because of the resonances of the test fixture. This measurement provided the band-limited low level direct strike transfer functions for various wire bundles.

The next test was a low-level, fast-rise-time test that the Air Force Flight Dynamics Laboratory performed. They used the same test fixture but their own equipment when they came out and ran their test, using their own high-voltage pulsar and recording equipment.

The Naval Surface Weapons Center were to perform what they call a Skin Current Injection (SCIT) test, which was developed during the NEMP testing on some of those aircraft that were tested for NEMP, including the F-14. NSWC performed that test for the F-14, and EMA performed it on the F-18.

Last, the high-level test, which was the one of most interest, was done at Sandia, using their lightning simulator. The Sandia equipment is capable of putting out up to 200 kA, depending on what the load is, with a rise time of 1 μ sec, and decay times of 75 to 150 μ sec. This high-level test is as close to full threat as could be achieved. We used the low-level CW transfer functions together with the high-level time domain input waveforms to see what kind of responses could actually be expected on bulk currents for the Sandia full level threat. It's perhaps tens of amps, in some situations.

Let me now show a picture that illustrates the test-bed configuration. That building to the right is where the Sandia high-voltage Marx generator capacitor banks sit. Two big oil-filled containers contain the Marx generator capacitors, and they're discharged through a special oil-filled coax cable to bring the current out to the corona/ring which is attached as shown to the F-14 nose pitot boom. The pitot boom is designed to be grounded to the aircraft structure using the outside of a rigid coax. The current follows the aircraft structure back to the exit point, which was the left wing in this case. You can see how the wood frame test fixture is built up with two-by-fours, to form a return path for the current as concentric as possible, to the fuselage of the aircraft.

Here's another view showing the nitrogen tanks, which were used to inert the fuel system. The fuel system is topped with jet fuel, and kept at a constant pressure of a few pounds per square inch of nitrogen to prevent the possibility of explosion because of the extensive arcing at various points on the aircraft (between missiles and wing tips) and at various times at locations on the wing joints of the F-14.

This picture also shows how the current exits, by some large aluminum straps bolted to the inside of the engine exhaust, which is electrically connected to the internal longeron structure of the aircraft, and then distributed to the coaxial cables and taken back to ground.

The last photo shows a high level test that was performed at night at a very high level of current, about 100 kA. Here you can see arcing from the wing tip

to that portion of the fixture that returns the current. This was an air gap exit point. In some cases we hard-wired to the nose, and hard-wired from the exit point. In other cases, we let it arc about 8 in. to ground. The aircraft is allowed to build up charge in these so-called shock excitation cases. They are quite spectacular at night.

I can't say much about the results of this test program. The data are yet to be reduced and analyzed, and this portion of the program is yet to be funded. But generally the measured results are as follows. If you take all of the bulk current measurements for the low level CW test from 10 kHz to 10 MHz, the F-14 and F-18 bulk currents exhibit an average behavior as illustrated here. This level is between 50 and 30 dB below the injected current level. This graph illustrates the bulk current measured at several connector plugs on the avionics boxes in various parts of the aircraft. The F-14 has a low-frequency slope of 20 dB per decade into its resonance region. The F-18 appears slightly less hard at the higher frequencies. It's difficult to say anything specific, because we haven't reduced the data; we've just taken rough looks at it. Ultimately, we hope to look at our computer models and see how much we have to do to bring them into line, as far as modeling some of the coupling mechanisms that we've seen here.

MR. SCHNEIDER: Stan Schneider from Boeing. That's bulk current that's measured in the aircraft?

DR. AUCLAND: Yes. By bulk current, I mean I have a cable bundle that is connected from the flight computer and goes someplace inside the aircraft. I take a current transformer and put it around the bundle, and that's what I'm measuring. This is the sum of all common and differential mode currents flowing in that bundle.

How the bulk current divides among the individual wires is another question. In the F-18, for example, most of the bundles contain twisted shielded wire pairs, which were terminated in pigtailed at each end of the particular bundles in question. What you're going to be seeing is just the current flowing on the shield of the twisted wire pairs, which is in most cases the differential mode current, or the loop current flowing on the shield and returning back via the structural ground.

MR. SCHNEIDER: Why is the F-18 curve flat? Are they electrically short cables?

DR. AUCLAND: No. I think we see two different coupling mechanisms here. I'm not sure exactly what the difference is. The F-14, of course, is a better Faraday Cage than the F-18 except for the cockpit. The F-18 has quite a bit of composite material on it, much more than the F-14. I really hesitate to say much about the difference.

MR. SCHNEIDER: What is the load inductance?

DR. AUCLAND: It was around 9 or 10 μ H for the F-18. The measurements were very close to what was calculated. With almost a negligible resistance on the F-18, we were able to get peak current input to the load of 160 to 170 kA with 1 μ sec rise times.

That's all I'm really going to say about the FLLASH Program.

MR. PITTS: Felix Pitts, Langley Research Center. I was curious, is the system operational?

DR. AUCKLAND: No. And that's a good point, because there are many relays and if the systems are not operational, the relays are not thrown, and a lot of loads aren't in the circuits that really should be.

However, on the F-18, the system was powered up, and it was powered up in the navigation mode, using the auxiliary power unit. That presented a few problems, as far as testing was concerned. The APU wasn't designed to run for a couple hours with its jet engine running continuously. There were overheating problems, which probably resulted in MTBF-type problems with equipment. It was very difficult to test under simulated realistic conditions. The F-18 was powered up, and those loads were in, that you should see. We found it very hard to measure individual wire currents because they're 90 to 100 dB below the threat. It's hard to get that kind of dynamic range. But we did get a few individual wire measurements.

The F-18 does represent a relatively new technology aircraft, the F-14 representing a relatively mature technology aircraft. It will be interesting to say something about the kinds of troubles one gets into with composite materials, or the types of technology used for shielding the cables, terminating the cables, things like that.

MR. SCHNEIDER: Stan Schneider, from Boeing. Was there any circuit damage in either aircraft that you know of?

DR. AUCKLAND: I don't know that there was any directly attributable to the lightning tests. Again, the data are yet to be completely reduced and analyzed.

MR. ZIGLER: Murray Zigler, Sikorsky Aircraft. Can you tell me if there's any kind of comparison you can make between low-level and high-level testing?

DR. AUCKLAND: Yes. The low-level test was used as a stepping stone. We took the low-level test results, the swept CW, to develop the transfer functions for those high-level responses. For example, if I know what that waveform and rise time are, I can compute the responses for a given input waveform, as long as it doesn't have a frequency content higher than swept CW transfer function results. Thus, I can fold the transfer function into the waveform that I think I'm going to put in during high-level testing, and I can come up with so many peak amps, on certain wires. Say I'm going to get 200 A on the mission computer bundle. What kind of problem is that going to cause? Then I can do some estimation and say that if I've got n wires in that bundle, the current is going to divide by a factor of n , and I'm going to potentially have so much current on one wire — and if you look at the devices that are attached to that pin, you might have a potential problem.

We were worried that a pin might carry too much current during high-level testing so we looked at as many of these things as we could during the testing, and tried to determine whether we were going to place anything in danger or not. That's what we used the low-level test results for.

MR. SCHNEIDER: You would say that in the future, you could possibly use only low level?

DR. AUCKLAND: Possibly. It's much easier to perform, but there's another point. We have to do it correctly. We have to make sure that all the loads are in, and all the switches and relays are thrown that are going to be thrown during operation, in case a lightning strike does actually occur. A lot of thought has to be put into how to do a really meaningful low-level test. The low-level test will not simulate arcing or other nonlinear effects, however. Also when you turn on the generators and power everything up, you could have more current induced than you would by the low-level tests.

On the F-14, a test was performed where we alternated switching back and forth between left and right generators, powering up the main power buses. We were just looking for transients induced on various wires when we switched the generators.

MR. SCHNEIDER: One quick question. Stan Schneider, Boeing. What was your frequency range of interest for the swept CW?

DR. AUCKLAND: From 0.01 MHz to 13 MHz. We used a phase locked loop with a network analyzer and took the ratio of the bundle or wire current to the input current. We did it in two ranges, 0.01 to 1 MHz, and 0.1 to 13 MHz, so they overlapped a decade.

MR. PEACOCK: Max Peacock, FAA. What sort of considerations did you give in your testing to how close you were to some possible nonlinear ranges, where a CW test might work fine with linear assumptions, but when you went to high-level testing you might find that the system is really not linear at higher levels?

DR. AUCKLAND: Most of the cable bundle and individual wire responses were pretty linear in the test results. Of course, you get much different excitation at joints of doors if arcing occurs. But that did not play an important part in the things that we were monitoring and measuring. I'm not saying that those things didn't occur. They did when there was arcing at various locations on the aircraft. But that did not seem to adversely affect any measured results.

Of course, none of my analysis includes any nonlinear effects. I'm assuming, with this transfer function methodology that I want to present, that everything is linear.

MR. ERICKSON: Jim Erickson, FAA. Were there any provisions for observation inside the fuel tanks?

DR. AUCKLAND: No. There was no video camera or other means of observing any arcing inside fuel cells. The only monitoring we did visually was in the F-18 where two video cameras were placed inside the cockpit and the displays were monitored for upset during the high-level shot.

MR. ERICKSON: You weren't worried about the fuel?

DR. AUCKLAND: Oh, we were worried about the fuel. The NavAir fuels people spent a lot of time considering this. McDonnell Douglas spent a good 3 or 4 wk making sure that they safely inerted their fuel system.

MR. ERICKSON: Was there any arcing going on in the tank that the NavAir fuels people were able to detect?

DR. AUCKLAND: I don't see how there could be any arcing inside the tank, because you'd have to have a big potential buildup across the tank, and that would occur primarily on the outside of the tank. If anything, there might be some trickling of currents around the outside. I just can't see how there really could be an arcing problem inside the tank. What we were concerned about was arcing near a fuel vent where you might get fumes ignited. That's why they came up with their purging idea. We did get a position from NavAir on the potential fuel tank hazards. And John Birken would be able to provide much more detail on that than I would.

MR. LA CROIX: I'm Steve La Croix, from Garrett Turbine Engine Company. You said you had the APU running?

DR. AUCKLAND: Yes.

MR. LA CROIX: That's a full electronic control. I was curious if the APU ran through all these lightning tests.

DR. AUCKLAND: Through the high-level tests, yes. I don't think that the APU was affected directly by any of the shots. But again, they had MTFB problems.

MR. LA CROIX: I'm glad I asked.

MR. SCHNEIDER: Stan Schneider, from Boeing. Was that the F-18?

DR. AUCKLAND: That was the F-18. What is the more interesting part to me is the development of coupling models to simulate the external lightning threat. We can estimate what the spectral content is, which interacts with the aircraft to produce skin currents flowing in the aircraft, which interact through various points of entry that are modeled by transfer impedance and joint admittance.

There are many approximate techniques based on various assumptions. An example might be using infinite ground plane results, but there's not much else you can do, unless you really want to make the problem complicated. Anyway, the issue is to calculate the internal coupled fields in the avionics bays, where all the equipment and the wires are.

Now, as has been mentioned before (and I think it is valid), the wire bundle running from point A to point B in the aircraft along the aircraft skin, and through bulkheads, can be modeled with some reasonable justification as a transmission line, a single wire above ground. This assumes you're going to be solving for the loop current or for the differential mode current. You're not going to be solving for the common mode or antenna-type received current in this analysis. The best way to analyze this problem would be to treat it just as an antenna loaded at each end, and then solve for both of the modes, as well as a directly injected mode of current that comes from the outside in through perturbations in the Faraday shield. An example of this would be if you have doors that aren't properly sealed. With a lot of composite material being used in aircraft, that's quite possible. So you could have direct paths right in through the bulkhead onto wires.

It's very easy to use a transmission line model once you come up with distributed voltage and current sources which drive it. These distributed voltage and current sources depend on the fields at that line location.

Eventually, what we want to be able to do is predict what current is flowing on the lines, say, at the point in which it connects to an avionics box, and try to figure out what the pin-to-ground voltage, pin-to-pin voltage, and maximum current flowing into the pin are. Each level has an order of magnitude of complexity, and you suffer the consequences because of that.

I now would like to go through how you describe these transfer functions, and how they go together. This vugraph defines all the transfer functions that I'm working with, and it gives you an idea of what I'm trying to do overall.

TRANSFER FUNCTIONS USED IN ANALYSIS AND MEASUREMENTS

$$\begin{Bmatrix} V_B(f) \\ I_B(f) \end{Bmatrix} = D(f)T_{AC}(f)T_{POE}(f) \begin{Bmatrix} T_C^V(f) \\ T_C^I(f) \end{Bmatrix} T_T(f)T_P(f)$$

$V_B(f), I_B(f)$ = voltage and current transfer function at input susceptible device

$D(f)$ = threat driving function spectrum

$T_{AC}(f)$ = band limited approximation to impulse response of aircraft

$T_{POE}(f)$ = points of entry transfer function

Z_{st} = material shielding transfer impedance

Y_j = joint admittance

$T_C(f)$ = transfer functions accounting for compartment detail T_C^V, T_C^I

$T_T(f)$ = transmission line coupling transfer function including cable shielding

$T_P(f)$ = avionics box protection function including penetration and circuit protection functions

These are idealistic models. We model the bulk cable as a closed loop consisting of a perfectly conducting wire of a certain radius, equivalent to whatever the bundle is. The current and voltage I want to measure are a combination of these transfer functions: the threat, the aircraft, the point of entry transfer function (by the way, there are various points of entry all along a particular wire bundle), and then the voltage and current transfer functions for the compartment that each particular point of entry excites, the transmission line function, which is very straightforward, from classical references on the subject, and perhaps some avionics box protection-type function. I'm going to describe how you characterize these things quantitatively.

Here's an F-14, for example. We start with whatever data base somebody has available. In this case, it was a survivability/vulnerability data base, where they simulated shooting bullets at it and calculated what panels got hit based on a statistical model. It has over 4000 edges and 1700 nodes and is made up of only triangular patches. The NASTRAN data base is another one we can work

with. But we have to take it in its raw form and reduce it. We cannot do anything with either data base analytically or numerically as they are.

Now what we have is a threat, either a field due to a lightning strike nearby, or a direct strike, or some other source. This source excites surface currents on the skin of the aircraft. Those currents will radiate on the airplane skin, in free space, to combine with the incident electric fields, so that the tangential component of the electric field is zero everywhere if it's a perfect conductor. If it's not, then it has to satisfy some impedance boundary condition at the surface of the aircraft, which we have in the computer model.

We use a method of moments scheme to solve the resulting integral equation in the frequency domain. We expand the current in terms of basic functions defined on these triangular patches, and end up satisfying the E-field equation at various points on the body. We then have N equations and N unknowns to solve for. With some 500 edges, and each edge representing an unknown electric surface current, minus the aperture edges, we end up with a 510 by 510 matrix to invert, with complex coefficients.

This is a bottom view of this surface patch model. We have some detail with the engines on the F-14. We leave the engine inlets as they are. They are open all the way through to the exhaust ports. We leave larger apertures open. Whenever we have composite materials or something we can model by an impedance boundary condition, we satisfy that instead of the perfectly conducting E-field equation.

The end result is a number of surface currents on the aircraft. Here's the way we plot it. What we're solving for is complex phasor coefficients to obtain the frequency domain current density. I've taken the real part of the phasor times $e^{j\omega t}$ for $\omega t = 0$ so just the real part is plotted. It's a vector on the surface of the aircraft skin. This analysis relates to a test where I've injected a current at the nose and taken it out at the tail of the F-14. The details of this formulation were presented at the Santa Clara EMC symposium last September.

Basically, this is how the current is distributed on the skin of the aircraft and these pictures show you how it is vectorally oriented. Here, I've plotted the magnitudes relative to the largest skin current density, 0.69 A/m, based on a unit input of current density. This is the percentage taken from zero to 90% of maximum. As expected, near the edges of the cockpit you get a large current density flowing back to the exit point. Over the wings you get a smaller current density. On the wings, which were not exited, you get a very small circulatory current, less than 2% of maximum.

MR. KENDALL: Of 0.6 A/m? Is that correct?

DR. AUCLAND: Yes.

MR. KENDALL: It seems awfully low.

DR. AUCLAND: Well, it's relative to 1 A. And I'm not counting the current densities that are adjacent to the node because, theoretically, they become infinite.

A QUESTIONER: I have trouble thinking of a phasor current, transient current.

DR. AUCKLAND: These are not transient currents. This is CW, which is frequency domain. I've got that 510 unknown matrix equation to solve. That's only good for one frequency. What I've got to do is re-solve the matrix equation for all the frequencies of the input spectrum. The best I can arrive at is a band-limited approximation to the impulse response to this aircraft. To do this I choose sample frequencies, not necessarily uniform, such that I end up with a piecewise linear approximation to the skin current spectrum. We find most of our models for lightning fall off fairly rapidly, so if we take the computations to the first resonance of the aircraft, the model can adequately determine skin currents for lightning threats.

A QUESTIONER: Which is in what neighborhood of frequency?

DR. AUCKLAND: The first resonance for the F-14 is about 7.5 MHz. Our models are good to about 10 MHz, but not much more, because the assumptions in the model about the current behaving properly before the triangular patches break down. You've got to have so many of these triangular patches per square wavelength in order for it to be valid. That's the shortcoming with the moment method. It starts breaking down as the frequency gets higher. I'm pretty sure that after we've analyzed these data, we will find that these models are valid for the lightning waveforms that we've been talking about.

I mentioned that that's a phasor that we're plotting in the time harmonic case, which oscillates through its period. In general, they follow an elliptically polarized path of rotation, following the oscillation of the input current. You can see this by enlarging a single triangular patch. As the frequency becomes low, these phasors become linearly polarized. They follow right along with the input current. As the frequency becomes higher, they deviate from the linear cases shown here. We have computed nose-to-wing and nose-to-tail excitations. We've got data files of surface current density for various frequencies, excitations, and aircraft. One must conduct the analysis for various projected excitations first and then store the results. That's good for any kind of input waveform you want, as long as it doesn't have a frequency content higher than your band-limited approximation to the transfer function.

It's informative to look at the case of a plain wave incident (similar to a Nuclear Electromagnetic Pulse (NEMP)), for near-strike lightning. One can approximate the fields impinging on the aircraft by an incident plain wave, and one can let the frequency become low and watch the magnetostatic behavior of the current as it circulates around to create an H-field that opposes the incident H-field. That's exactly what we see here, where the plain wave is incident from the top, and you see the currents circulating around for the bottom view. That's an interesting way to look at these currents.

I've said something about what we do to model the aircraft. The threat is another story. If you've got an incident NEMP or a near-strike discharge of lightning of a few hundred meters or so away from the aircraft, then the source is most likely independent of the aircraft. The time domain behavior of the source waveform is often modeled by a double exponential ($e^{-\alpha t} - e^{-\beta t}$, where $1/\beta$ is approximately your rise time).

This vugraph shows the normalized spectrum for lightning waveforms which have rise times on the order of 1 to 0.1 μ sec. NEMP has higher rise times, and the frequency content is much higher. Into the megahertz region, our models of what we think the lightning spectrum is has dropped off considerably. That's

based on the assumption that the lightning doesn't have a rise time much less than a microsecond. If the lightning has tens of nanoseconds rise time (there are data to support that), then the spectrum is going to be extended in frequency. We have to really work hard to get this effect in our models.

Here are various surface currents plotted, for NEMP, and direct-strike lightning, and near-strike lightning. Also shown is the unweighted response from the skin current transfer function. Now, in the frequency domain, we excite points of entry which couple into the avionics bays. Using descriptions of the internal bay geometries, we are able to compute internal fields and internal distributed voltage and current sources for the transmission lines.

Should you want time domain information, you can always do an inverse transform. This is an example of that computation. You can't get any responses, however, for times less than Δt , depending on the highest frequency you've got all your information out to.

This vugraph shows what the skin current might look like at a particular location on the aircraft for a unipolar double exponential lightning pulse. Boeing has done a lot of work with joints and composite material panels, measuring surface transfer impedance and joint admittance with their quadraxial coaxial test fixture, as far as points of entry are concerned. We have done a lot of theoretical analysis on joints and cracks and holes.

This is an overview of several panels, and these are plots of surface transfer impedance, which is a ratio of surface current on the outside of the panel to the tangential electric field inside the panel. Titanium and aluminum provide excellent shielding. Graphite epoxy is a couple of orders of magnitude less, because the conductivity is less. Boron epoxy is even worse, as far as shielding is concerned.

Joints are characterized by their so-called joint admittance parameters, and small holes by their electric and magnetic polarizabilities.

It is very difficult to accurately treat coupling into large apertures like the cockpit. Really, to do the whole problem right, I should cover everything up with perfect conductors and solve for the short circuit current — like Schelkunoff developed in his equivalence principle years ago — and then I should excite a new inhomogeneous problem, with the negative of that short circuit current right where the aperture is, radiating in the presence of the complicated airplane and the internal compartment. It's just prohibitive to do that now.

For large apertures, we assume that the way the test fixture is set up is like a TEM cell, where the fields are fairly TEM, at least at the lower frequencies, to the axis of the test fixture. If you can make an assumption that the fields are TEM, then the problem may be treated by transmission line analysis.

A QUESTIONER: Can you define some of those initials?

DR. AUCLAND: I'm sorry. Transverse electromagnetic. That means that the electric and magnetic fields lie in a transverse plane to the direction of propagation. That's what a transmission line mode is. There is no electric field or magnetic field directed longitudinally to the axis of propagation or parallel to the axis of propagation.

In this test fixture, most of the predominant field will be electric field lines from the return cables into the aircraft structure, and magnetic field lines circulating around the current flowing down the structure. That's the transverse electromagnetic mode. Once you make this assumption, all you have to do is solve a static field problem. Then the E- and H-fields are very simply related. But a good guess is what the fields are doing inside the cockpit or the wheel well.

Now, let's say that the end effects of the wheel wells and cockpits can be neglected, and we can just look at the two-dimensional coupling problem. This vugraph shows the two-dimensional fields on the TEM line. In our solution of the field lines, we see the coaxial cables returning the current and the field flux lines circulating around them. The main current is flowing down a section of the fuselage, and the field lines couple into the cockpit. There's various correction factors that people have derived experimentally for adding to the two-dimensional result for a more realistic three-dimensional result, which is really what you want. We use these fields for exciting lines that run exposed in the cockpit regions.

MR. PEACOCK: Would you say, then, the two-dimensional is more conservative than the three-dimensional view?

DR. AUCLAND: Yes. The two-dimensional analysis would give a weaker field strength in the cockpit and wheel well area. This analysis is conservative in that respect.

I've given you various ideas about how I get the fields inside the aircraft. Now another big problem exists. Everybody knows how terribly complicated wire bundles are on the aircraft, and what a hopeless job it is to geometrically define where they go. But we tried, because we were naive and very optimistic in our modeling efforts.

In this particular case, I am showing a heater wire bundle in the F-14. It goes along the bulkhead and then inside and down under and around, and up through a switch in the cockpit, behind a console, back to an inductive generator load. We tried to geometrically define on the models where that wire went.

So we considered three points of entry and summed up the contributions: coupling to the heater wire in the radome, the coupling to the heater wire in the cockpit, and the coupling to the heater wire in the nose wheel well, all exposed areas.

This is a plot of the ratio of measured current to injected current at the pitot tube. I'm measuring the current flowing out of the suppressor; that's I_m .

What we really want is the end result. We want to know what the peak current and voltage are, the rise time is going to be, and what the decay times are going to be. We're computing this for inputs modeled by double exponential waveforms. That's all I'll say on the modeling efforts during the FFLASH program.

I'd like to conclude by going over what I've developed. We look at the problem by partitioning it into various levels of decoupled interactions. For example,

when I excite my aircraft in the model by a direct lightning strike, it's like having an independent current source exciting the aircraft. When we shot the F-14 and F-18 at Sandia, the generator waveform was not independent of the load. And that's one thing that was assumed in these computer models. I don't know what the true effects are out in the sky, when the aircraft gets hit. Certainly, the aircraft affects to some extent the electromagnetic behavior of the channel of lightning.

At the various levels of interaction, we have a threat which interacts with the aircraft to produce a surface current. We take that surface current interacting with the point of entry to produce internal sources. We just keep going like this until maybe we can even compute damage thresholds, based on what kind of devices we're going to hook up at pins. But that's pretty optimistic thinking. It's not impossible.

Now, we've got a lot of capability in those computer models, as far as having them debugged and tested. Given files with surface current density versus frequency, we've got a user-oriented program that allows us to place cable bundles and loads in the models, vary the loads and the point of entry, and look at the design problem. It allows you to see what actually happens when you change the routing of the bundle, or joint admittance, say, by using finger stock, etc.

What we do is take these reduced models, obtained from NASTRAN, and our models of the threat, and use them to compute all the files containing the currents. That's at one level, it's not user-oriented. Then we put them into our so-called coupling program, which draws from transmission line specs and point of entry specs for a variety of wire bundles and other kinds of specifications for the problem, and it computes the specific sources from which we need to excite this model. Eventually we obtain the voltage and the current at the terminals.

So, the designer that's laying out these circuits can try various ideas of routing cables for potential problem points of entry.

If there are any questions, I'll be glad to answer them. Much of this has been presented elsewhere, at the Albuquerque IEEE Propagation Symposium, and also at the EMC Symposium in Santa Clara. We have various reprints and reports if anyone's interested.

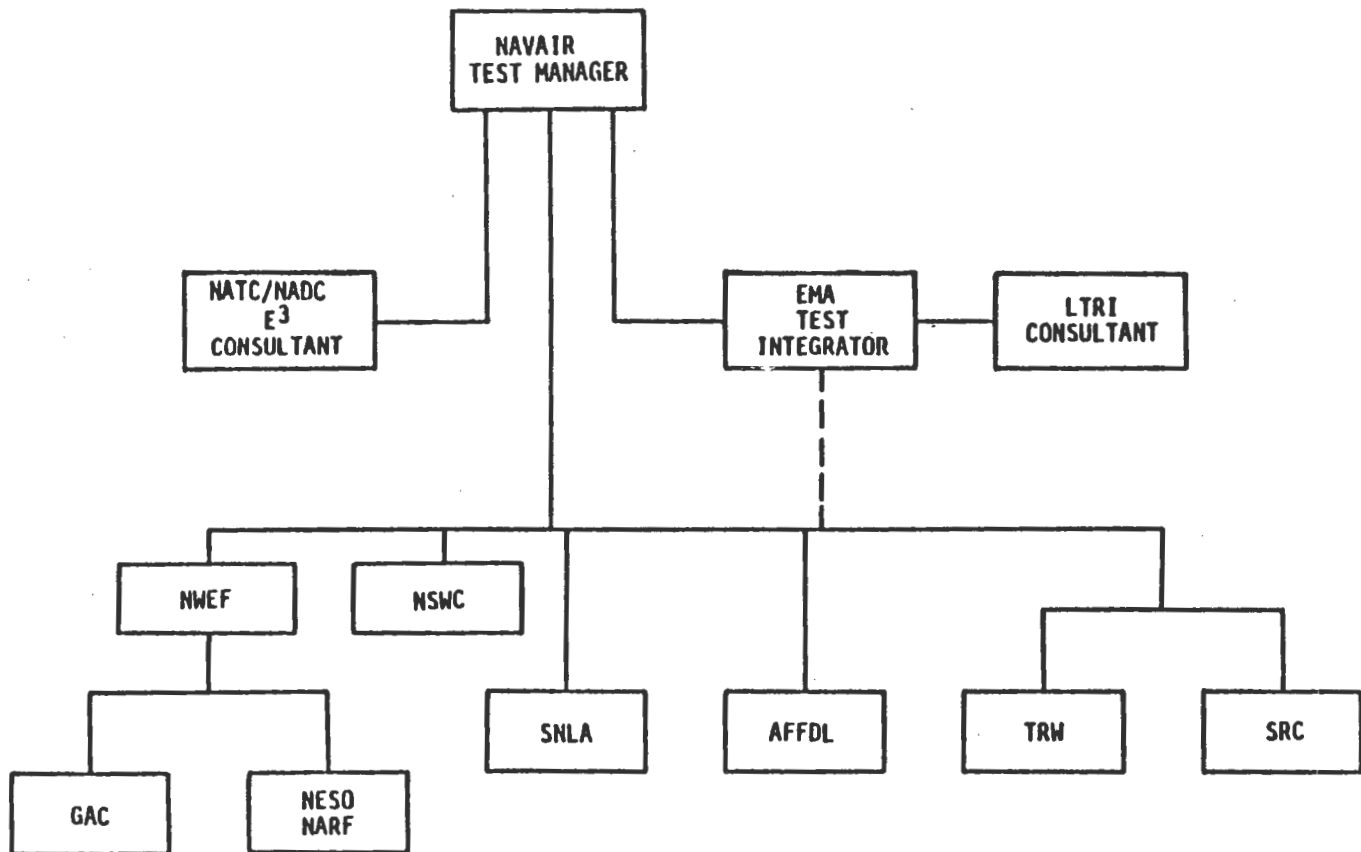


Figure 10-1.- Test organization chart.



Figure 10-2.- Test setup.



Figure 10-3.- Test setup.

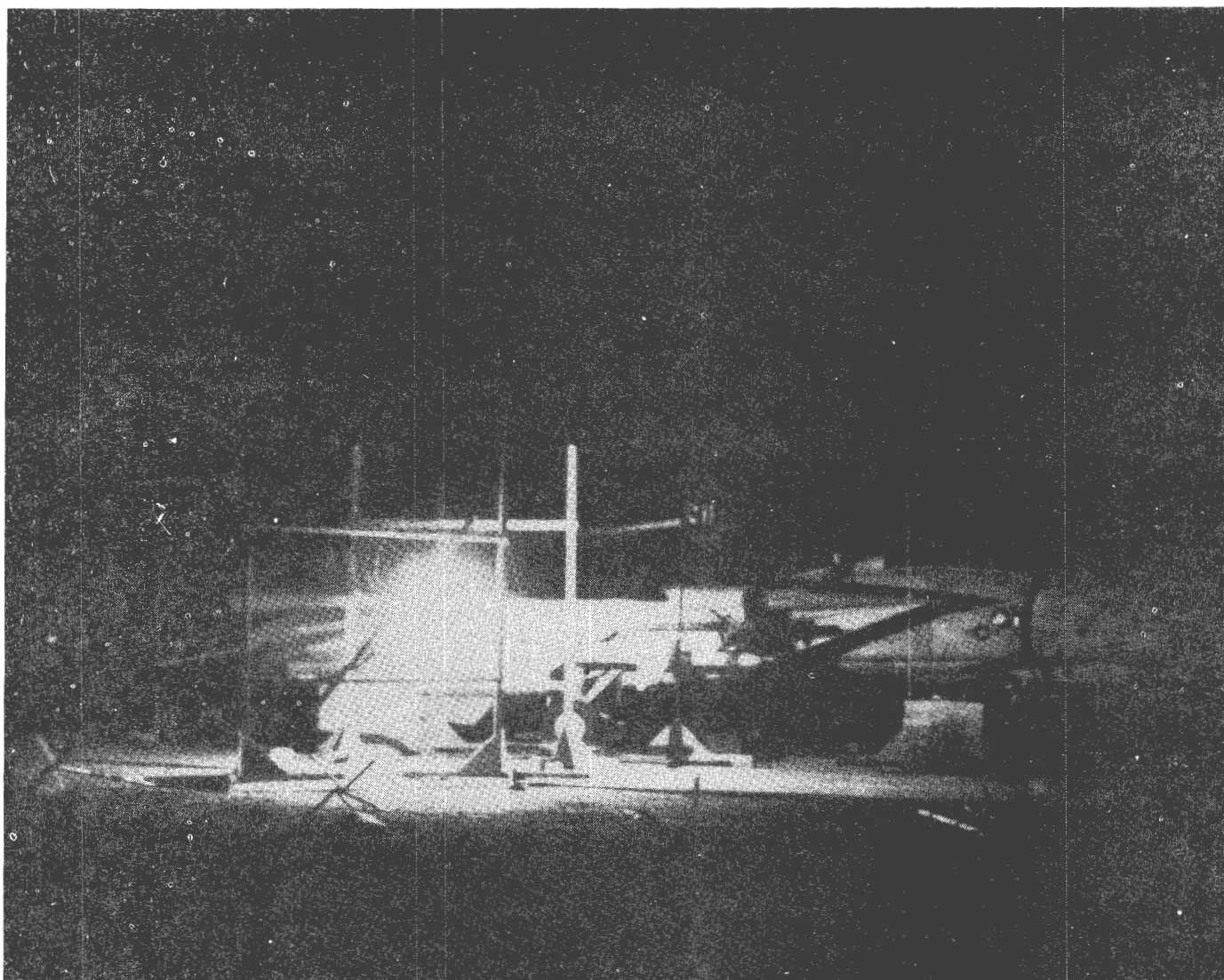


Figure 10-4.- Test setup.

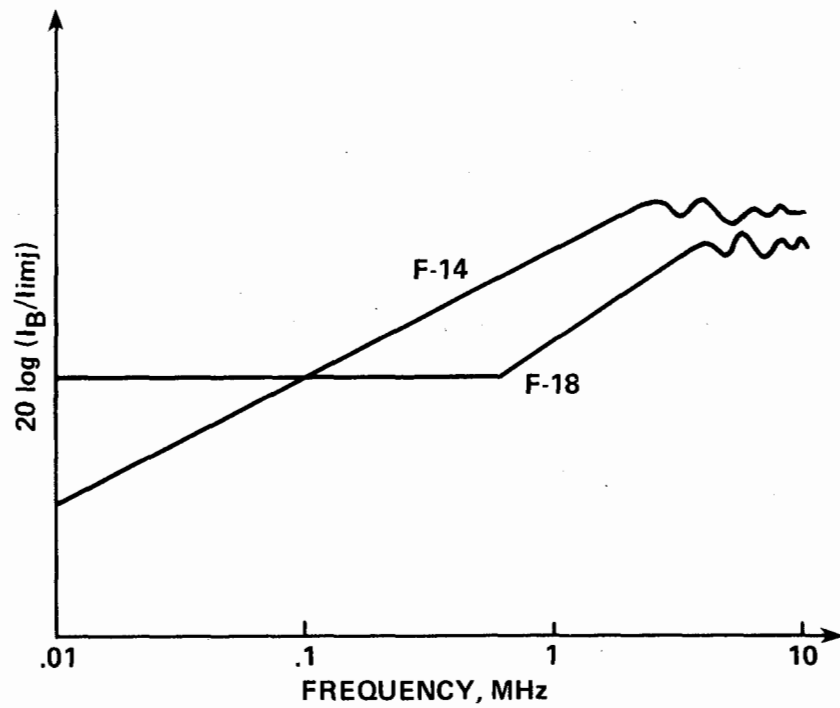
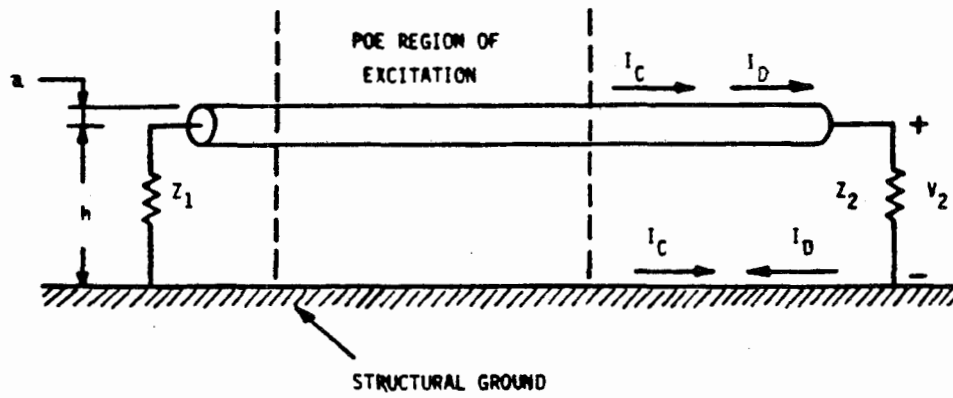


Figure 10-5.- Qualitative behavior of bulk current.



$$Z_L = 60 \ln \left[\frac{h}{a} + \sqrt{\left(\frac{h}{a}\right)^2 - 1} \right] \Omega$$

Figure 10-6(a).- Single-wire transmission line above ground.

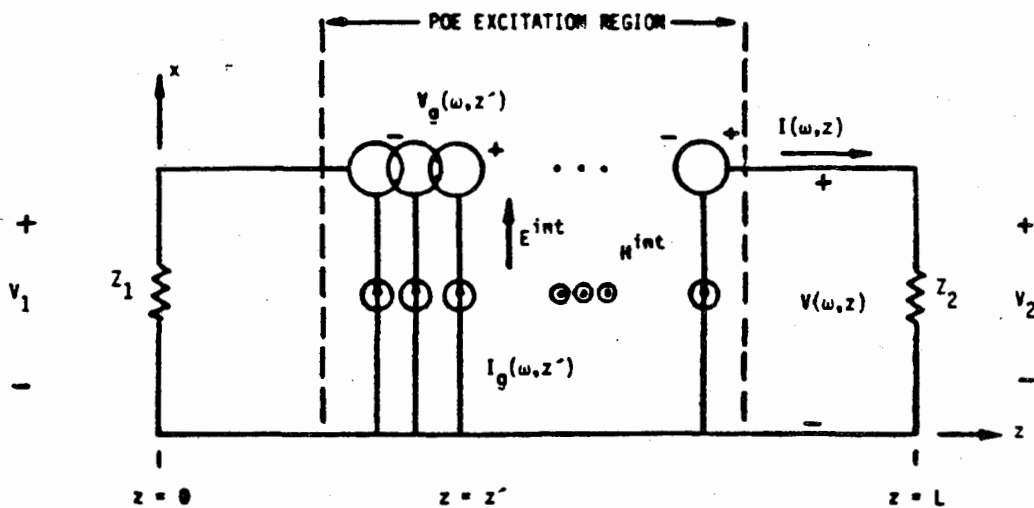


Figure 10-6(b).- Equivalent circuit for single-wire transmission line above ground with POE region replaced by distributed sources.

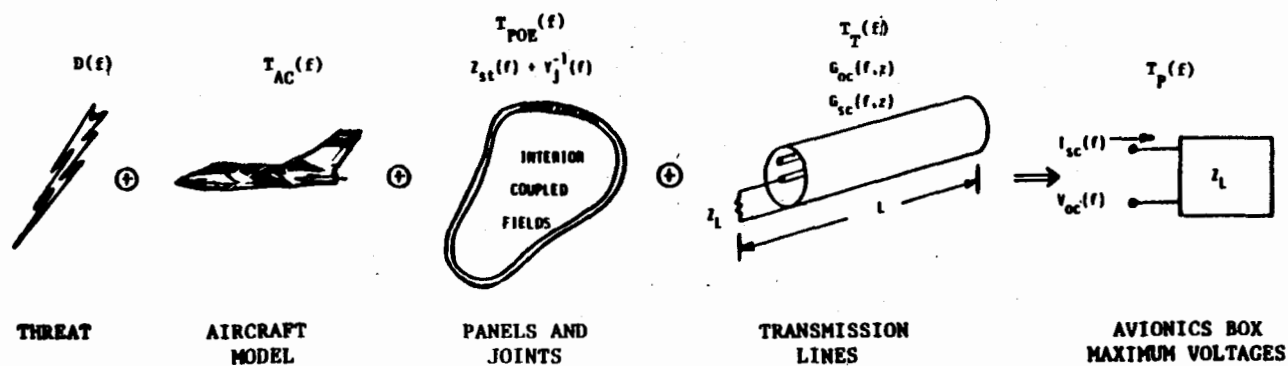
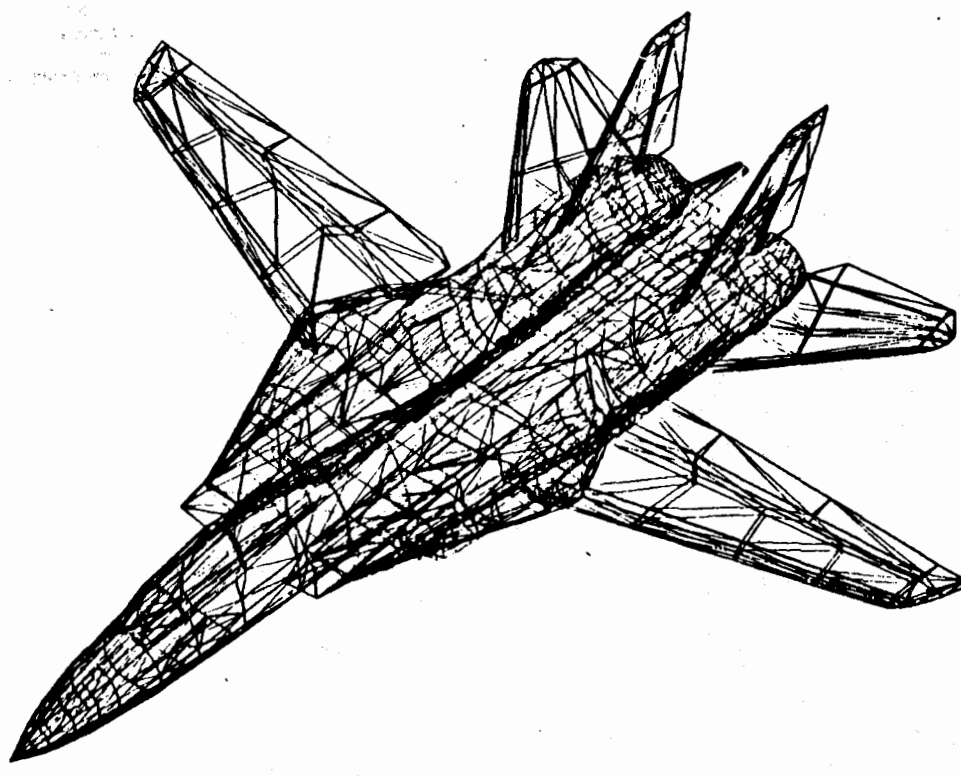
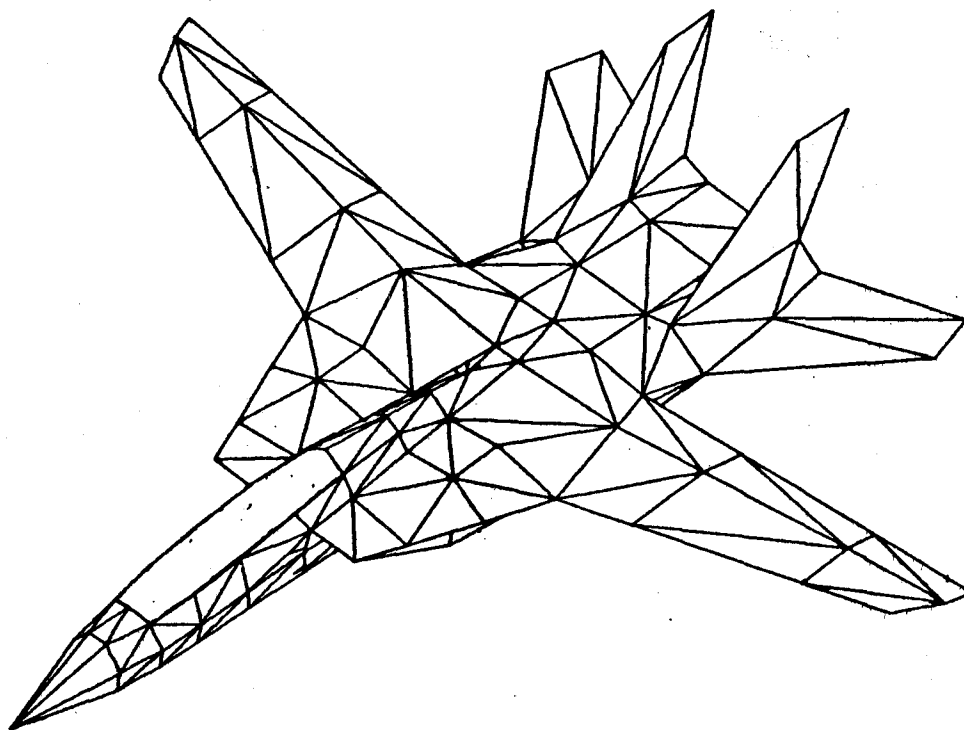


Figure 10-7.- Frequency domain cascaded linear coupling model.



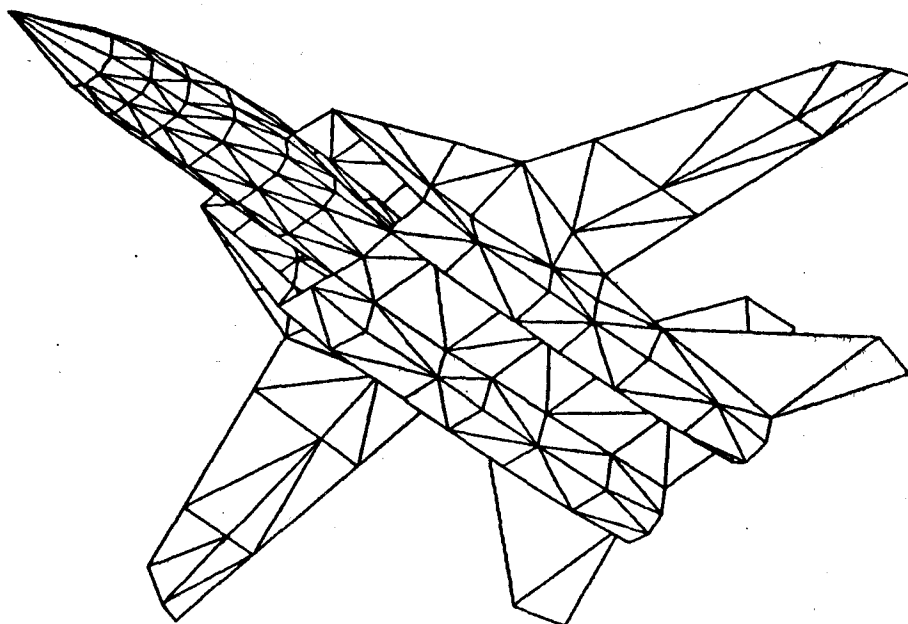
-1700 NODES
>4000 EDGES

Figure 10-8.- Top oblique view of F-14 model from raw S/V data base.



191 NODES
546 EDGES
352 FACES
36 APERTURE EDGES

Figure 10-9.- Top oblique view of F-14 model obtained directly from S/V data base.



191 NODES
546 EDGES
352 FACES
36 APERTURE EDGES

Figure 10-10.- Bottom oblique view of F-14 model obtained directly from S/V data base.

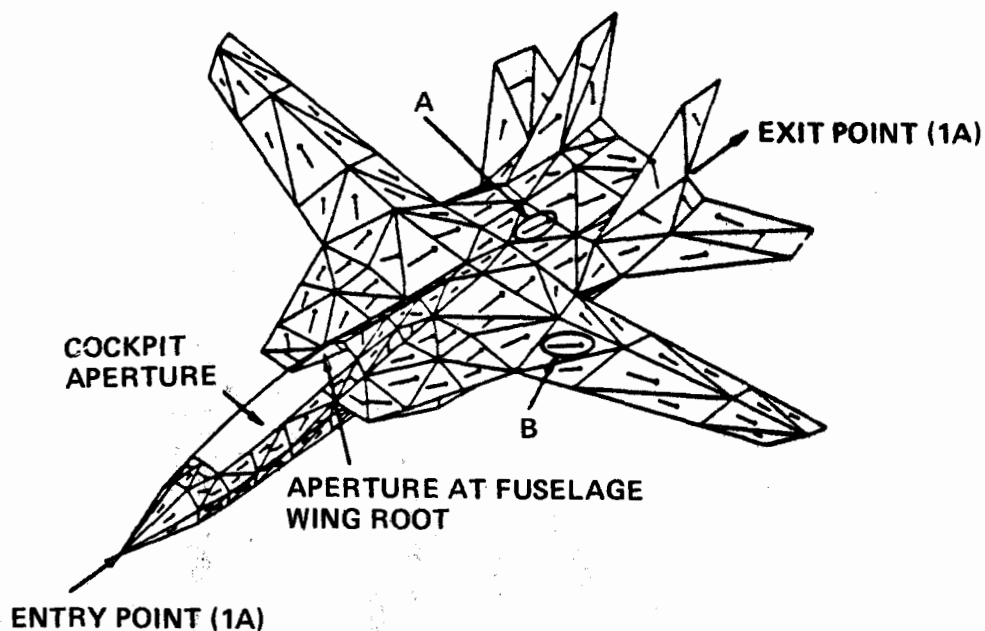


Figure 10-11.- Top oblique view of F-14 showing surface currents $\text{Re}\{\underline{J}^b\}$ for nose-to-tail injection current of 1 amp at frequency of 1 MHz.

$|\underline{J}^b|_{\text{MAX}} = 0.05 \text{ amp/meter}$

No. % OF $|\underline{J}^b|_{\text{MAX}}$

0	0 - 10
1	10 - 20
2	20 - 30
3	30 - 40
4	40 - 50
5	50 - 60
6	60 - 70
7	70 - 80
8	80 - 90
9	90 - 100

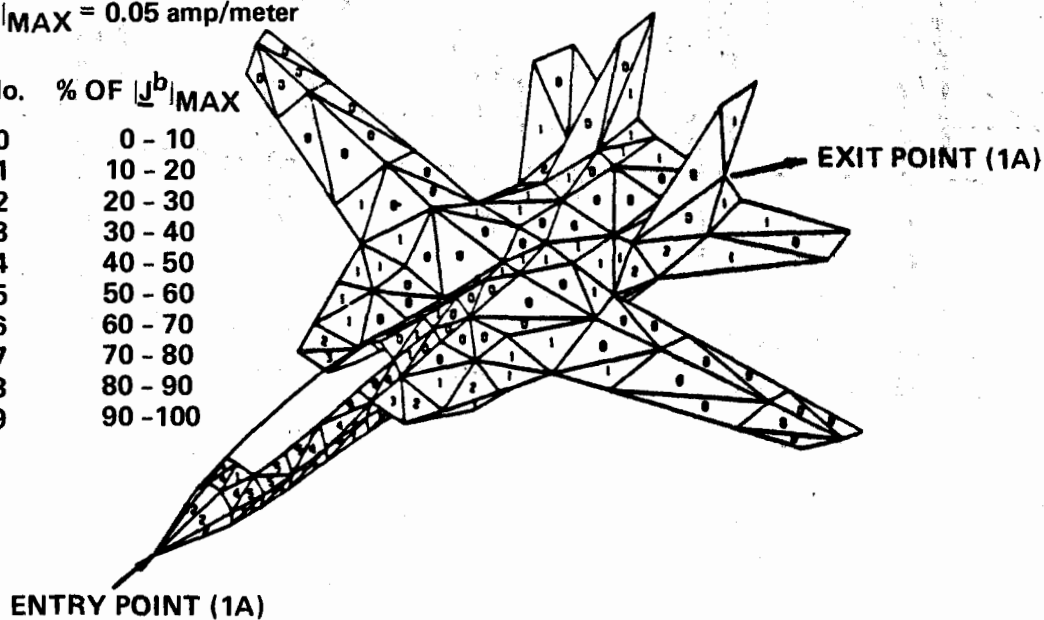


Figure 10-12.- Illustration showing magnitudes of current vectors in figure 10-11 scaled relative to $|\underline{J}^b|_{\text{max}}$.

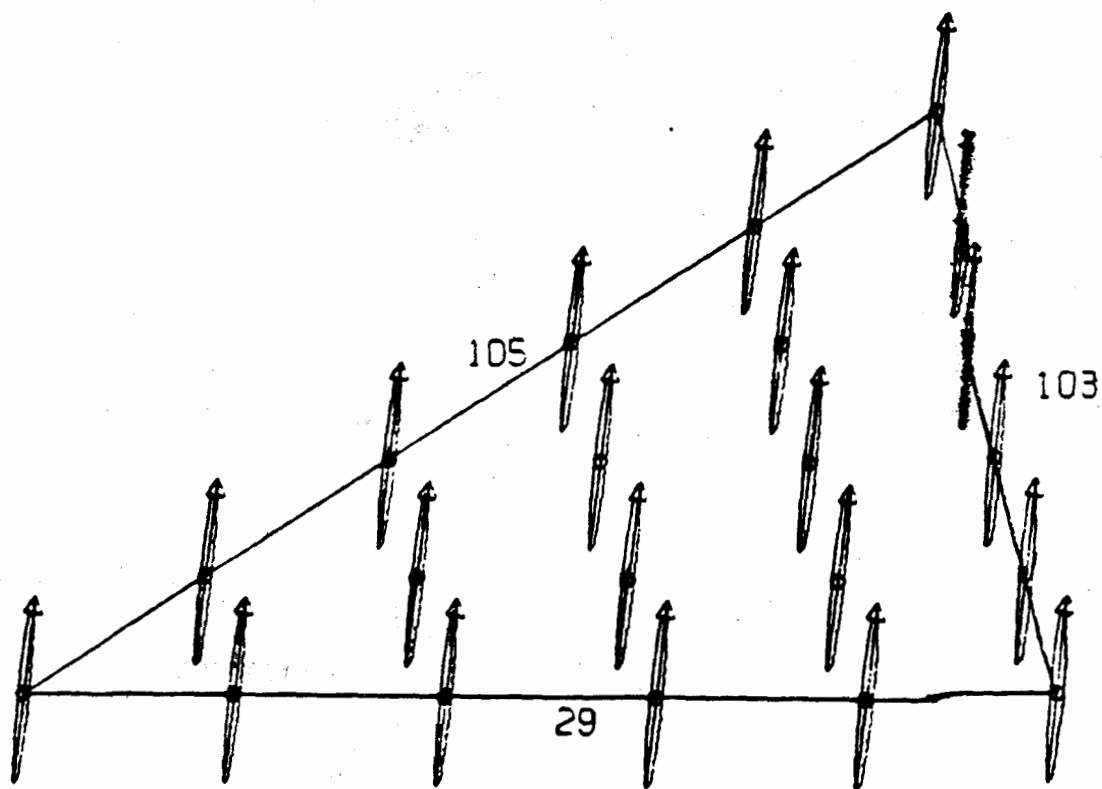


Figure 10-13.- Detail of complex current density trace in triangular surface patch on F-14 for one period of 1 MHz excitation frequency.

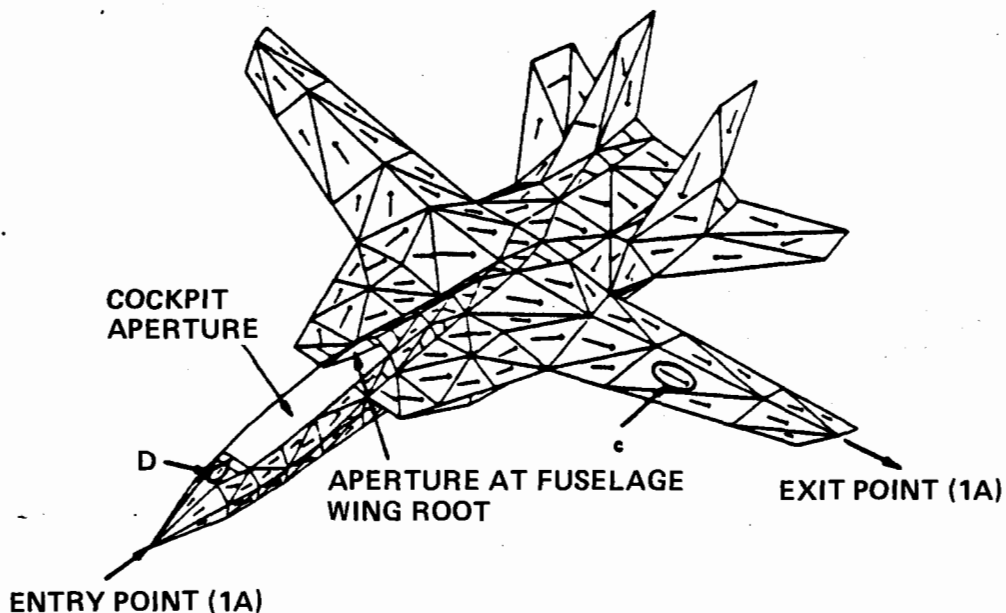


Figure 10-14.- Top oblique view of F-14 showing surface currents $\text{Re}\{J^b\}$ for nose-to-wingtip injection current of 1 amp at frequency of 1.0 MHz.

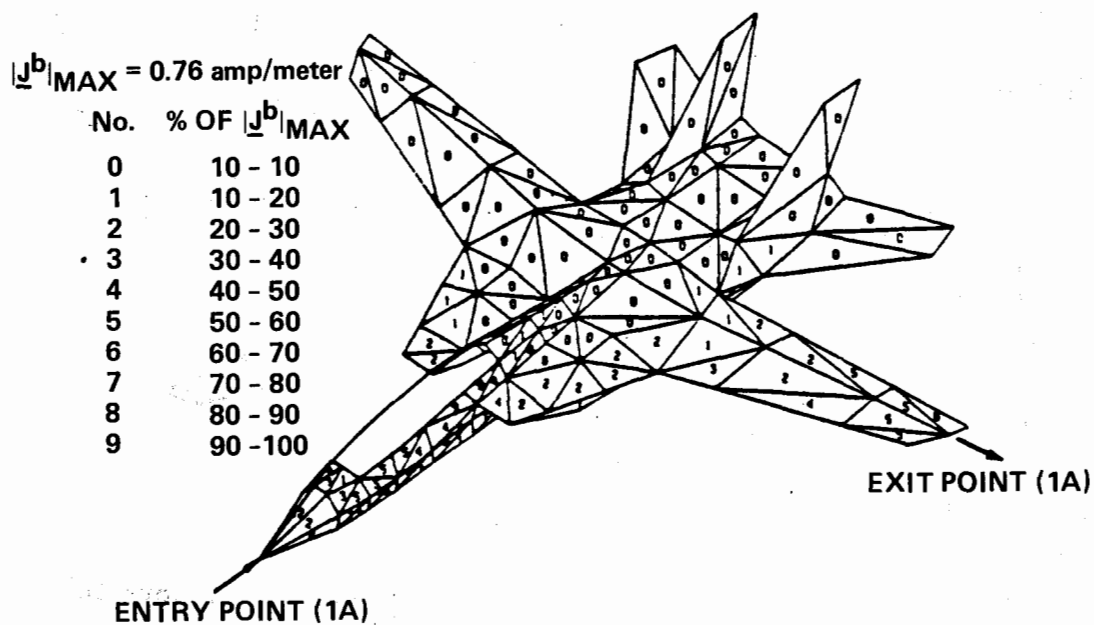


Figure 10-15.- Illustration showing magnitudes of current vectors shown in figure 10-14 scaled relative to $|J^b|_{\text{max}}$.

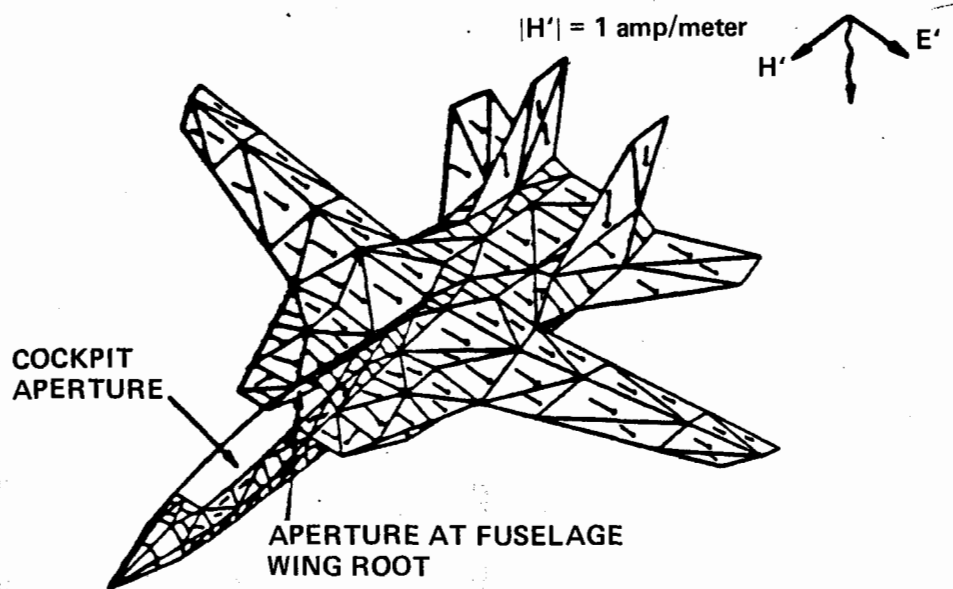


Figure 10-16.- Top oblique view of F-14 showing surface currents $\text{Re}\{\underline{J}_s\}$ for incident plane wave polarized wingtip-to-wingtip.

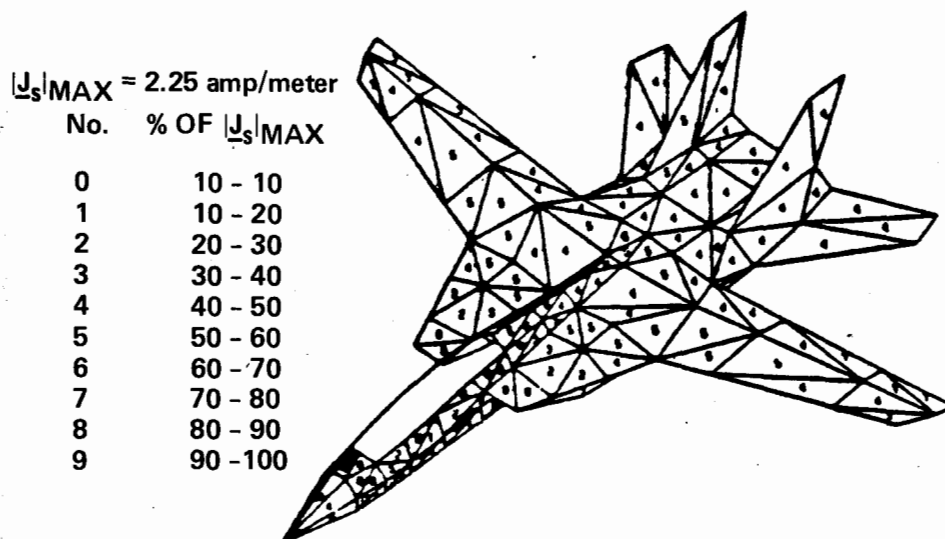


Figure 10-17.- Illustration showing magnitudes of current vectors in figure 10-16 scaled relative to $|\underline{J}_s|_{\text{max}}$.

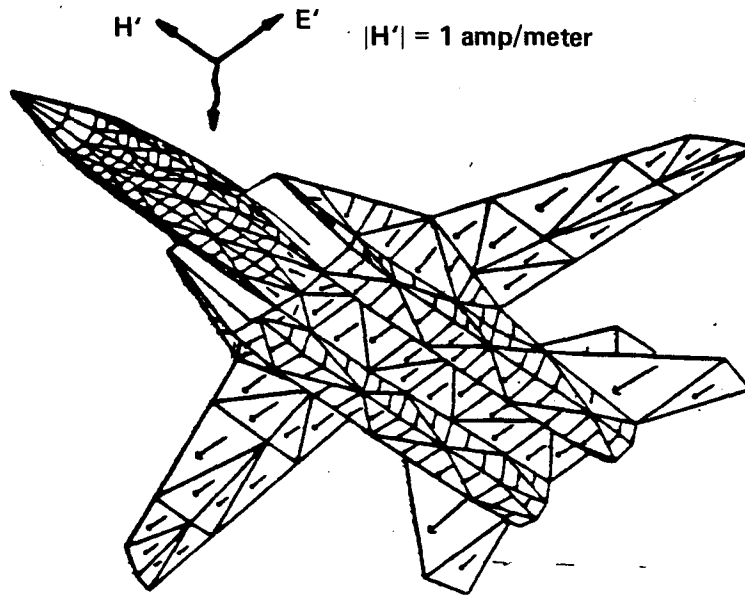


Figure 10-18.- Bottom oblique view of F-14 showing surface currents $\text{Re}\{\underline{J}_s\}$ for incident plane wave polarized wingtip-to-wingtip.

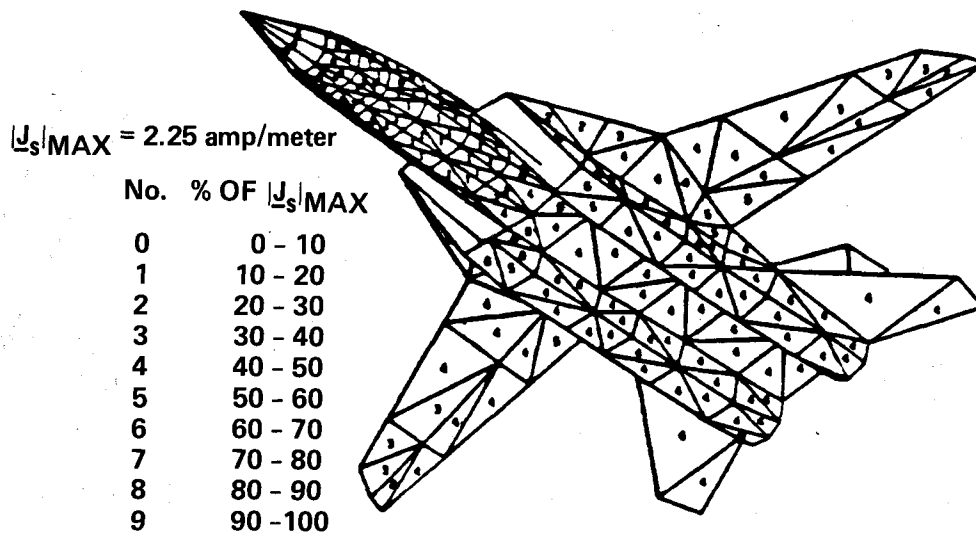


Figure 10-19.- Illustration showing magnitudes of current vectors scaled relative to $|\underline{J}_s|_{\text{max}}$.

EXAMPLES OF THREAT TRANSFER FUNCTION $\underline{D}(f)$

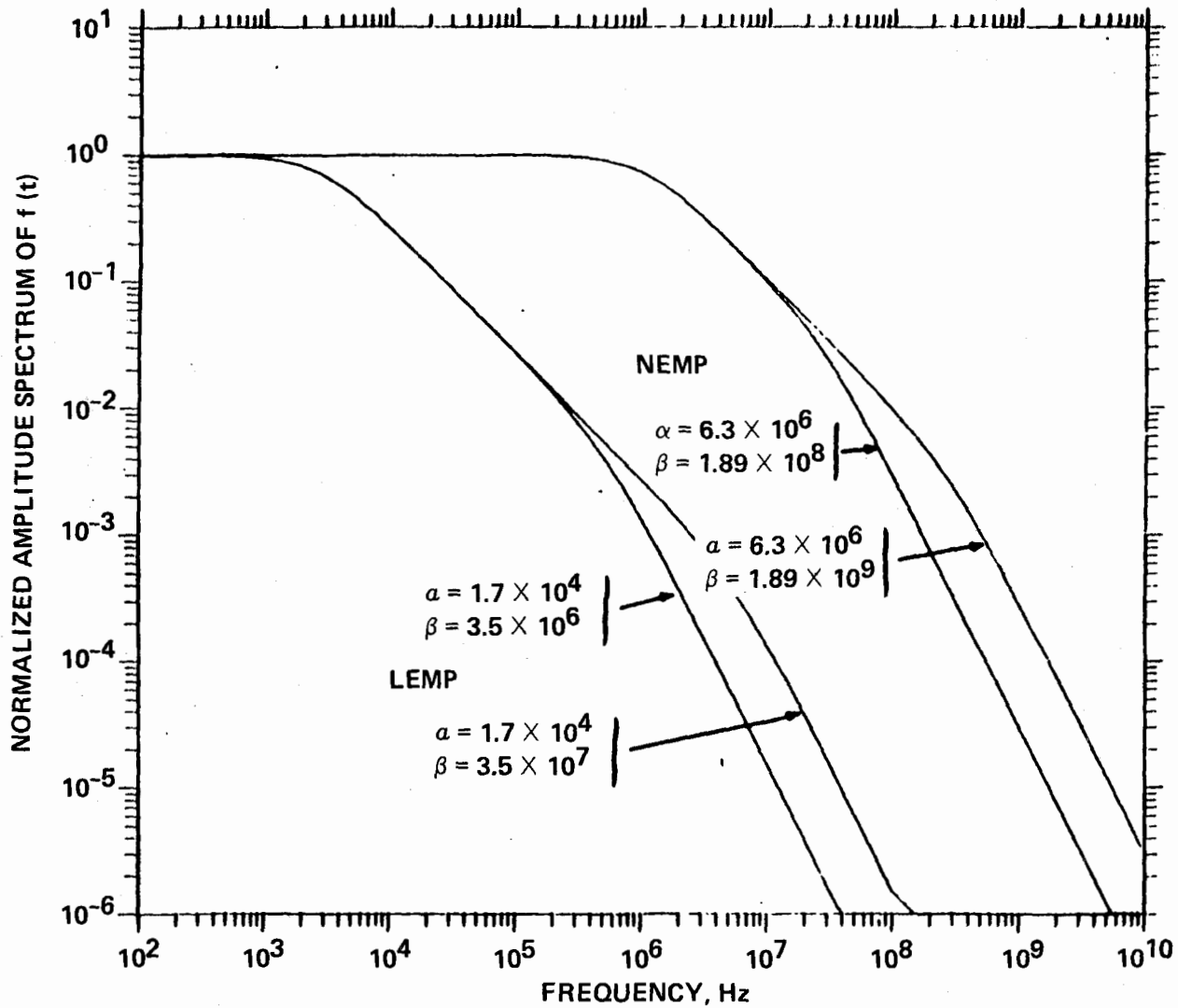


Figure 10-20.- Normalized amplitude spectrum of double exponential waveform for various values of α and β .

EXAMPLE OF SKIN CURRENT TRANSFER FUNCTION $T_{AC}(f)$

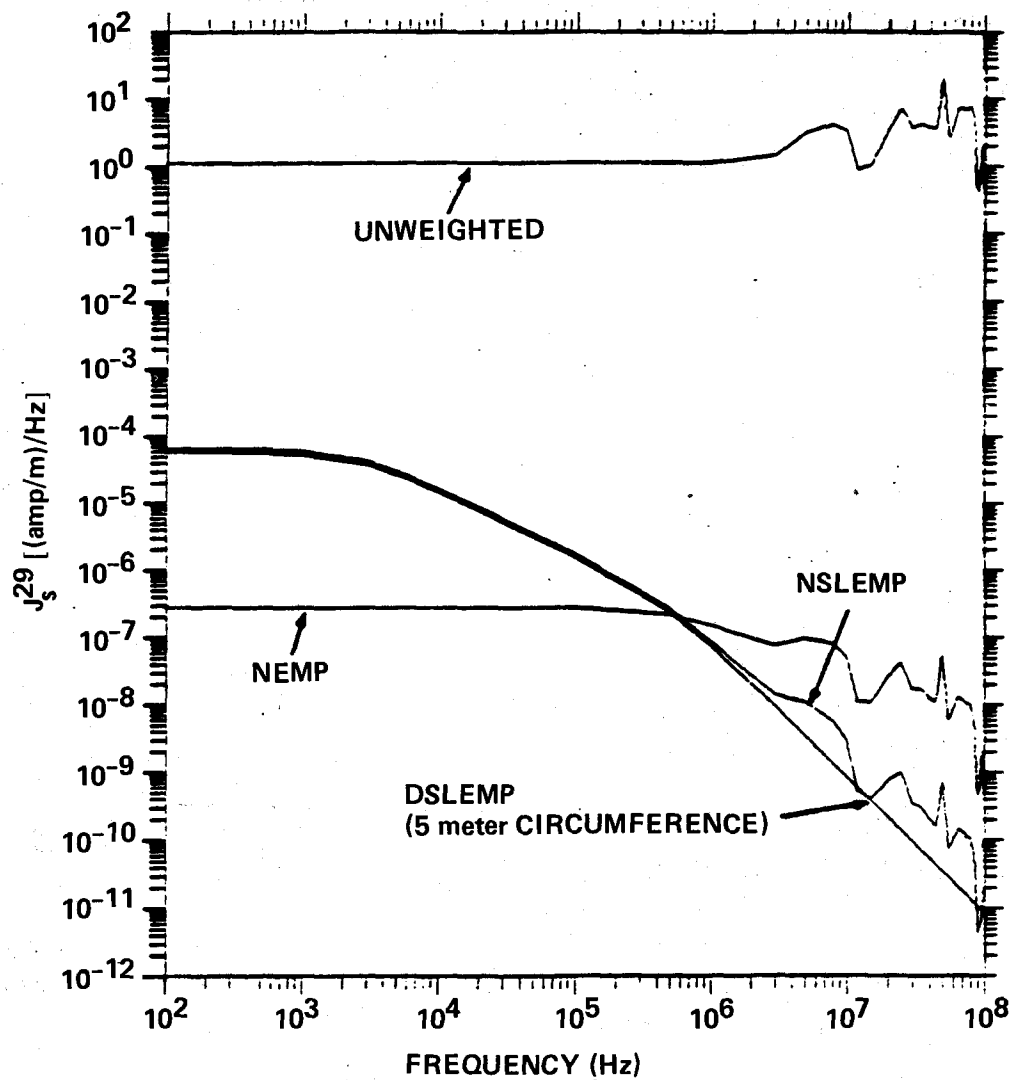


Figure 10-21.- Skin current amplitude spectrum for currents across edge 29 for unweighted ($H_0 = 1$) and weighted excitations.

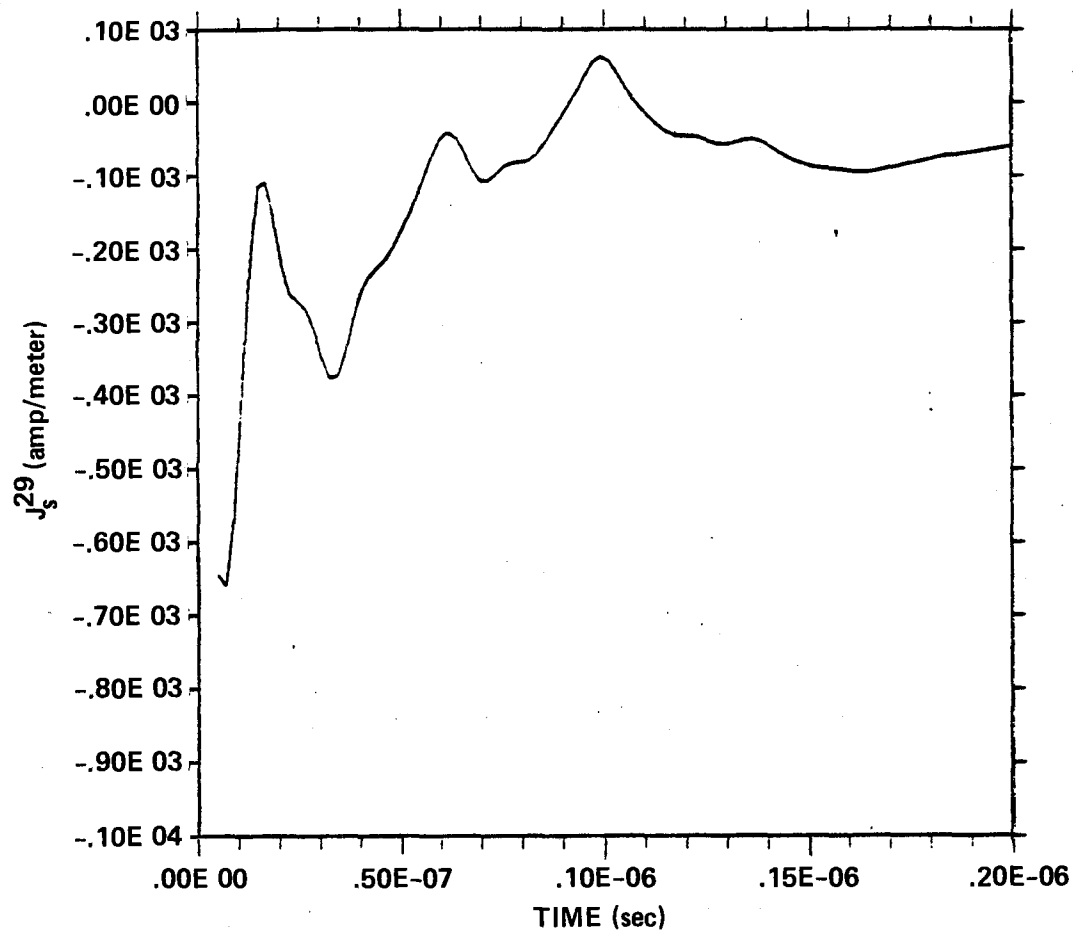


Figure 10-22.- Plot of surface current at edge 29 of F-14 model due to NEMP threat of Section 3; break interval near origin indicates time resolution interval of $\Delta t = 1/2F_{\max}$ where $F_{\max} \approx 100$ MHz.

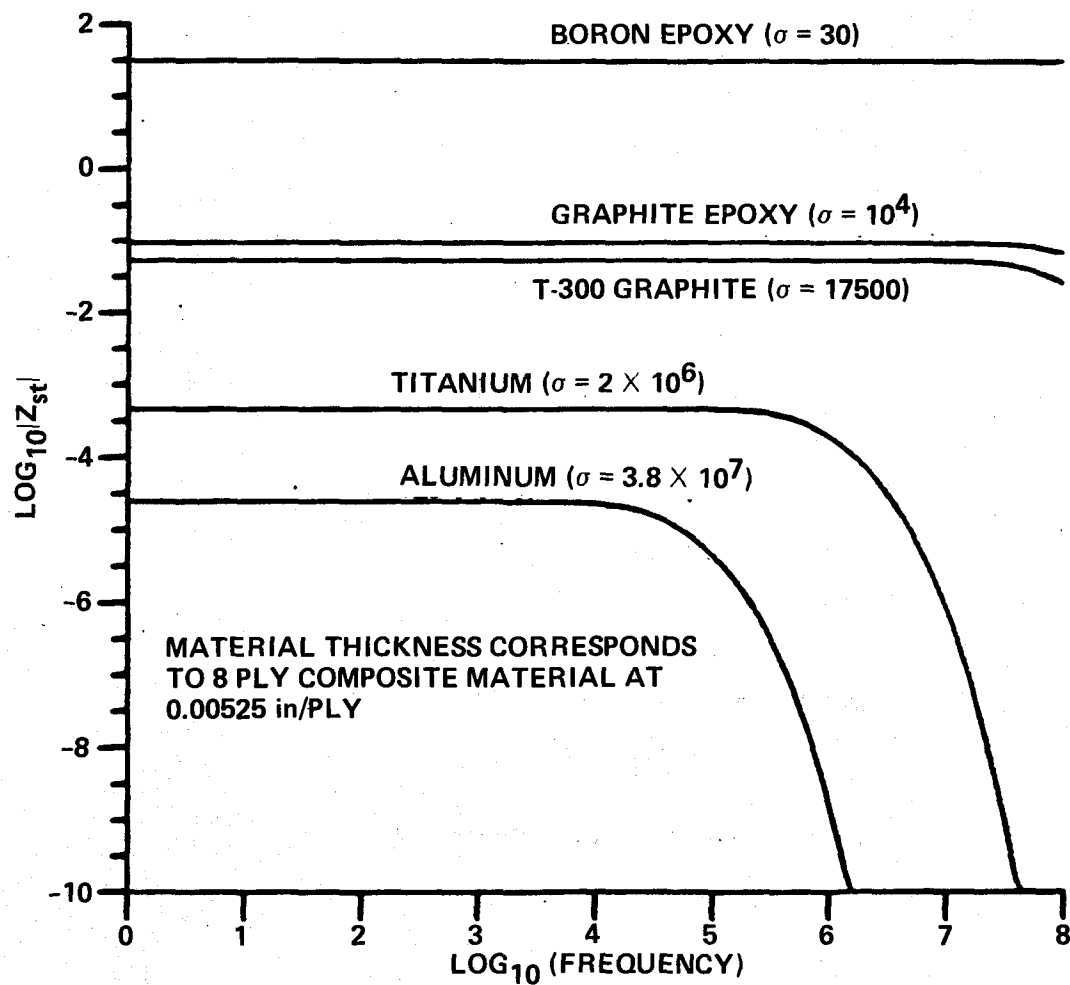
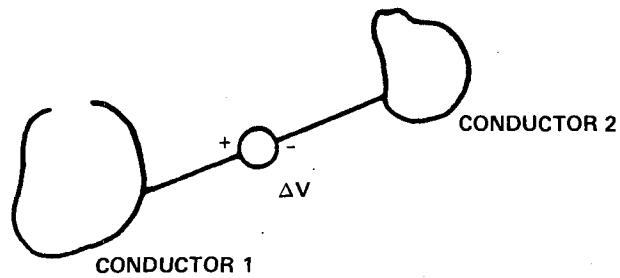


Figure 10-23.- Examples of computed transfer impedances; surface transfer impedance Z_t as a function of frequency.



SOLVE FOR POTENTIAL FUNCTION $\phi(x, y)$

ELECTRIC FIELD IS OBTAINED FROM

$$\underline{E} = -\underline{\nabla}\phi$$

MAGNETIC FIELD IS OBTAINED FROM

$$\underline{H} = \frac{1}{\eta_0} \hat{z} \times \underline{E}$$

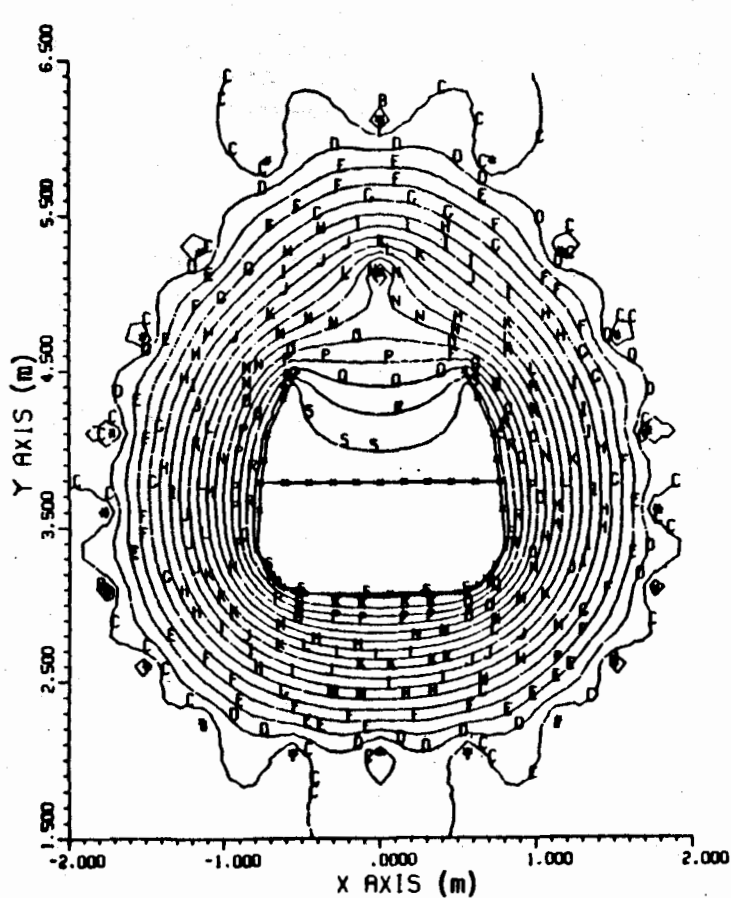
MUTUAL CAPACITANCE BETWEEN CONDUCTORS

$$C_{12} = \frac{Q}{\Delta V}$$

CHARACTERISTIC IMPEDANCE OF TEM MODE

$$Z_0 = \frac{1}{v C_{12}}$$

Figure 10-24.- Mathematical relationships.



CONTOUR LEVEL	-10.000	LABELED BY	A
CONTOUR LEVEL	-5.0000	LABELED BY	B
CONTOUR LEVEL	0.0000	LABELED BY	C
CONTOUR LEVEL	5.0000	LABELED BY	D
CONTOUR LEVEL	10.000	LABELED BY	E
CONTOUR LEVEL	15.000	LABELED BY	F
CONTOUR LEVEL	20.000	LABELED BY	G
CONTOUR LEVEL	25.000	LABELED BY	H
CONTOUR LEVEL	30.000	LABELED BY	I
CONTOUR LEVEL	35.000	LABELED BY	J
CONTOUR LEVEL	40.000	LABELED BY	K
CONTOUR LEVEL	45.000	LABELED BY	L
CONTOUR LEVEL	50.000	LABELED BY	M
CONTOUR LEVEL	55.000	LABELED BY	N
CONTOUR LEVEL	60.000	LABELED BY	O
CONTOUR LEVEL	65.000	LABELED BY	P
CONTOUR LEVEL	70.000	LABELED BY	Q
CONTOUR LEVEL	75.000	LABELED BY	R
CONTOUR LEVEL	80.000	LABELED BY	S
CONTOUR LEVEL	85.000	LABELED BY	T
CONTOUR LEVEL	90.000	LABELED BY	U

$$\phi_f = 83.39V$$

$$\phi_r = -16.61V$$

$$A \equiv -10V$$

.

.

.

$$S \equiv 80V$$

5 Volt Intervals

Figure 10-25.- Equipotential lines at fuselage station 320 for $\Delta V_{fr} = 100 V$.

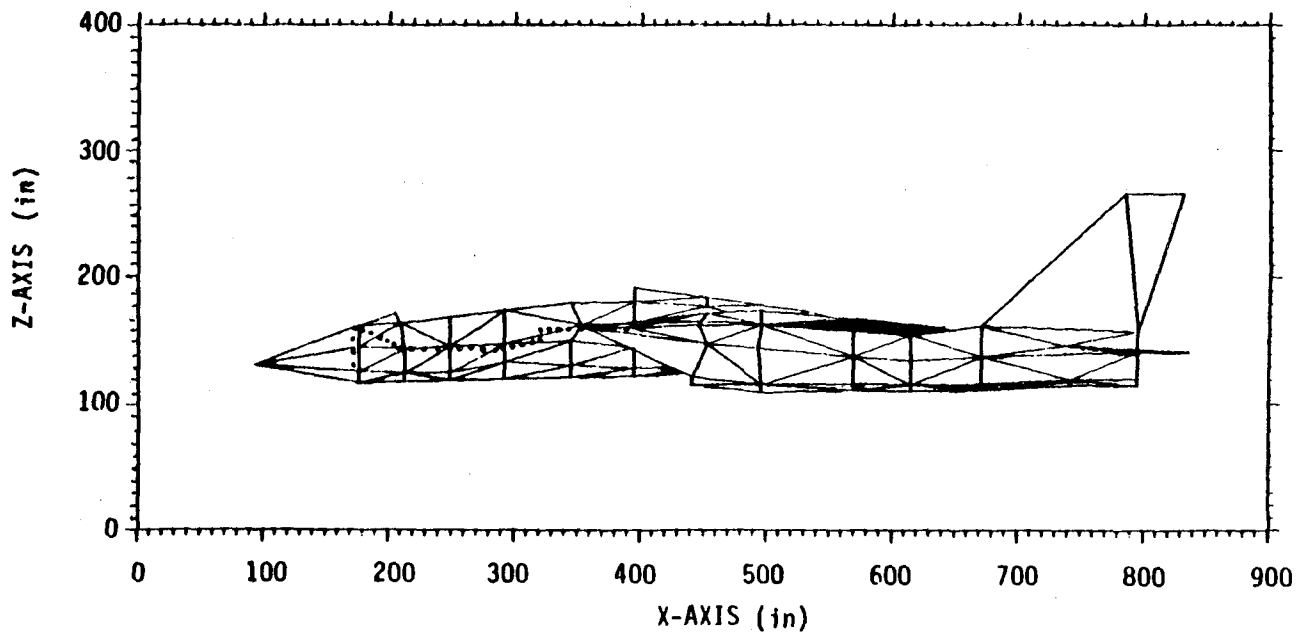


Figure 10-26.- Left side view of F-14 showing heater wire bundle (shown dotted).

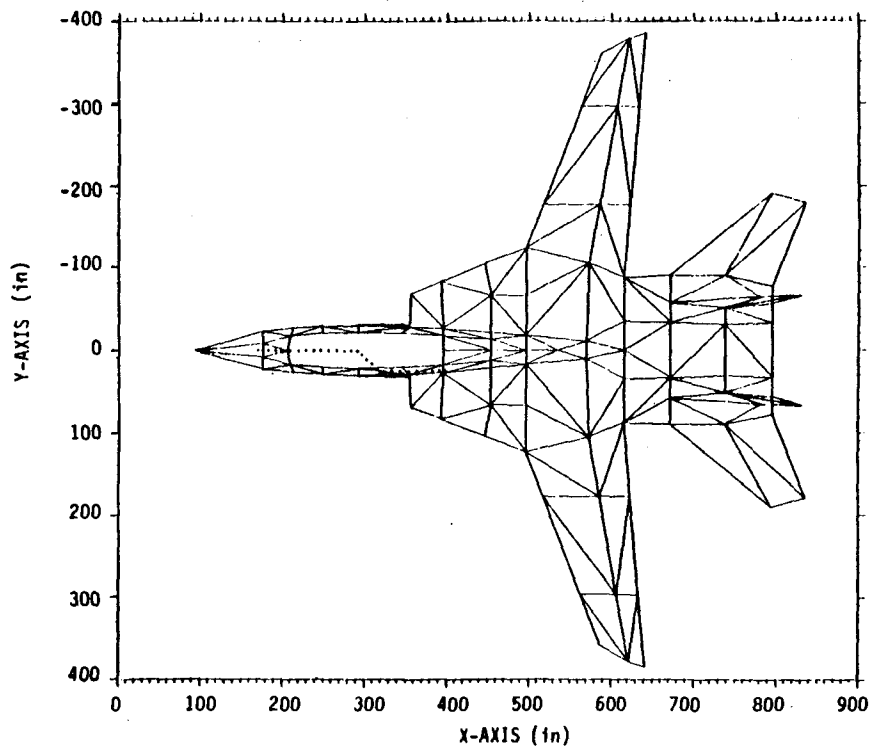


Figure 10-27.- Top view of F-14 showing heater wire bundle (shown dotted).

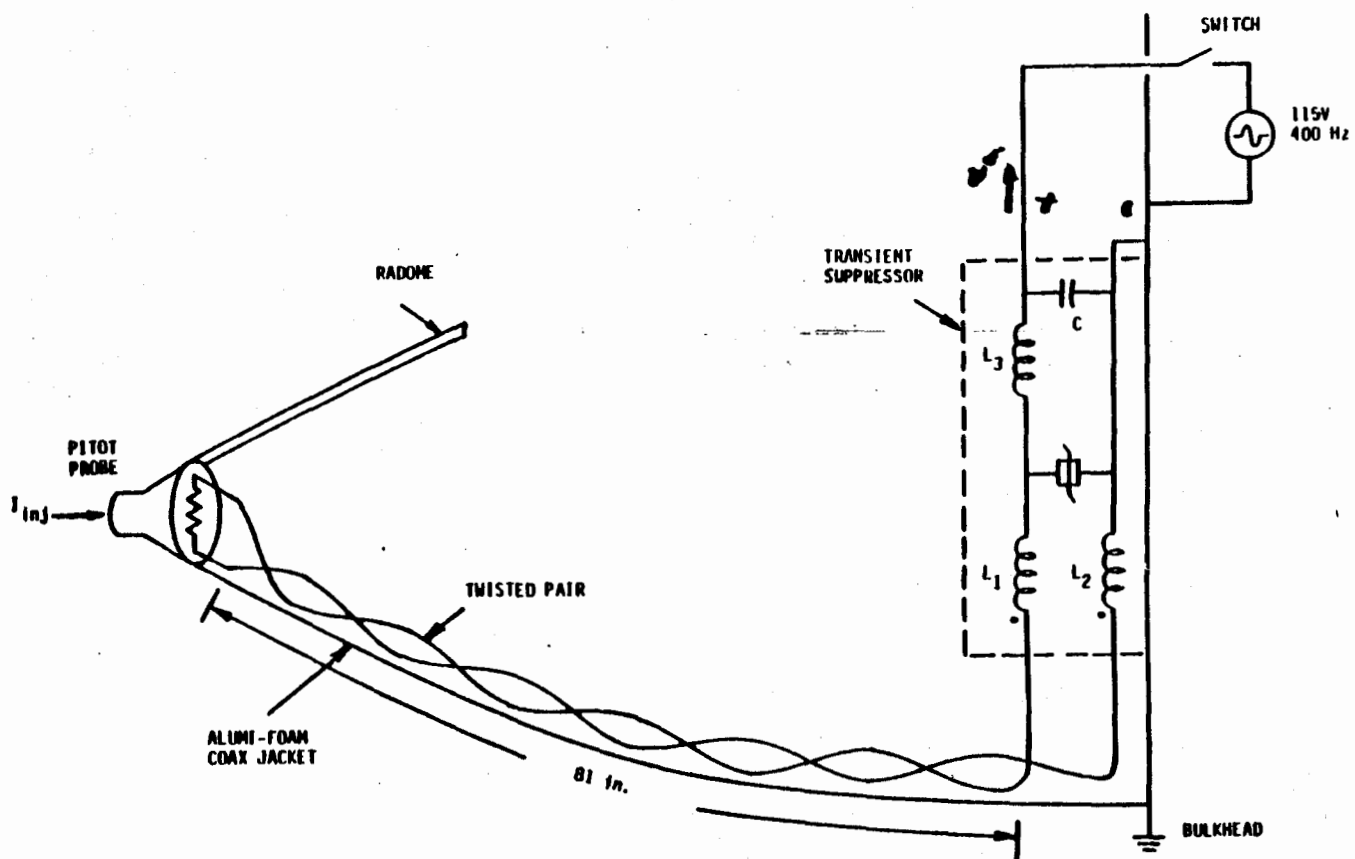


Figure 10-28.- Pitot heater circuit in nose radome.

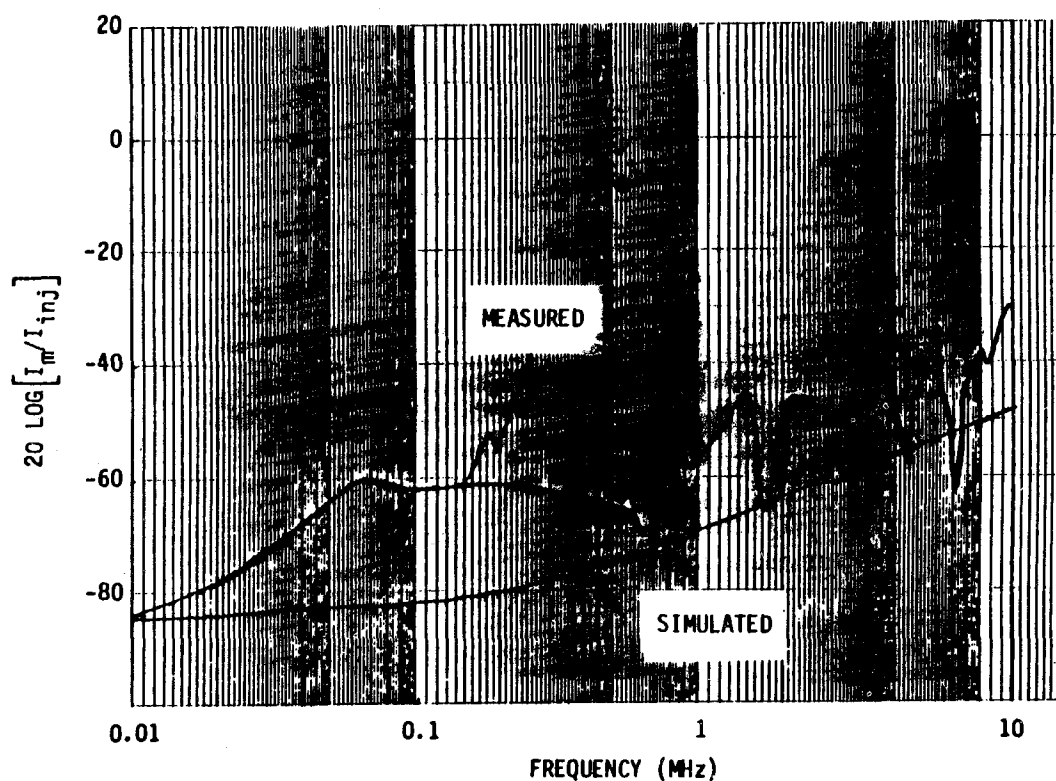


Figure 10-29.- Current at suppressor output (test point 1E).

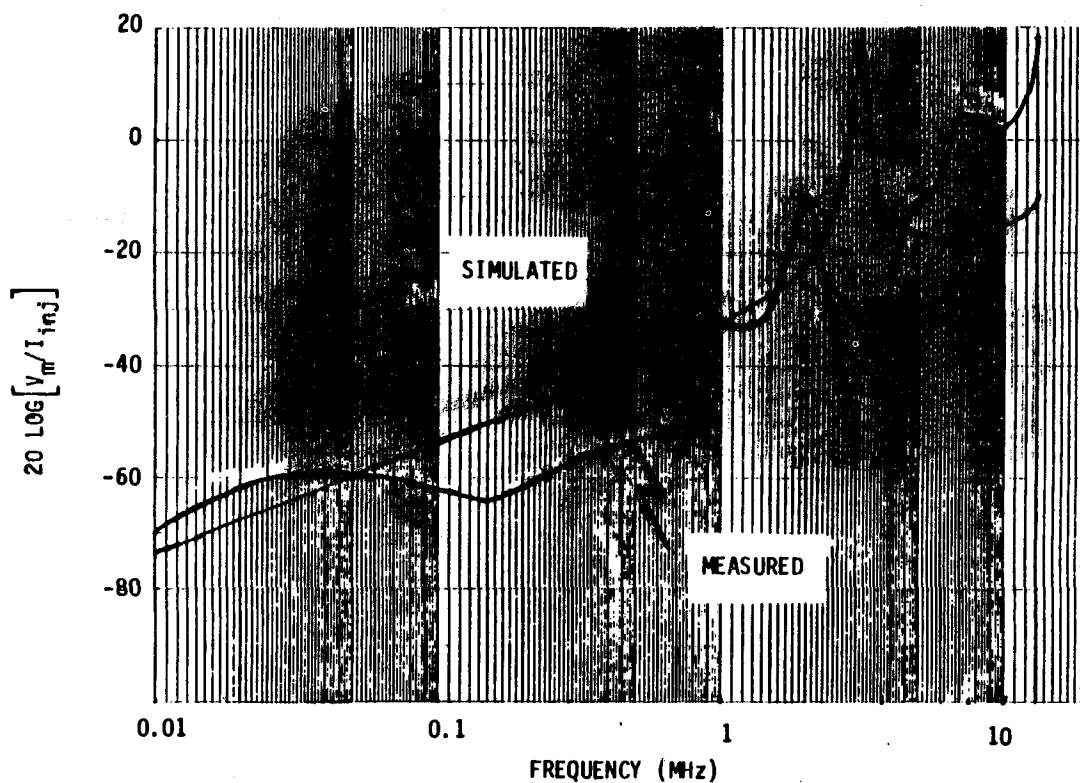


Figure 10-30.- Voltage at suppressor output (test point 1E).

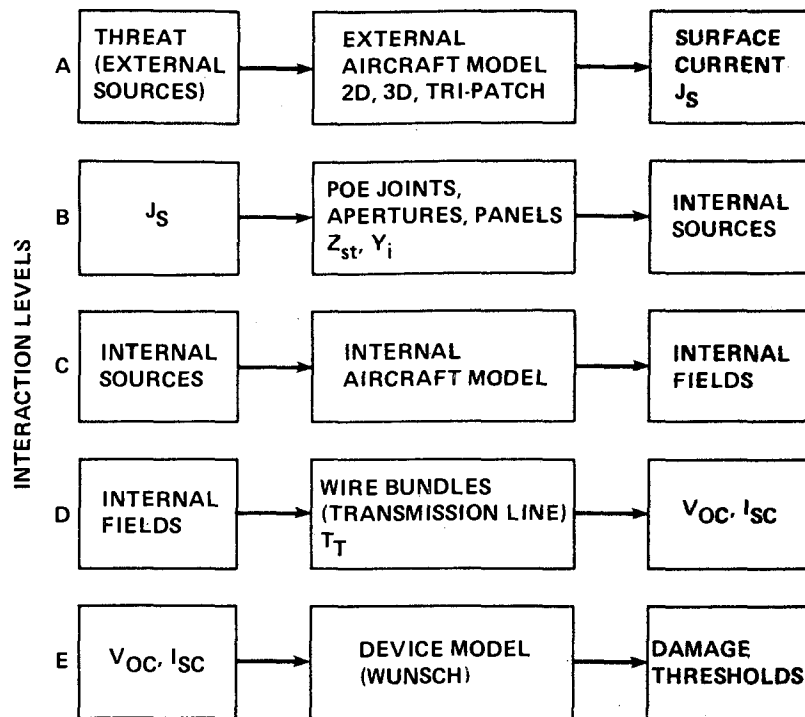


Figure 10-31.- Interaction partition table; source interacts with characteristic for result.

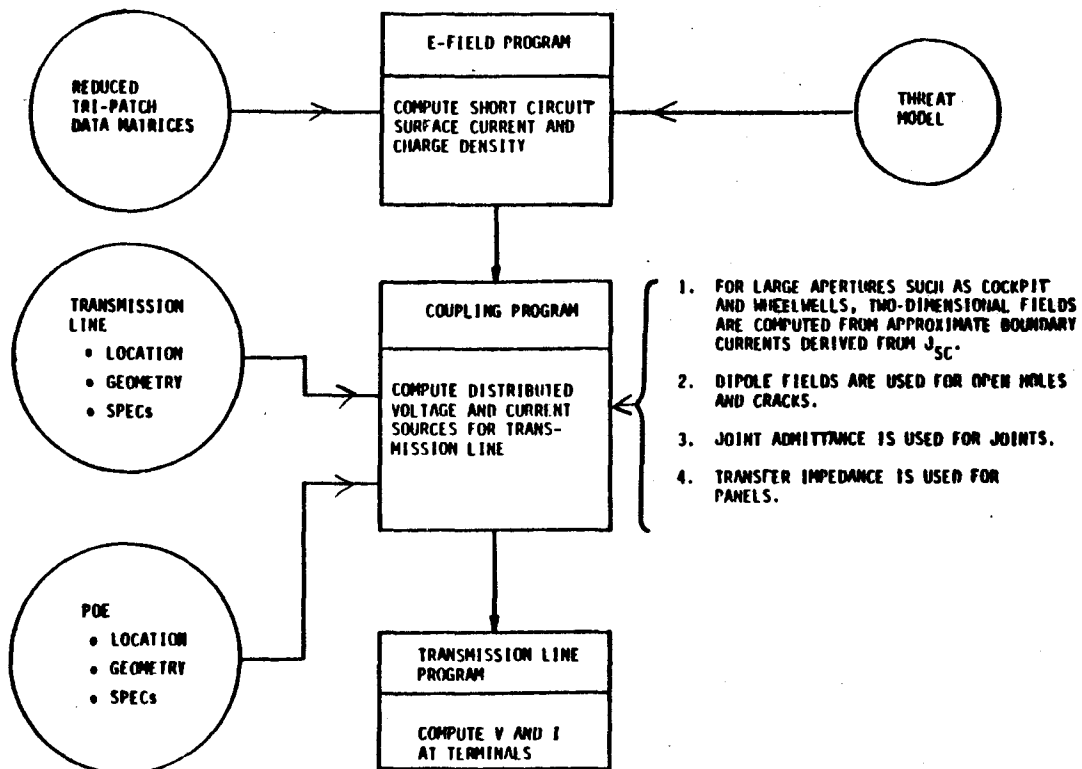


Figure 10-32.- Flow chart of transfer function approach to coupling analysis.

REVIEW OF ARINC 429 DATA BUS

The Specifications, Operations, and Limitations of the ARINC 429 Digital Data Bus

John Small

The Boeing Company
Seattle, Washington

MR. SCHNEIDER: Our next speaker this afternoon is talking about the 429 data bus.

This gentleman has been with Boeing since 1968. He comes from Plessey, England. Since he's been with Boeing, he's been in the Commercial Aircraft Company's Systems Research group. He's very well versed to talk about our ARINC 429 commercial data bus, because he was a member of the committee that established the bus, called ARINC SAI. That's Systems Architecture and Interface.

He also was a member of the ARINC 453 Committee, which established a 1-megabit data bus, which we are flying commercially in selected applications.

He's going to give you a review of the ARINC 429 data bus.

It gives me great pleasure to introduce John Small.

MR. SMALL: (Table 11-1) This afternoon, I'd like to go over the ARINC 429 bus briefly and describe some of its details, where its design specifications relate to the EMI performance of the bus, and discuss some testing that has been carried out at Boeing, and some of the results we've obtained.

TABLE 11-1.- INTRODUCTION

-
- DESCRIPTION OF THE ARINC 429 DATA BUS
 - THE USES OF ARINC 429
 - DETAILS OF IMPLEMENTATION
 - INTERFERENCE
 - ERROR CONTROL POLICY
 - TESTING
 - RESULTS
-

(Table 11-2) ARINC is an abbreviation for Aeronautical Radio, Incorporated. They set up standards for avionics units. The ARINC 429 is a standard for the digital interface system that provides the means for communicating between avionics units.

The ARINC 429 specification defines the data transfer in some detail, so that the units connected to these buses are interchangeable between airplane types and between box manufacturers.

TABLE 11-2.- WHAT IS ARINC 429?

-
- AERONAUTICAL RADIO, INC. (ARINC)
 - ARINC 429 IS A SPECIFICATION FOR A DIGITAL INFORMATION TRANSFER SYSTEM (DITS) FOR USE IN COMMERCIAL AIRCRAFT
 - ARINC 429 SPECIFIES DITS TO ENSURE INTERCHANGEABILITY OF UNITS CONNECTED TO THE BUS, FOR EXAMPLE:
 - DATA RATES
 - WORD FORMATS
 - WIRE TYPE, ETC.
-

(Table 11-3) ARINC 429 is used extensively in our later generations of airplanes, the 767 and 757. It's used for many critical functions: instrumentation, autopilot, engines, etc.

TABLE 11-3.- USE AND IMPORTANCE OF 429

-
- NEW AVIONICS (ARINC 700 SERIES) USE ARINC 429 FOR DIGITAL DATA TRANSFER
 - ARINC 429 IS USED FOR
 - AUTOPILOT FUNCTIONS
 - NAVIGATION AND FLIGHT MANAGEMENT
 - ENGINE INSTRUMENTATION
 - COMMUNICATION RADIO TUNING, ETC.
 - ARINC 429 HAS A VITAL ROLE IN MODERN COMMERCIAL AIRPLANE SYSTEMS
-

(Table 11-4) ARINC 429 is a single-transmitter data bus. By that, I mean there's only one unit connected to the bus that can actually send data. There can be up to 20 receivers on the bus. It uses standard twisted shielded cable. The bus is bit serial, which uses one of two speeds: 12,000 bits per second or 100,000 bits per second. The bus uses a standard 32-bit word format. The transmitter output impedance is selected to approximately backmatch the impedance of the line.

Figure 11-1 is a schematic of the ARINC 429 bus with its transmitter output impedance, approximately matching the characteristic impedance of the bus transmission cables.

The wire line topology is not constrained to a linear bus. Very long stubs and short stubs can be used. Receivers have high input impedance and can be connected to the bus or removed without upsetting the bus operation.

I'd like to talk about the three parts of the bus, the transmitter, the cable, and the receivers.

(Table 11-5) First of all, the transmitter. The output voltage is balanced to ground at the output of the transmitter. The output levels are +10, null, and -10 V, differential.

TABLE 11-4.- ARINC 429 DETAIL

-
- SINGLE TRANSMITTER BROADCAST DATA BUS
 - STANDARD TWISTED SHIELDED WIRE USED; NO CONSTRAINT ON WIRING TOPOGRAPHY
 - UP TO 20 RECEIVERS CAN BE CONNECTED TO THE DATA BUS. RECEIVERS CAN BE REMOVED FROM THE BUS WITH NO IMPACT ON BUS OPERATION
 - 429 IS A SERIAL BUS WITH TWO BIT RATES
 - 12 KILO BITS PER SECOND, AND
 - 100 KILO BITS PER SECOND
 - A STANDARD 32 BIT WORD FORMAT IS USED
 - THE TRANSMITTER OUTPUT IMPEDANCE IS USED TO PROVIDE A "SINGLE ENDED" TERMINATION TO THE BUS
-

TABLE 11-5.- DETAIL OF TRANSMITTER

-
- TX OUTPUT VOLTAGE IS DIFFERENTIAL, BALANCED TO GROUND
 - DIFFERENTIAL OUTPUT VOLTAGE
 - HIGH = +10 V
 - NULL = 0 V
 - LOW = -10 V
 - OUTPUT IMPEDANCE IS 70 OHMS BALANCED
 - RISE AND FALL TIMES ARE CONTROLLED TO LIMIT BANDWIDTH OF OUTPUT SIGNAL
-

The output impedance is 70 ohms, which was selected to approximately match the characteristic impedance of the transmission line. The rise and fall times of the output waveform are controlled to reduce the level of EMI radiated from the system.

MR. THOMAS: Ron Thomas, Sperry. What are those rise times? Have you identified them?

MR. SMALL: Yes. It's 0.5 μ sec rise and fall time for the high-speed ARINC 429 (the 100 kilobit system).

(Table 11-6) The cable is run-of-the-mill twisted shielded type with various wire gauges. The wire can use either extruded or wrapped insulation. The length and the configuration of the bus are not critical. The bus is terminated only at the transmitter, and the receivers have high input impedance. The shield is grounded at all connection blocks and at all connectors.

(Table 11-7) The receiver has high impedance differential input and the threshold voltage is typically ± 6 V which is designed to work with the normal transmitter output.

TABLE 11-6.- ARINC 429 TRANSMISSION MEDIUM

-
- TRANSMITTER OUTPUT IMPEDANCE, WITH TOLERANCE
 - STANDARD AIRCRAFT TWISTED SHIELDED CABLE WITH GAUGES FROM 20 to 26 AWG; VARIOUS INSULATION SYSTEMS AND HENCE NO CONTROL ON CHARACTERISTIC IMPEDANCE
 - VARIOUS LINE LENGTHS, CONSTRAINED ONLY TO LENGTHS THAT WOULD REASONABLY BE USED ON A B-747 SIZED AIRCRAFT
 - UNCONTROLLED STUBBING OF THE CABLE LINES, CONSTRAINED ONLY TO LENGTHS THAT WOULD REASONABLY BE USED ON A B-747 SIZED AIRCRAFT
 - HIGH INPUT IMPEDANCE RECEIVERS OR OPEN CIRCUIT STUBS WHERE RECEIVER UNITS HAVE BEEN REMOVED. NO LINE TERMINATION COMPONENTS ARE SPECIFIED
-

TABLE 11-7.- DETAIL OF RECEIVER

-
- DIFFERENTIAL INPUT
 - HIGH IMPEDANCE, RESISTOR ISOLATION INPUT
 - RECEIVER THRESHOLDS TYPICALLY ± 6 V
 - INPUT FILTERING AND TRANSIENT SUPPRESSION USED
-

Input filtering is used in the receiver. Because of the low bit rates used, low-pass filters provide a benefit in signal to noise ratio by attenuating the high frequency components of noise and transients.

Transient suppression is used on some of the receivers, where diodes are used to block high level transients present at the input of the receiver.

(Figure 11-2) This is a schematic of the waveform. The format is "return to zero" where a high, followed by a null, represents a one, and a low, followed by a null, represents a zero. This would be a signal of one, zero, zero, one, one.

(Table 11-8) Now, touching on the EMI features of the 429 bus. Differential signaling is used, therefore common mode noise can be rejected. The transmitter has 70 ohms balanced drive impedance onto the line, with 35 ohms from each line to ground. Twisted shielded wire is used.

The low bit rate provides high energy per bit. Low-pass filtering is used at the receiver to remove the higher-frequency components of transients.

The signal has controlled rise and fall times to prevent the system from exporting EMI.

Between each 32-bit word, there is a 4-bit interword gap which is used to synchronize the receiver. The gap normally inhibits short transients from affecting but one word.

Figure 11-3 is a schematic of two possible ways that transients can interfere with the ARINC 429 bus. At this point (A), the transmitter was sending a zero,

TABLE 11-8.- EMI FEATURES OF 429

-
- DIFFERENTIAL SIGNALING
 - LOW IMPEDANCE LINES
 - TWISTED SHIELDED WIRE
 - LOW BIT RATES:
 - HIGH ENERGY PER BIT
 - LOW PASS FILTERING IMPROVES S/N
 - SLOW RISE AND FALL TIMES REDUCE EMI RADIATION
 - THE 4-BIT INTERWORD GAP LIMITS TRANSIENT EFFECT TO ONE WORD ONLY
-

there was transient which prevented the signal from crossing this receiver threshold and the bit would be lost. Neither a one nor a zero would be declared at this point. In the second example (B), the signal was going towards a one, and the transient caused a reversal of the polarity, causing the receiver to actually detect a zero. This error is termed a crossover error; in effect, a one was sent and a zero was received.

These are two different types of errors. The first is where a bit is lost or gained. For example, during the interword gap, if a transient is present, an additional bit may be detected or a bit may be lost during a word, as previously noted. The second type of error is crossover error.

Because of the high voltage levels and the low impedance of the transmitter drive, it will take a few watt-microseconds of energy to cause these types of errors. High energy is required in the transient to cause a bit error in the data transmission.

Once a bit error has been caused, we move from the transient domain into the information domain. Data processing can be performed in the information domain to make the system more tolerant to transients.

(Table 11-9) All words are 32 bits long; therefore, the receiver can count the number of bits received in a word and declare a word invalid if a bit is gained or lost.

Each word has a parity bit included. If there is a single crossover error within the word, or an odd number of crossover errors within the word, the parity will be invalid at the received end; therefore, that word would be rejected.

Quite a lot of data on commercial airplanes are parametric data, for example, altitude, airspeed, etc. The data are sent more frequently than required, so that if there is a detected error, that word can be rejected, and the receiving equipment can wait for the next occurrence of that word, which would not cause a system problem. The receiver will not shut down the system if it loses one word.

TABLE 11-9.- 429 ERROR CONTROL POLICIES

-
- ALL WORDS ARE 32 BITS LONG; THEREFORE, SHORT OR LONG WORDS INDICATE BIT ERRORS
 - EACH WORD HAS A PARITY BIT; THEREFORE, ODD NUMBERS OF BIT ERRORS CAN BE DETECTED
 - PARAMETRIC DATA ARE TRANSFERRED MORE FREQUENTLY THAN REQUIRED; THEREFORE, LOSS OF ONE WORD DUE TO BIT ERROR HAS NO IMPACT ON SYSTEM OPERATION
 - IMPORTANT FUNCTIONS UTILIZE DIGITAL FILTERING AT THE RECEIVER TO PREVENT AN UNDETECTED ERROR WORD IMPACTING SYSTEM OPERATION
-

For important functions, for example, mode switching where it is very important to be sure that the correct data are received, the receiving equipment might wait for the third occurrence of the change before it actually takes action.

The words are sent frequently; therefore, the time penalty, in waiting for the third occurrence of the word, is acceptable.

Another error control feature is that the receiver can apply digital filtering to the data so that if an undetected error is received, the information would be filtered out by the data that were received previously (for example, a weighted average of the information). The system should not glitch if one word was received in error.

Going back to the transient domain again, some tests were performed at Boeing. (Fig. 11-4) The ARINC 429 transmitter and receiver were located outside the screen room, and the cable was installed inside the screen room. A bit error-detecting system was used, which checked that each bit received by the receiver agreed with that sent by the transmitter.

Various transient levels were applied to the cable while testing various shielding and grounding configurations.

(Table 11-10) Interference levels, defined in Boeing document D6-16050, were applied to the cable, including the chattering relay test. A well-designed receiver was used with proper filtering and the cable shields were grounded as specified in the ARINC specification. We operated with very low bit error rates.

The radiation from the cable was acceptable because of the slow rise and fall times specified. We applied the lightning transient tests to the system to check for damage on the transmitters and receivers. The results were satisfactory.

MR. PATTERSON: Bob Patterson, Rockwell. Do you have any data on what your specific error rates were?

MR. SMALL: Yes. The error rates were running $10E-7$. Some of the results were included as an attachment to ARINC 429, so that the industry could have access to this information.

TABLE 11-10.- ARINC 429 TESTING

- SUSCEPTIBILITY TO BIT ERRORS TESTED WITH DO-160 INTERFERENCE LEVELS APPLIED TO THE CABLE
- EMI RADIATION FROM CABLE TESTED
- TX AND RX SUBJECTED TO DO-160 LIGHTNING TRANSIENT LEVELS

RESULTS

- ACCEPTABLE BIT ERROR RATES UNDER INTERFERENCE
- EMI RADIATION ACCEPTABLE
- RX AND TX NOT DAMAGED BY LIGHTNING TRANSIENT

One of the error control policies is to send the data more frequently than it is needed. The loss of one word is acceptable, but if a multiple transient occurred, this error policy could be defeated.

A multiple transient event might be from lightning, although the probability of a multiple stroke occurring at the repeat time of a particular word is very remote.

(Figure 11-5) We investigated this effect and developed test equipment to inject such errors on an ARINC 429 data bus. The test bus is connected to the error test set. The bus data traffic is evaluated and select words are identified by label. A predetermined error pattern can be imposed on the selected words at predetermined error rates.

This tool is useful for the investigation of error control policies of utilization equipment which control the effect of a burst-mode-type transient which might happen to hit the repeat of a particular word.

(Figure 11-6) This is a picture of the unit with the Intel chassis, the Intel 8085 computer cards, and terminal. This cable is the ARINC 429 data bus, input and output.

(Table 11-11) The experience gained from the ARINC 429 development is the importance of EMI and transient features being designed and built into the specifications right from the start. Features such as low transmitter impedance, twisted shielded cable, and high signal energy, which gave low bit error rates, were considered.

Extensive development testing has been accomplished on this ARINC 429 system which has given a great deal of confidence. Many systems have been installed and tested. Systems were flight tested, in our 767 and 757 programs. There are about 150 of these ARINC 429 buses on each of the 767 aircraft.

The commercial aircraft industry is gaining experience with data transfer on twisted shielded wires with low bit rates in an airplane environment, in the presence of transients and lightning.

(Table 11-12) In commercial airplanes, we are also using a 1-megabit bus, the ARINC 453, for transfer of digitized weather radar data. ARINC 453 is based on

TABLE 11-11.- EXPERIENCE WITH ARINC 429

-
- THE INITIAL DESIGN OF ARINC 429 INCORPORATED EMI FEATURES
 - EXTENSIVE DEVELOPMENTAL TESTING WAS CARRIED OUT TO ESTABLISH DESIGN AND INSTALLATION CRITERIA
 - THE 767 AND 757 FLIGHT TEST PROGRAMS HAVE VERIFIED THE ARINC 429 CONCEPT
 - THE 767 FLEET IS NOW ENTERING SERVICE - EACH AIRCRAFT USES IN EXCESS OF 150 ARINC 429 DATA BUSES
-

TABLE 11-12.- ARINC 453 AND HIGHER BIT RATES

-
- ARINC 453 IS A 1 MEGABIT PER SECOND DATA BUS USED ON THE WEATHER RADAR SYSTEM. 453 IS BASED ON MIL-STD-1553
 - ARINC AND BOEING ARE WORKING WITH THE SAE AE9B SUBCOMMITTEE WHICH IS DEVELOPING A 10 TO 20 MS/S DIGITAL INFORMATION TRANSFER SYSTEM FOR AIRCRAFT
 - THE OPERATIONAL EXPERIENCE GAINED WITH ARINC 429 AND 453 WILL BE USED IN THE DEVELOPMENT OF THIS NEW, VERY HIGH BIT RATE SYSTEM
-

MIL-1553 technology; it uses the same waveforms, voltages, and cable, but it does not use multiple transmitter operation. A single transmitter is located in the radar central T/R unit, and digitized video data are sent to the display units. Tests were made on this ARINC 453 system similar to those made on the ARINC 429 system. This system is flying on numerous aircraft.

ARINC and Boeing are working with the SAE AE9B subcommittee on a high-speed data bus which would be a generation beyond MIL-STD-1553B. The hope is that this new bus would satisfy both the commercial and military requirements.

MR. THOMAS: Ron Thomas, Sperry. Is that 453 a bidirectional bus?

MR. SMALL: Not the way we use it. It's a single transmitter, single-direction bus. It is used for the ARINC 708 weather radar.

MR. THOMAS: So it's just a high-speed bus. Can you describe it? 1553 is bidirectional.

MR. SMALL: ARINC 453 was developed specifically for sending digitized video information from the ARINC 708 weather radar to the display units. A 1-megabit bus was needed, so ARINC developed the 453 from the MIL-1553, taking advantage of the cable that had been developed and all the testing that had been done.

The 453 uses the electrical format of the MIL-1553 bus, but it doesn't use the word format, or the multiple transfer feature.

MR. THOMAS: In your 429, do you require a transformer coupler, or cable?

MR. SMALL: No. The ARINC 429 waveform has a dc component. A one is a positive pulse and a zero is a negative pulse. If a word contains more ones than zeroes,

you get a net positive voltage during the word. It has a dc component, so you can't use transformers with an ARINC 429 data bus.

We have been experimenting with optical isolation on the ARINC 429 bus with good results. We now have optical isolators in dual, in-line packs, with 7500 V of isolation.

MR. PATTERSON: Bob Patterson of Rockwell. Would this bus have bidirectional capabilities?

MR. SMALL: Yes, it would be a multiple transmitter bus. I don't believe it would use the central bus controller that the MIL-1553 bus uses.

MR. KENDALL: Chris Kendall, Consultant. Could you share with us some of the findings and early testing regarding the termination of shields at both ends as opposed to one end?

MR. SMALL: Yes. I agreed with your point about the grounding shields at one end. The shielding effectiveness drops to zero, at the $\lambda/4$ frequency.

If interference was applied at this frequency, and one shield end grounded, you would find that the shielding effectiveness would drop to zero at $\lambda/4$.

If you grounded both ends, you'd find the shielding effectiveness would drop to zero at $\lambda/2$.

The ARINC specification calls for grounding a shield wherever possible. Within Boeing, we require limits on the length of the pigtail to ground. We feel the higher-frequency components of the transients are going to be more trouble to us on these digital systems than the low-frequency components.

MR. THOMAS: Ron Thomas, Sperry. Could you give us your opinions of where the buses are going in the future? Are they going to stick with 429 and go bidirectional?

MR. SMALL: Yes. In the commercial airplane industry, the introduction of ARINC 429 was a very large step. It took us from the analog domain to the digital domain. We've had an order of magnitude reduction in a number of wires. If we were to connect all the data we have now flowing on the 767 by individual wires and send the data along, we'd need 10 times the number of wires that we're using now.

At present, we're using 150 ARINC 429 buses. It's interesting to project that in the next generation we could improve one order of magnitude again, to 15 multiple transmitter buses, having information flowing in multiple directions around the data bus.

In the business world, they're pointing the way with local area networks.

A QUESTIONER: You quoted a bit error rate of 10^{-7} . Fifty data buses, that would be one error. Kind of excessive, isn't it?

MR. SMALL: No.

A QUESTIONER: With telephone wires, you get 10^{-8} bit error. Does that include everything?

MR. SMALL: I didn't hear.

A QUESTIONER: The bit error rate you're quoting seemed rather high. I'm saying it compares with a dedicated telephone line, for example, that has a bit error rate of 10^{-8} .

MR. SMALL: Yes, these bit error rates were under interference conditions, with the chattering relay and the RF, etc. This would be the lower level of bit error rate. It would be difficult to measure error rates with no interference; you'd get 10^{-8} or 10^{-9} , something like that.

A QUESTIONER: Did this include a burst error? Did you detect burst errors?

MR. SMALL: Yes, I was counting every bit error in that. If there was a burst error from a chattering relay test, we'd detect that. We didn't test for lightning levels. But as I indicated, the burst error from a single-stroke event would be contained within the time of one word. It wouldn't slop over into two words. The event is very short. If it was a multiple-stroke event, then we have got ways of studying this. But the probability of the multiple-stroke occurring at a time when it exactly obscures a group of words would be very low.

A QUESTIONER: What was the average burst duration?

MR. SMALL: The bit rate is so slow that the transient occurs within 1 bit. We have a 4-bit blank period on the bus between words. If the last bit of one word is upset, it doesn't persist through the 4-bit blank period on the bus, so the following word is correct. The following word will be some other piece of data anyway.

A QUESTIONER: So the single bit error is satisfactory?

MR. SMALL: Together with the other error control mechanisms that we have, yes. We count the number of bits in the word and use a data reasonableness check and the filtering techniques.

I think that is satisfactory. And we seem to see this from operation of the bus in service.

SUMMARY

The ARINC 429 Data Bus: Background

- Aeronautical Radio Incorporated (ARINC) 429: sets the standard for digital communications interfacing between avionics units.
- ARINC 429 configured units are interchangeable between airplane types and unit manufacturers.
- ARINC 429 used extensively in Boeing 757 and 767 aircraft.

ARINC 429: System Details

- ARINC 429 uses a single transmitter bus, with up to 20 receivers per bus.
- Uses standard twisted/shielded pair as the bus medium.
- Bit-serial data transmission with two rates: 12 kbit/sec and 100 kbit/sec.
- Word length: 32 bit.
- Transmitter Z_{out} matches line impedance.
- Transformer couplers (to the bus line) are not used.

ARINC 429: Transmitter

- Output voltage balanced to ground.
- Voltage range; +10 V, null, -10 V.
- Transmitter $Z_{out} = 70$ ohms.
- Rise/fall times controlled to reduce radiated EMI.
- Rise/fall times for 100 kbit system: 0.5 μ sec.
- Waveform encoding system uses an RTZ (return to zero) format.

ARINC 429: Transmission Medium

- Twisted/shielded pair in various gauges.
- Uses extruded or wrapped insulation.
- Length and configuration of the bus not critical.
- Bus is terminated only at the transmitter.
- Bus shield is grounded at all connection blocks and at all connectors.
- Boeing requires a limit on shielding pigtail lengths.

ARINC 429: Receiver

- Has a high-impedance differential input.
- Threshold voltages typically ± 6 V.
- Waveform has a dc component.
- Receivers can be added/removed from the bus without upsetting system operation.

ARINC 429: EMI Protection

- Differential signaling used.
- Low impedance lines (70 ohms).
- Low bit rate results from high energy per bit. Any transient must be energetic enough to cause a bit error in transmission.
- Low-pass filtering used at the receiver end.
- Transient suppression diodes are used in some receivers.
- Four bit interword gap localizes transient effects to one word.
- Experimentation with opto-isolators (7500 V of isolation).

ARINC 429: Error Detection/Protection

- Parity bit in each word. Detects single bit error.
- Data are sent more frequently than required (allows for rejection of a bad data word).
- Digital filtering is applied to the received waveform. A "weighted average/reasonableness" test is used to discriminate against bad data.

Boeing ARINC 429 Tests

- Boeing Document D6-16050 was authority for the tests (chattering relay, lightning, etc.).
- A bit-error detecting system was used.
- Measured error rates under interference conditions were of the order of 10^{-7} . Burst error rates were included.
- Measurements done on multiple errors per bus (as in the case of a multiple lightning stroke).

ARINC 453 System

- Based on MIL-1553 technology.
- Transmits at 1 megabit.
- Currently being used to transmit digitized video data for the weather radar system (Boeing 767).

- ARINC 453 is a single transmitter, single direction bus, terminated at both ends of the bus.
- ARINC 453 doesn't use the 1553 word format or the multiple transfer feature.

Data Bus: Future Developments

- SAE AE9B subcommittee work on a high speed bus suitable for commercial and military applications.
- Future bus: multiple transmitter with no central bus controller.
- Multiple transmitter architecture could offer an order-of-magnitude improvement over the 150 buses typically used on existing aircraft.
- Local area networks suggested as a model for future developments of data buses for aircraft.

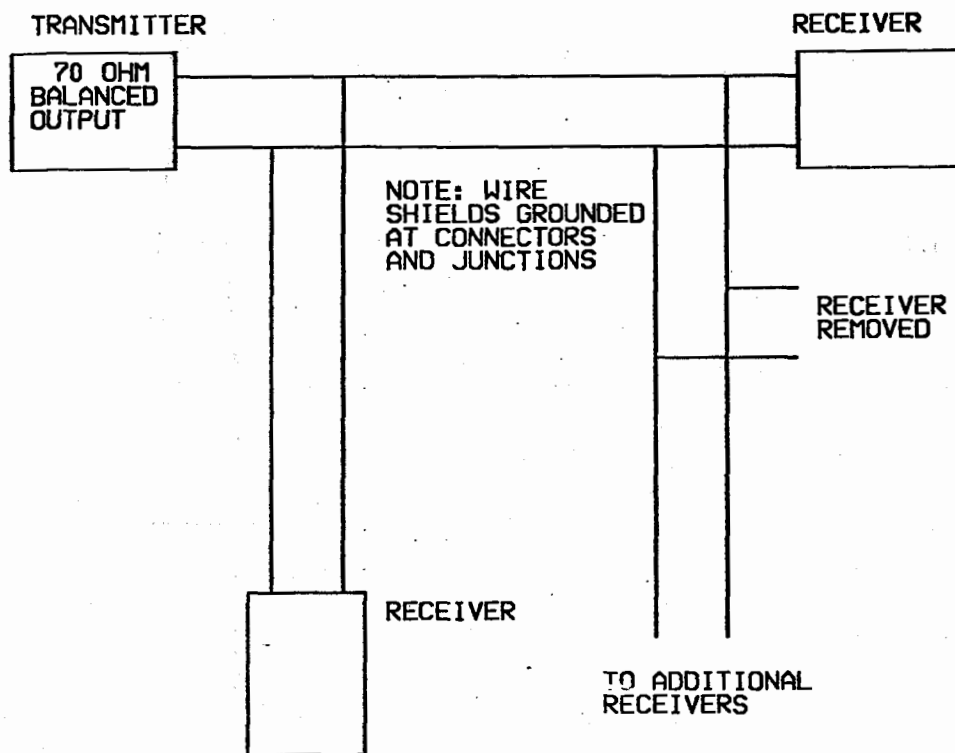


Figure 11-1.- ARINC 429 schematic.

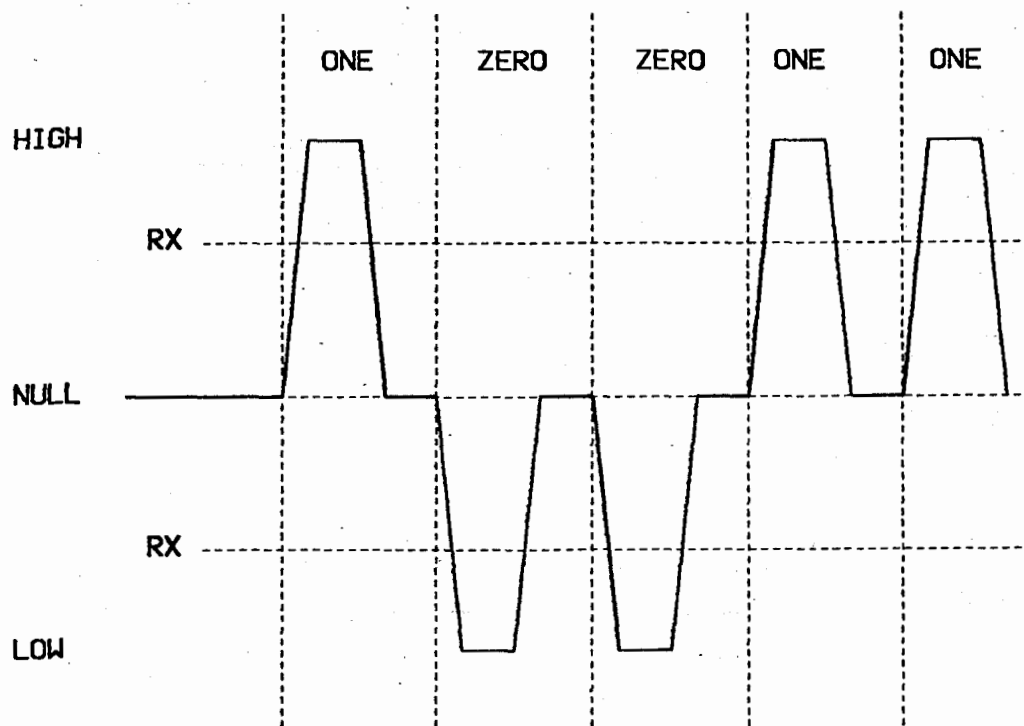


Figure 11-2.- ARINC 429 waveform.

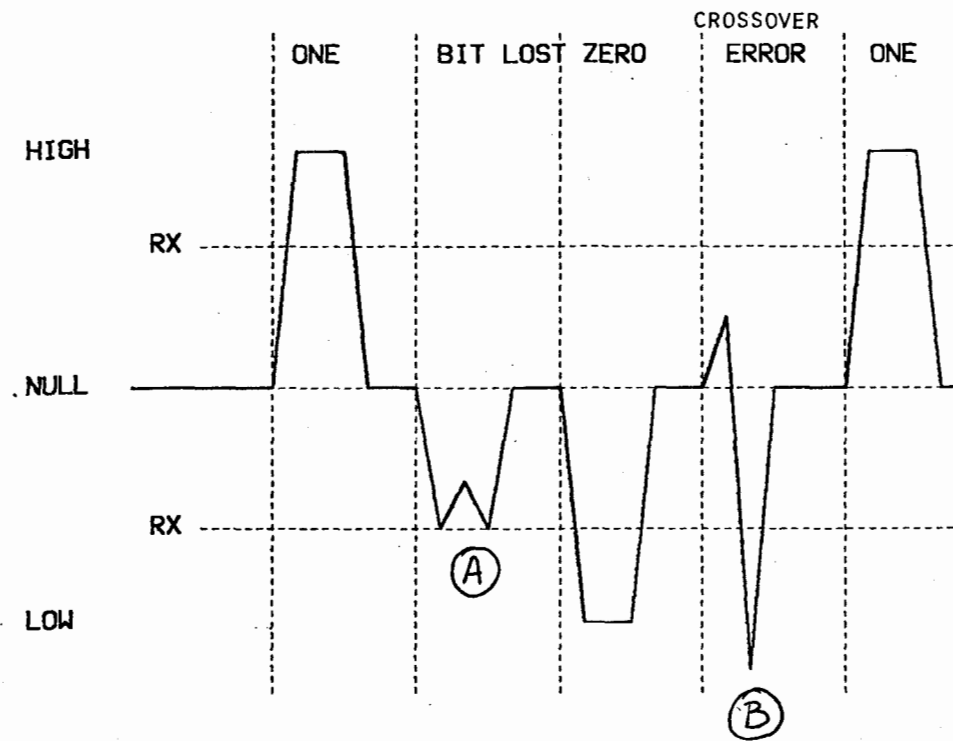


Figure 11-3.- Bit errors on 429.

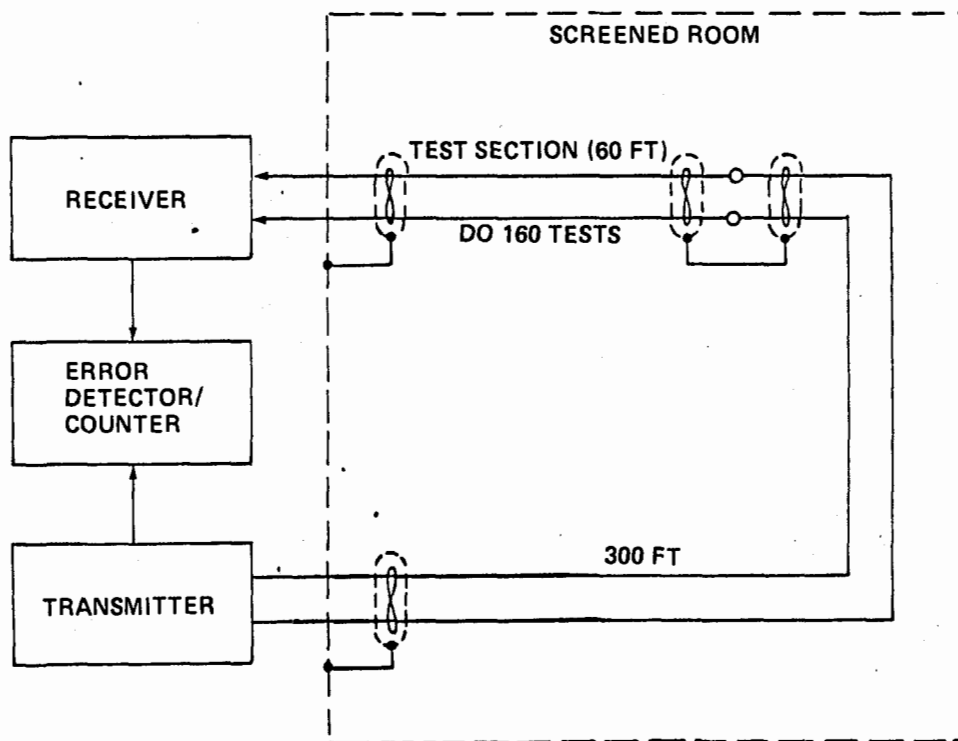


Figure 11-4.- Configuration for susceptibility tests.

O TO TEST FOR THE EFFECTS OF REPETITIVE TRANSIENTS
ON A RECEIVING UNIT A "BURST MODE ERROR ADDER"
TEST SET HAS BEEN DEVELOPED.

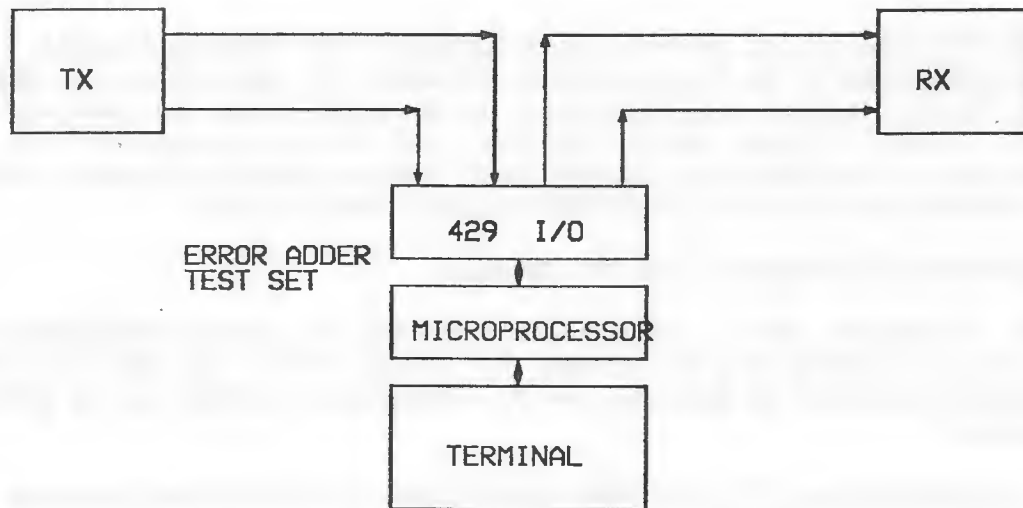


Figure 11-5.- Repetitive transients.

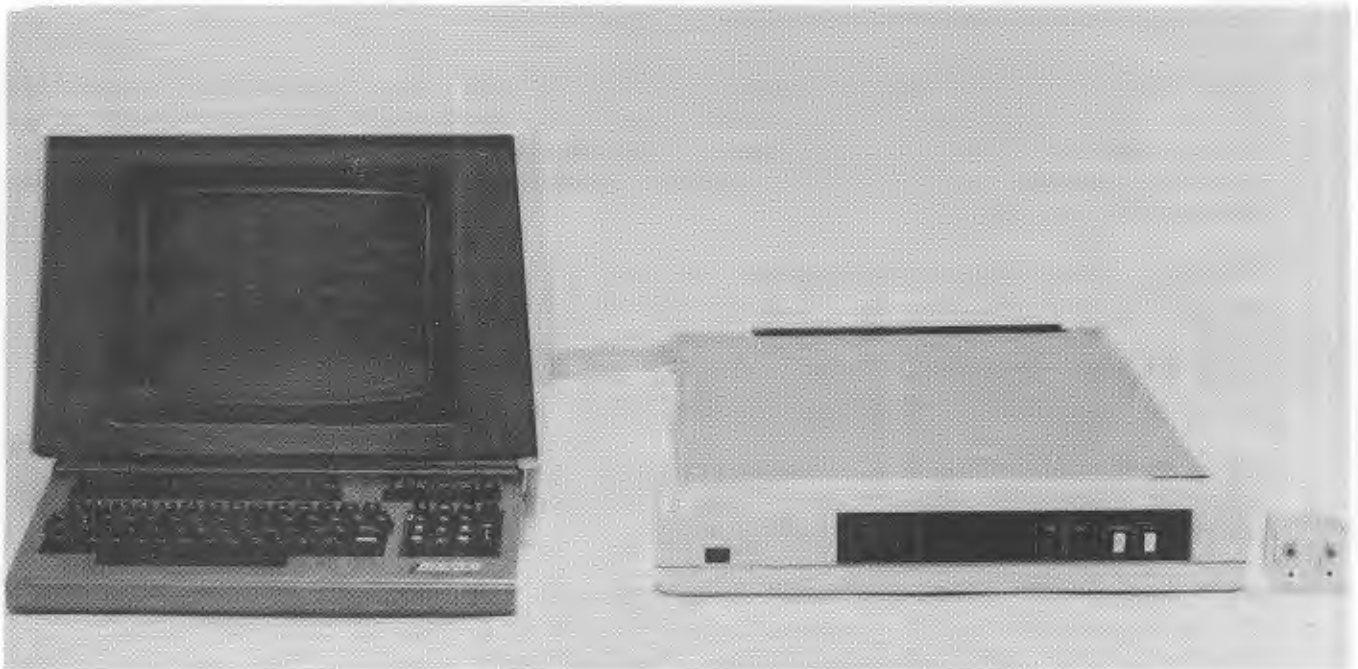


Figure 11-6.- Test unit with Intel chassis, 8085 computer cards and terminal.

HARDENING CRITERIA OF AIRCRAFT DIGITAL COMPUTER BASED SYSTEMS

Hussein Youssef

Lockheed-California Company
Burbank, California

MR. LARSEN: I'd like to introduce the next speaker, Dr. Hussein Youssef.

Dr. Youssef comes to us from Lockheed, Burbank. He has worked on various digital flight control systems there. He happened to be the lead engineer on the L1011 digital flight control project, and also is responsible for some of the validation software the company used, both at their Rye Canyon facility for that airplane and the Cat 3 autoland system, and so forth.

I'd like now to present to you Dr. Youssef.

DR. YOUSSEF: Thank you, Bill. For the introduction, my strong background is flight controls, and I have been monitoring the effect of the EMI and lightning threat on digital equipment in general, and the digital autopilot in the L1011 in particular.

In my presentation, I'll also talk about some of the military aspects of hardening criteria of the digital equipment.

I'll be talking in general about how we proceed at Lockheed for our EMI protection plan in general. We start, of course, with the parametric threat level, a different level of threat than we would have envisioned encountering, and the threat model -- you have heard previously about the model. The model can give you some idea of what threat level you're going to be facing. Taken together this constitutes the total envelope of the threat.

From this, you can study the susceptibility of the electronic equipment to that threat. From this you do a vulnerability assessment of how the equipment reacts to the threat. Then you start doing your design criteria based on the criticality of the system. You don't want to overdesign a system that would not be considered critical.

I'll talk about how you establish your design criteria based on the level of criticality of your system. Then you will perform an effectiveness trade-off, which will include the liability, measurability, cost, and weight analysis of the hardening criteria. Based on this, you reach the recommended guidelines necessary for your overall protection plan.

This chart summarizes the overall envelopes of the threat that's coming from attached lightning and far away lightning (1000 m), and the nuclear electromagnetic pulses.

Here are the EMI environmental levels that you'll be faced with. You can see if you've hardened your system against attached lightning that you're well covered in the low-frequency range. Then you must consider the high-frequency effect of the EMI threat for these three or four different levels.

Next I'll discuss the compatibility control program at Lockheed, which includes analysis, prediction, evaluation for equipment design, and the installation of equipment according to the EM topology and criticality.

Next I'll discuss configuration, bundle grouping, and wire segregation. Then I'll talk about electric bonding and grounding, shielding, and hardening.

I'll go further in detail on each of these, and then discuss some of the equipment requirements under Lockheed specs, and include some of the testing according to the RTCA DO 160 document.

Lockheed enforces this plan for the military. We have an Electromagnetic Board that supervises any new project in Lockheed. From Lockheed's point of view this board includes four different aspects of the company: engineering, manufacturing, flight test, and field service. Then we interface with our customer, our black box supplier, and also the different component manufactures used inside the LRUs.

We work to MIL-STD-6051 at the systems level and enforce the MIL-STD-460 series, especially when the military is our customer.

Some of the design techniques that I will be talking about include bonding, grounding of equipment and cables, interconnection of cables, separation and segregation, shielding, filtering, and software and hardware hardening techniques inside the box.

Finally, I'll talk about how Lockheed separates the electronic equipment and wiring, how additional suppression devices are added, how we do frequency management with different systems, and then time sharing.

I'll start with lightning. As I mentioned before, if you're hardening your system against attached lightning per lightning prediction requirement of the vulnerability analysis, then you'll be covered for the low-frequency range. Some of these numbers have recently changed. We used to test to ± 100 V for the long cables, and 600 V for the power lines. Recently we realized it was necessary to test to 600 V for the long cable also.

Another hardening feature used for the digital autopilot is program timing. We use a dual-dual channel system, that is, redundant channels that run in a sequence so that a given channel is not in the exact place in the program as any other. Therefore, if you're hit by a momentary lightning strike, the four channels will not be affected the same way at the same time.

During bench testing we found we had to add compensating circuits in the power supply and isolate the circuitry from the case for the autopilot. Prefiltering was also added on the input signal lines to block the high-frequency noise.

We used the single-point grounding for all short cables, and multiple grounding for shielded cables that connected the digital systems. The L-1011 has relatively large windshields which caused problems that required the glass to be coated with a thin conductive oxide film. In several cases the glass had to be electrically bonded to metal Z strips and riveted to the structure.

Other techniques that we used for protection that are standard among all the airframe companies were (1) all equipment cases grounded to structure, (2) the

This is one of the tests that we do on the airplane when we install the avionics equipment, and you can see the emissions at certain frequencies from the total airplane.

Part of the tests that you have to do is a matrix evaluation, where you check for all emission sources, and for all victims. You will look for potential problem areas that you'll concentrate on.

After conducting these tests and uncovering the problem areas, you will apply corrective action by adding more suppression or you will do a frequency management analysis.

If you receive and transmit on the same frequency, you must separate the antennas to prevent interference or time share. A typical example might be the radar and radio altimeter; depending on the two signals, when you receive on one, you shut the other one off. Another likely corrective action might be rerouting some of the cables, which is a pain you don't really want to go through. If that fails, maybe the specs are too severe or are unrealistic, and you have to weigh your corrective action against cost effectiveness.

This chart shows how the negotiation starts, especially with the military. We start by developing the perfect aircraft specification, and give that to the avionics manufacturers when they design, build, and test the equipment. If the data meet the specification, then we just accept them. If they don't, then we reject them, and start to resolve the rejection by either making corrections, and repeating the procedure, or modifying and negotiating or issuing a deviation. If the equipment does not meet the specification, we must weigh the cost of the change against what's really going to be accomplished.

This is another example of the testing we do in interconnecting wiring and computers. When we have established our test source, we don't want to synchronize that with testing the computer.

We also have a separate source coupling wire for the induced spikes. Generally, we segregate the bundles of wires, and make the cables up so they are not any larger than 0.5 in. in diameter. These are some of the values of the magnetic and electric fields; 100 A/m at 400 Hz, which tapers off at high frequency. Then we have induced transients at 600 V peak to peak, with a duration of 250 μ sec. We also inject a 100-V spike into all the computer harnesses.

MR. KENDALL: Chris Kendall. On the 100-V transient to the cable harnesses, is there a particular waveform reference for that? Particularly the rise time is what I had in mind.

DR. YOUSSEF: Yes. Well, I tend to think it's about 5 μ sec, but I'm not sure. Usually, the rise time is from 1 to 5 μ sec, and then let it go for another 15 μ sec, but I don't know.

Finally, after we bench-test our equipment and wiring, the last two things we do, especially at Lockheed, is flight-testing. In the Iron Bird we connect all the systems together, and test as we do on the airplane, with both ground and flight test.

Recently, we've been conducting full-scale lightning tests on the L-1011 wing. We have had a couple of incidents in which the active control system was lost. We have had to do some additional testing in that area. I'll be reviewing that.

MR. MULLIN: Kevin Mullin, FAA. Do you know what current levels you're approaching during your full-scale lightning testing?

DR. YOUSSEF: Yes. We started with low voltages, and I think we ended up introducing 1 MV at the wing tip.

A QUESTIONER: Will you elaborate some more on that for us, please?

DR. YOUSSEF: Yes. These are just the mean measurability that I'll be covering in the next five or ten charts. And I'll talk a little about the equipment lab testing, and if it's more interesting I'll just skip through these very quickly and go to lightning. This shows the conductive susceptibility tests we do in the audio and radio frequency to meet DO 160, and what the test signals and acceptable levels are.

These are very much standard tests that we do for the audio frequency, conductive susceptibility. This is the digital autopilot, where an audio frequency test signal is being introduced into the power leads.

Here again the digital autopilot is being tested in the radio frequency range, and this shows the test setup for the power leads and the interconnecting signal cables.

That vugraph shows the current probe injection that we use on the airplane, not just on the bench test.

These are the results that show how the computer emission level is below requirements, whether you test using a narrow band or broadband pickup for the power line, and for the category A and Z requirements for DO 160.

This shows a different frequency band; this vugraph shows the broadband power line test.

I'm going to skip through some of these test results. I think the lightning strike tests are more exciting.

A QUESTIONER: I'd like to see the result of your radiated susceptibility.

DR. YOUSSEF: I don't have that. But I can assure you that we met the requirements. I have the conductive susceptibility here. We conducted this test 3 or 4 months ago. We've been testing the right wing on the L-1011 by applying voltage of about 1 MV to the wing tip. This vugraph shows the return wires back to ground. This is another view of the ground return, and what we've been doing.

The purpose of this test is to duplicate what happened in the two incidents where the L-1011 had been hit by lightning. We were trying to induce the same failure mechanisms that we got in flight. During the strike, we installed a fix, and retested to assure ourselves that the fixes provided the desired protection.

MR. MULLIN: Kevin Mullin, FAA. Did you get the correlation with the actual events?

DR. YOUSSEF: Yes, we did. We increased the voltage until failure — the actual failure was in the servo amplifier. Surprising enough, it was in the analog part, not the digital part of the circuit. The servo amplifier burned out, which is outside the digital at the control system computer.

We'd keep increasing the voltage until it failed. We applied a correction to your grounding, to some of the cables going through the servo amplifier to the actuators, shielded the wires, and we grounded two other areas, and then repeated the test. It didn't fail. Then we doubled the voltage and then repeated again, and the failure didn't happen again. We went to 1 MV, and showed that the corrective action was adequate.

MR. PEACOCK: Max Peacock, FAA. Could you translate that voltage and impedance path, so we could compute the kiloamperes?

DR. YOUSSEF: The induced kiloamperes actually exceeded what's required in the specs. I think we got up to 110 kA/sec maximum rise time.

It's the maximum rise that we achieved, not what was actually seen on the wire. We actually tested to an induced current rate of rise of about 110 kA/sec.

We were interested in the wire that connected the servo amplifier to the actuators. This is the area where the servoamps actually failed.

MR. ECKLAND: Eckland, Syracuse Research. What was the peak current you were able to drive into the wing, out of the generator?

DR. YOUSSEF: The maximum current we got inside this wire was about 15 A. I'm not sure what the skin current was.

MR. ECKLAND: There's a lot of open areas around the flaps. Right?

DR. YOUSSEF: Yes. We have a very thick report about how we defined and measured these parameters, the sensitivity of the skin, and what the current was. We actually started with a sinusoidal signal, just to make it easy to identify the parameters of the structures. We found out that if we used a high-rising, exponentially decaying current waveform instead of sinusoidal, it would actually double, and sometimes multiply by four times, the maximum current achieved.

It's also the wave shape that makes the difference, not just the rate.

MR. SCHNEIDER: Stan Schneider, Boeing. Was that John who ran the tests?

DR. YOUSSEF: Yes. And he supplemented that report.

MR. THOMAS: Ron Thomas, Sperry. Was the servo amp out in the servo itself, or back inside?

DR. YOUSSEF: It was the closest to the computer, in that area.

MR. THOMAS: So it was in the digital box?

DR. YOUSSEF: Right.

MR. THOMAS: And it blew out that.

DR. YOUSSEF: Right.

That's just a summary of the test setup, where we have the high-voltage generator, and how we established the ground plane return. The area that's been the concern was the active control system computer, and it was instrumented and located inside the main electronic service computer section. The people who were observing the test inside the cargo compartment, where it's isolated.

The maximum voltage we tested to was about 1 MV.

A QUESTIONER: These are all analog problems. This was not a digital problem.

DR. YOUSSEF: Yes, it happened that the part that failed was really analog. But when we did the lightning test, we tested other points on the system as well. We tried to get inside the rest of the equipment, the computer itself.

A QUESTIONER: No digital bus in the way.

DR. YOUSSEF: No, there wasn't any digital bus involved. It was just the end of the wire from the computer.

A QUESTIONER: Theoretically, if it was located in the main gear well, would you have had the problem?

DR. YOUSSEF: There would have been more of a problem.

A QUESTIONER: Would you have had the problem — would you be exposed to the problem if your servos were located in the gear well instead of in the wing tip?

DR. YOUSSEF: I don't know. It's very theoretical.

A QUESTIONER: It would be impractical.

DR. YOUSSEF: Yes, that's true. Adding more microcomputer components to connect between the central computer and the servo would still be digital communication between the remote terminal and the main computer, that would save quite a few wires, especially considering feedback from the servo. That installation will be particularly hazardous. What most of the people are doing is locating it in the wing, close to the servo, and not bringing the servo inside. I thought that was your question.

A QUESTIONER: The latest generation of airplanes have the servos and control inboard, is my point. It seems to me that there's no evidence to say that they would be sensitive to this threat.

DR. YOUSSEF: No. It wouldn't be evidenced. We haven't experienced that either.

MR. PEACOCK: But then there might be some other lightning threat if it was located in the wheel well.

DR. YOUSSEF: Yes, it's very much a functional of the airplane's shape and where it's going to be hit.

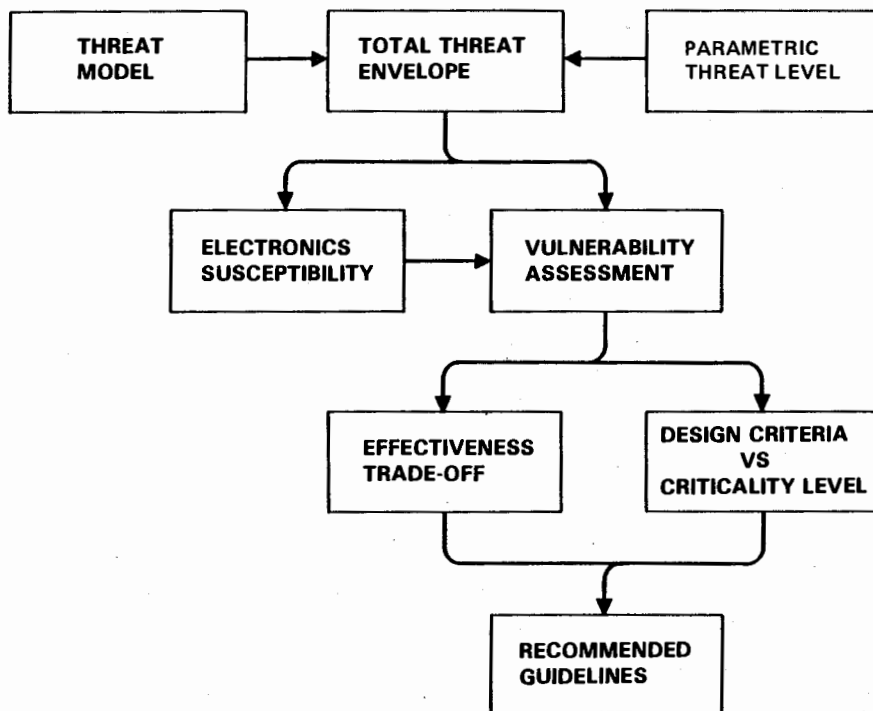


Figure 12-1.- Protection plan.

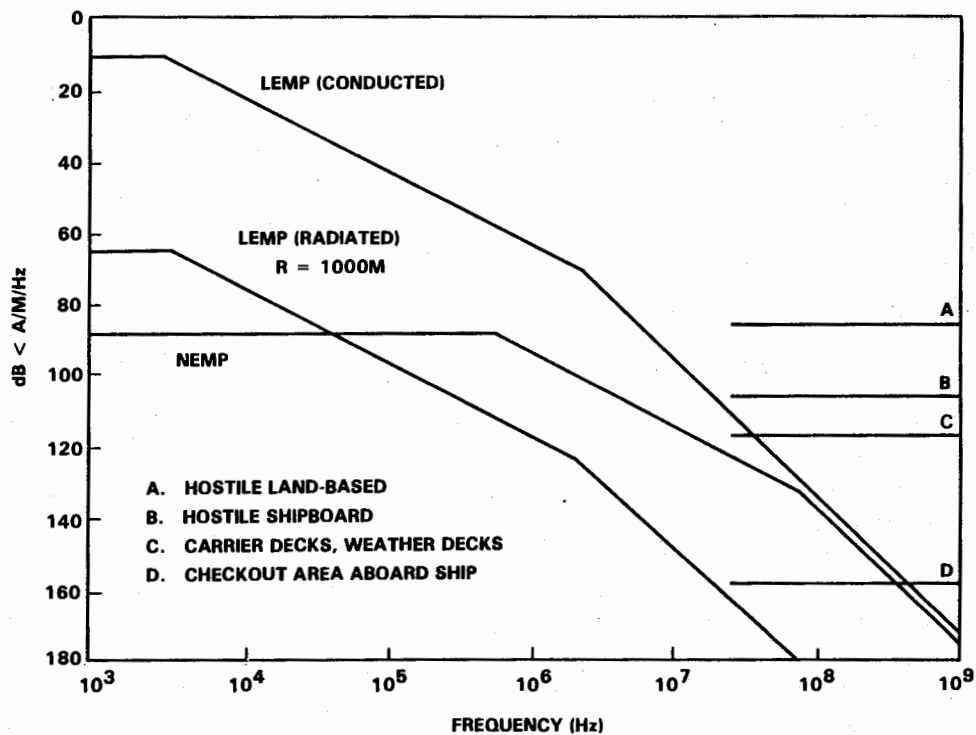


Figure 12-2.- LEMP, NEMP, and EMI comparison.

- **ANALYSIS AND PREDICTION EVALUATION**
 - **EQUIPMENT DESIGN**
 - **INSTALLATION ACCORDING TO EM TOPOLOGY**
 - **WIRING CONFIGURATION/SEGREGATION**
 - **ELECTRIC BONDING & GROUNDING**
 - **SHIELDING**
 - **HARDENING (SUPPRESSION)**
- **EQUIPMENT REQUIREMENT UNDER LCC SPEC IMPOSING RTCADO-160A WHICH CONTROL EMI AT THE DESIGN/DEVELOPMENT AND TEST PHASE**

Figure 12-3.- EMC control program.

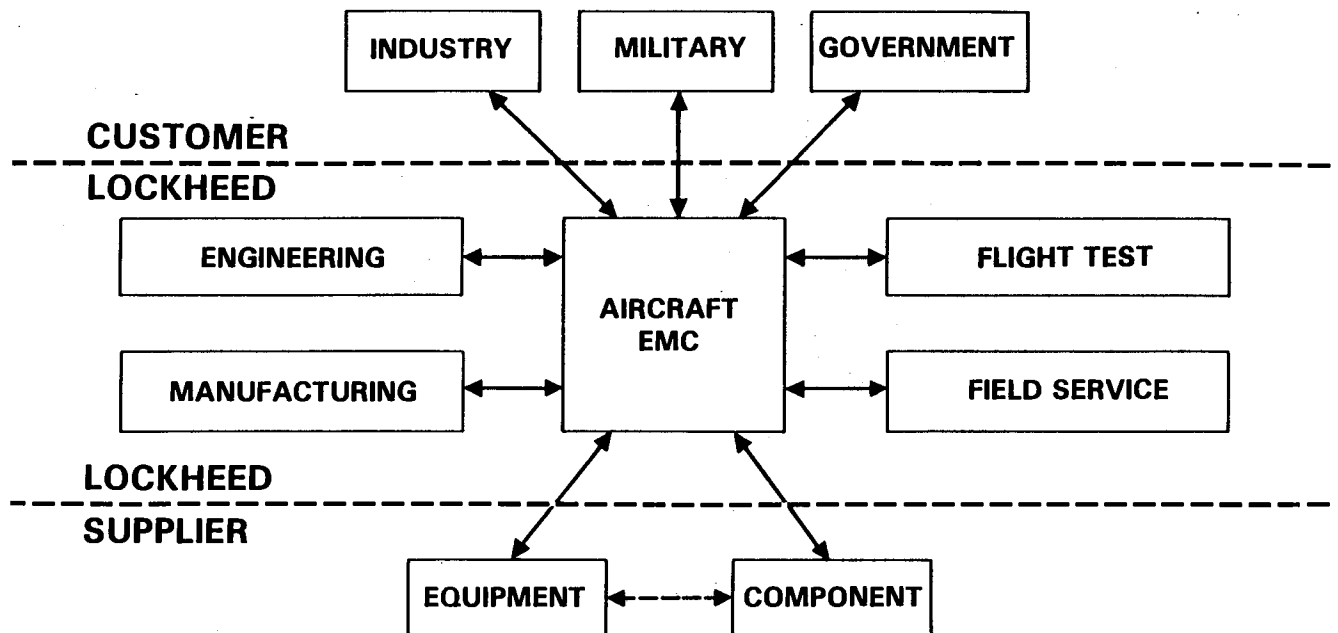


Figure 12-4.- EMC coordination.

- **AIRCRAFT (MIL-E-6051)**

- **EMC PROGRAM PLAN**
- **GROUNDING, SHIELDING AND CABLING REQUIREMENTS**
- **EMI CONTROL REQUIREMENTS**
- **EMC TEST PLAN**
- **EMC TEST REPORT**

EQUIPMENT (MIL-STD-461)

- **EMI CONTROL PLAN**
- **INTERFACE CONTROL DOCUMENT**
- **EMI TEST PLAN**
- **EMI TEST REPORT**
- **FREQUENCY ALLOCATION & SPECTRUM SIGNATURE**
- **WAIVERS AND DEVIATIONS**

Figure 12-5.- EMC documentation.

- **BONDING**
- **GROUNDING**
- **CABLING**
- **SHIELDING**
- **FILTERING**
- **SEPARATION**
- **SUPPRESSION**
- **FREQUENCY MANAGEMENT**

Figure 12-6.- EMC design techniques.

- **VULNERABILITY ANALYSIS**
 - $\pm 600\text{V}$ INDUCED SPIKES FOR ALL LONG CABLES
 - $\pm 600\text{V}$ FOR ALL POWER LINES INCLUDING RETURN
- **ASYNCHRONOUS REDUNDANT CHANNELS**
- **COMPONENT HARDENING — COMPENSATING CIRCUITS**
- **ISOLATION OF SENSOR ELECTRONICS FROM THE CASE**
- **INPUT ANALOG SIGNALS PRE-FILTER**
- **DIGITAL SYSTEM SINGLE POINT GROUNDING**
- **DIGITAL SYSTEM SHIELD MULTIPLE GROUNDING**
- **WINDSHIELD DISCHARGE THRU CONDUCTIVE COATING**

Figure 12-7.- Lightning protection requirements.

- **ALL EQUIPMENT CASES GROUNDED TO STRUCTURE**
- **ALUMINUM SKIN/STRUCTURE PROVIDES NATURAL SHIELDING**
- **NON-METALIC SECTION IS PROTECTED BY DIVERTING STRIPS OR CONDUCTIVE MATERIAL**
- **INSTRUMENT AND CONTROL PANEL PROTECTION FROM HIGH EM FIELDS PENETRATION THRU WINDSHIELDS BY USING METALLIC COATING TO THE UNDERSIDE OF THE GLARESHIELD**
- **INSULATION DIELECTRIC STRENGTH TESTS (600 - 1500 VOLTS) IS CONDUCTED ON ALL EQUIPMENT TO ASSURE ISOLATION OF INTERNAL CIRCUITS FROM STRUCTURE**

Figure 12-8.- Equipment installation requirements.

- WIRING IS ROUTED IN FUNCTIONAL GROUPS IN A SEPARATE BUNDLE OR WITH OTHER LOW LEVEL SIGNALS
- WIRING IS ROUTED AS CLOSE TO THE ALUMINUM STRUCTURE GROUND PLANE AS POSSIBLE
- SEPARATE GROUND (NEUTRAL) RETURNS ARE USED ILO AIRCRAFT STRUCTURE
- TWISTING HIGH SIDE OF THE LINE WITH LOW SIDE OF THE LINE (NEUTRAL) FOR LOW FREQUENCY SENSITIVE CIRCUITS
- SHIELD GROUNDING IS OPTIMIZED AT HIGH FREQUENCIES REQUIRING PROTECTION
- WIRING LOOPS ARE MINIMIZED TO AVOID CREATING A LOOP ANTENNA FOR LIGHTNING STRIKE TRANSIENTS
- CRITICAL WIRING IS NOT ROUTED WITH WIRING GOING TO EXTERNALLY MOUNTED COMPONENTS TO ELIMINATE VOLTAGES COUPLING DUE TO LIGHTNING STRIKE

Figure 12-9.- Wiring requirements.

CATEGORY	DESCRIPTION	GROUP	DEFINITION	CONFIGURATION
1	DC REFERENCE	I	VERY SENSITIVE	TWISTED PAIR SHIELD AS REQ'D
2	AC REFERENCE	II	SENSITIVE	TWISTED PAIR
3	DC POWER AND CONTROL	III	NOISY	TWISTED PAIR
4	AC POWER AND CONTROL	III	NOISY	TWISTED PAIR
5	SYNCHRO	II	SENSITIVE	TWISTED PAIR
6	AUDIO EMISSION	III	NOISY	TWISTED PAIR
7	AUDIO SUSCEPTIBLE	I	VERY SENSITIVE	TWISTED PAIR SHIELD AS REQ'D
8	RF SUSCEPTIBLE	I	VERY SENSITIVE	SHIELDED
9	RF EMISSION	IV	VERY NOISY	SHIELDED
10	DATA BUS	V	SENSITIVE AND NOISY	TWINAX
11	VIDEO	V	SENSITIVE AND NOISY	TWINAX
12	ANTENNA	VI	VERY SENSITIVE AND NOISY	COAX OR TRIAX

Figure 12-10.- Wire and cable classification.

AIRCRAFT

- **ELECTROMAGNETIC ENVIRONMENT**
- **SHIELDING EFFECTIVENESS**
- **CABLE CONFIGURATION**
- **EQUIPMENT INSTALLATION**
- **TRADE-OFFS**

EQUIPMENT

- **VOLTAGE AND CURRENT WAVEFORM**
- **CIRCUIT CONFIGURATION**
- **EMISSION AND SUSCEPTIBILITY LEVELS**
- **FILTERING AND SHIELDING**
- **DEVIATIONS AND WAIVERS**

Figure 12-11.- EMC analysis.

- **FOR STATE-OF-THE-ART CIRCUITS, SHORT WIRE RUNS AND BALANCED/DIFFERENTIAL INPUT CIRCUITS ARE DESIRABLE**
- **MULTIPOINT GROUNDS TO WIRE SHIELDING**
- **DEDICATED GROUND-CURRENT RETURN LINE**
- **HIGH RATING HARDER COMPONENTS**
- **TRANSIENT SUPPRESSOR OR CURRENT LIMITER**
- **REROUTING WIRES**
- **REDESIGNING CRITICAL CIRCUITS**

Figure 12-12.- Overall protective measures.

$$P_F = P_H (1 - P_S)$$

P_F = PROBABILITY OF FAILURE/FLIGHT HR

P_H = PROBABILITY OF HAZARD (EVENT & LOCATION)

P_S = PROBABILITY OF SURVIVABILITY

$$= \frac{1}{\sigma_{SM} \sqrt{2\pi}} \int_0^{\infty} \frac{e^{-0.5 (x - \overline{SM})^2 / \sigma_{SM}^2}}{e} dx$$

$$\overline{SM} \text{ (dB)} = 20 \log_{10}(V_T/V_C) = \overline{V}_T \text{ (dB)} - \overline{V}_C \text{ (dB)}$$

$$\sigma_{SM} = (\sigma_T^2 + \sigma_L^2 + \sigma_{TF}^2)^{1/2}$$

V_T, σ_T = EQUIPMENT THRESHOLD MEAN AND STANDARD DEVIATION

V_C = PEAK AMPLITUDE OF INDUCED TRANSIENT

σ_L = LIGHTNING STANDARD DEVIATION

σ_{TF} = TRANSIENT COUPLING TRANSFER FUNCTION STD DEV

Figure 12-13.- Survivability analysis.

CRITICALITY		P_F	P_H	P_S	SM/σ_{SM}
CAA	FAA				
PROBABLE	PROBABLE	10^{-4}	2×10^{-4}	0.500000	0.00
REMOTE	IMPROBABLE	10^{-5}	2×10^{-4}	0.950000	1.65
EXTREMELY REMOTE		10^{-7}	2×10^{-4}	0.999500	3.29
EXTREMELY IMPROBABLE	EXTREMELY IMPROBABLE	10^{-9}	2×10^{-4}	0.999995	4.40

Figure 12-14.- Design requirements versus criticality.

EQUIPMENT

- RADIATED SUSCEPTIBILITY (100 V/M, 2-400 MHz)
- CONDUCTED SUSCEPTIBILITY (600 VOLTS OPEN, 12 AMPS SHORTED)
- RADIATED AND CONDUCTED SUSCEPTIBILITY (MIL-STD-461)
- RADIATED AND CONDUCTED EMISSIONS (MIL-STD-461)

AVIONICS INTEGRATION TEST FACILITY

- INSTALLATION EVALUATION
- TROUBLE SHOOTING

AIRCRAFT

- CONDUCTED SUSCEPTIBILITY (CURRENT PROBE)
- AUDIO ISOLATION (COMSEC/TEMPEST)
- HERO
- RAD HAZ
- ELECTROMAGNETIC SIGNATURE (QUANTITATIVE)
- SOURCE/VICTIM MATRIX (QUALITATIVE)

Figure 12-15.- EMC tests.

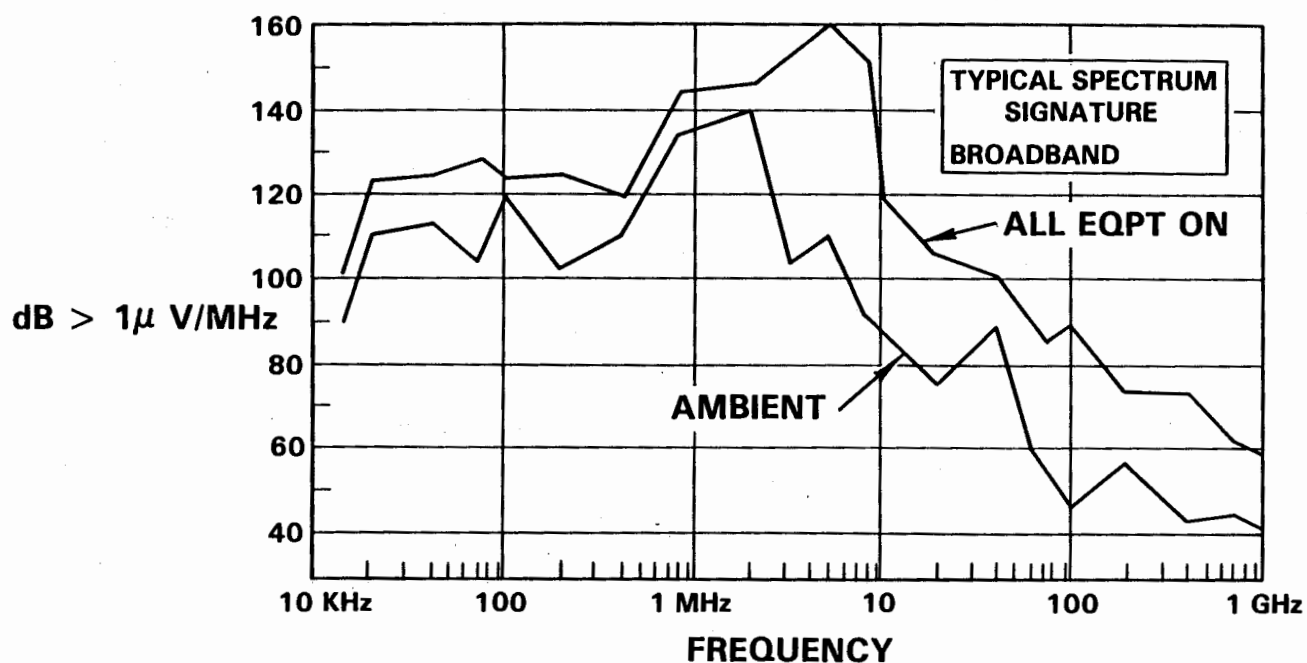


Figure 12-16.- Quantitative EMC test - EME measurement.

VICTIM	SOURCE						
		HF TRANS	UHF TRANS	RADAR	DOPPLER	WINDSHIELD WIPER	ADP
LF/ADF	✓	✓	✓	✓	✓	✓	
IFF	✓	✓	✓	✓	✓	✓	
UHF DF	✓	X	✓	✓	✓	✓	
RAAWS	✓	✓	✓	✓	✓	✓	
SLU	X	✓	✓	✓	✓	✓	
DTS	✓	✓	✓	✓	✓	✓	
ETC.							

Figure 12-17.- Qualitative EMC test - EMC evaluation matrix.

CORRECTIVE ACTION

- SUPPRESSION TECHNIQUES
- FREQUENCY MANAGEMENT
- CABLE ROUTING

WAIVER & DEVIATION

- SPECS TOO SEVERE
- S.O.R. UNREALISTIC
- CORRECTIVE ACTION NOT COST EFFECTIVE

Figure 12-18.- EME/EMS resolution.

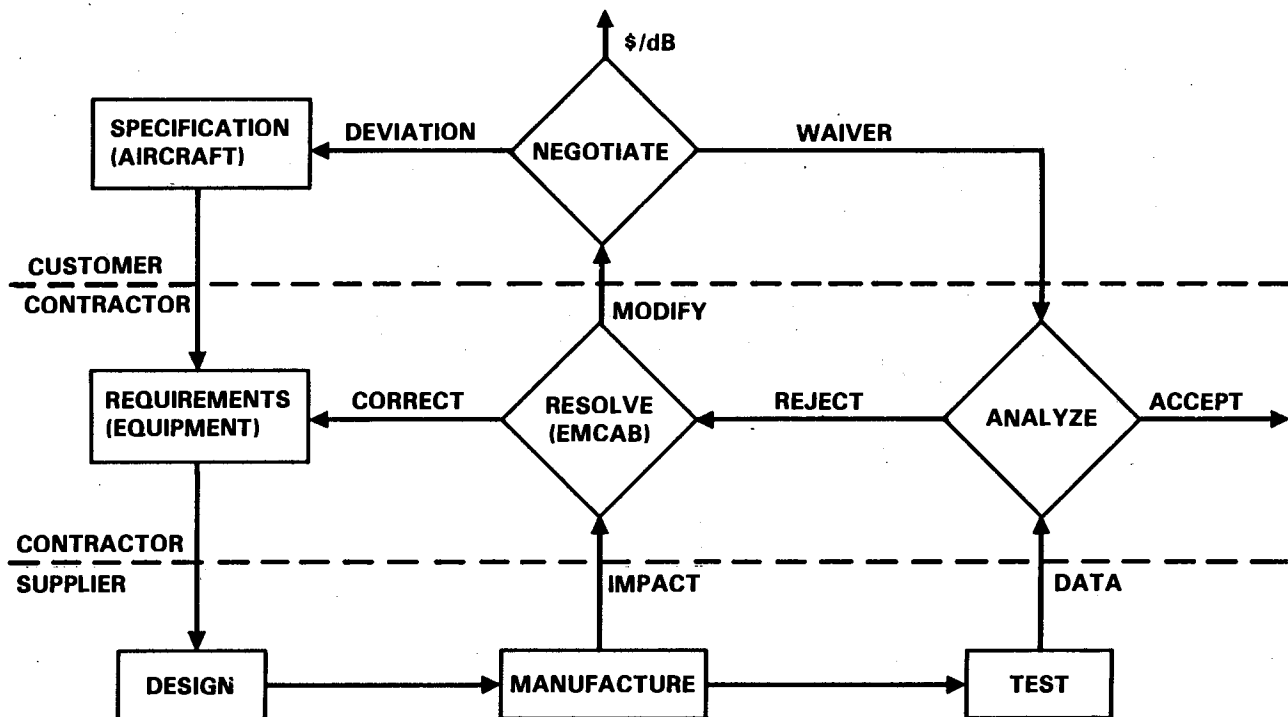


Figure 12-19.- EMI control.

- TEST POWER SOURCE & COMPUTER POWER ARE NOT SYNCHRONIZED
- A SEPARATE SOURCE COUPLING WIRE
- SEGREGATION OF BUNDLES NOT TO EXCEED ½ INCH IN DIA.
- MAGNETIC FIELD TEST 100 AMP/METERS @ 400 Hz,
20 A/M @ 4800 Hz
- ELECTRIC FIELD TEST 6000 VOLT/METERS @ 400 Hz
- INDUCED TRANSIENT 600 V P-P @ 250 μ SEC DURATION
- 100 VOLT SPIKE INJECTION TO COMPUTER HARNESS(ES)

Figure 12-20.- Interconnecting wiring and computer testing.

- CONDUCTED SUSCEPTIBILITY
- AIRCRAFT SIMULATED LIGHTNING STRIKE

Figure 12-21.- Laboratory and aircraft testing.

- DO-160A, PARA 18.0 FOR CAT A EQUIPMENT
- FREQUENCY RANGE 750 Hz — 15 KHz
- SINUSOIDAL SIGNAL IS APPLIED IN SERIES WITH EACH UNGROUNDED AC INPUT POWER LEAD

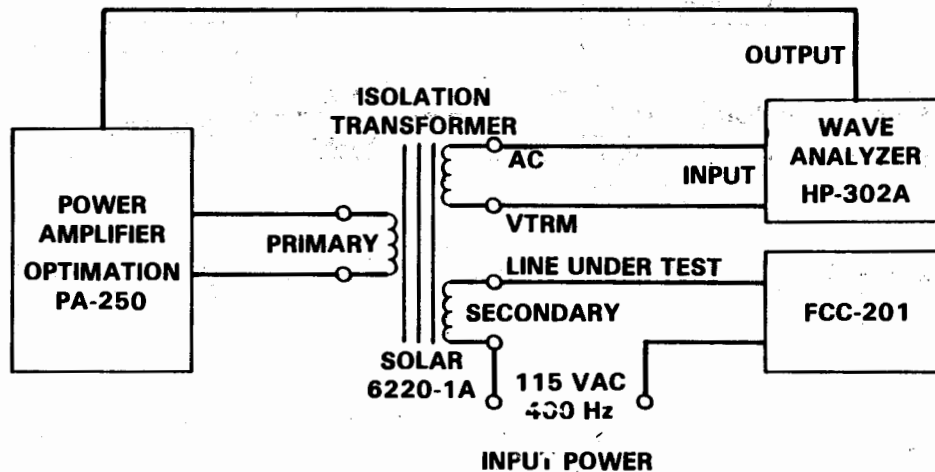


Figure 12-22.— Audio frequency conducted susceptibility.

- DO-160A PARA 20.2 FOR CAT Z EQUIPMENT
- SIGNALS APPLIED TO THE INPUT POWER LEADS
 - 90 KHz TO 2 MHz — 100 MV MODULATED 80% WITH 400 Hz
 - 2 TO 30 MHz — 500 MV MODULATED 80% WITH 400 Hz
- SIGNALS APPLIED TO THE INTERCONNECTING CABLES
 - 15 TO 100 KHz — 100 MV MODULATED 30% WITH 400 Hz
 - 0.1 TO 2 MHz — 100 MV MODULATED 80% WITH 400 Hz
 - 2 TO 30 MHz — 500 MV MODULATED 80% WITH 400 Hz
 - 30 TO 150 MHz — 100 MV MODULATED 80% WITH 400 Hz

Figure 12-23.— RF conducted susceptibility.

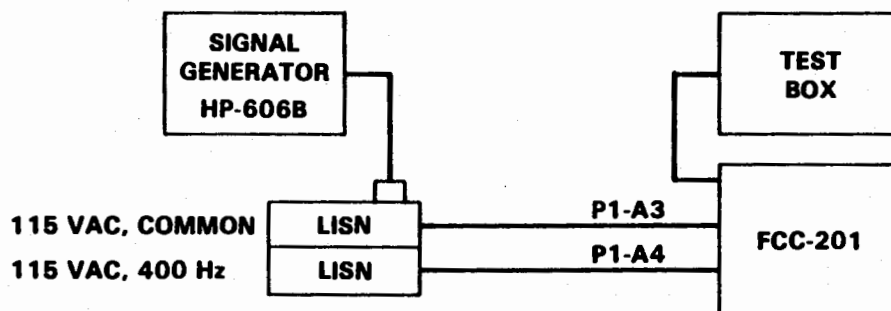


Figure 12-24.- RF conducted susceptibility power input lead (LISN).

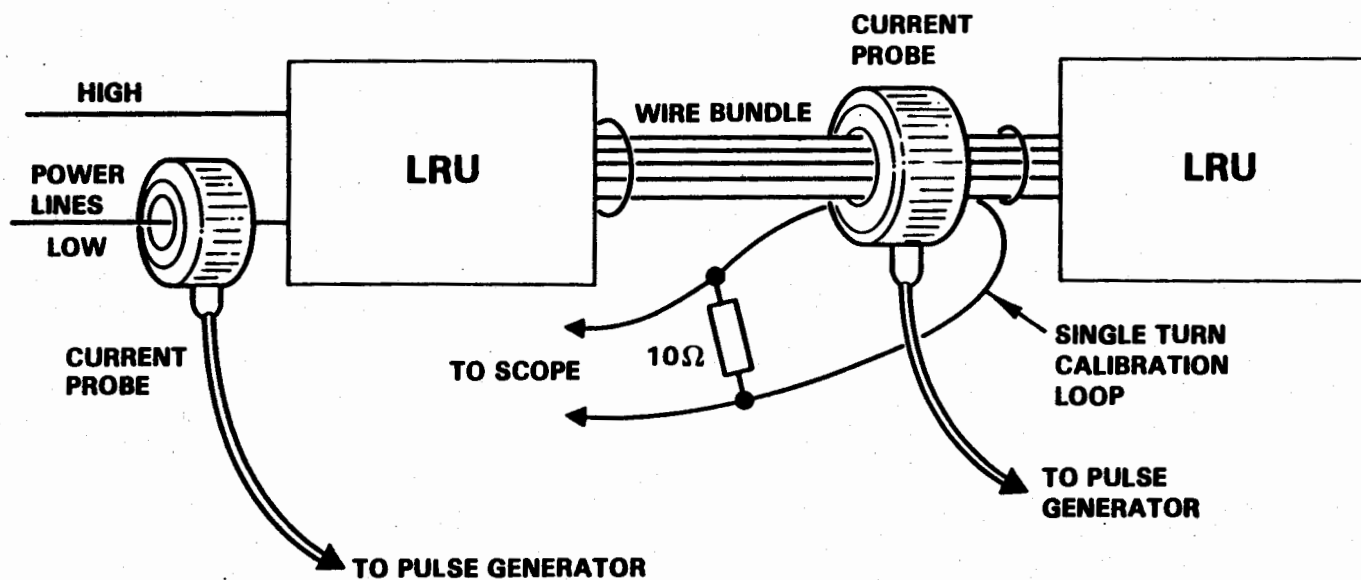


Figure 12-25.- Test method - current probe injection.

TEST SPECIMEN

FCC-201

TEST CONDITION OR MODE
SELF TEST**PROCEDURE PARA NO.**

N/A

LINE TESTED

115V 400 Hz HI

DATE

10/09/80

TECHNICIAN

39728

SERIAL NO.

18

NRT ☐**CURRENT PROBE**

GENISCO GCP5130A

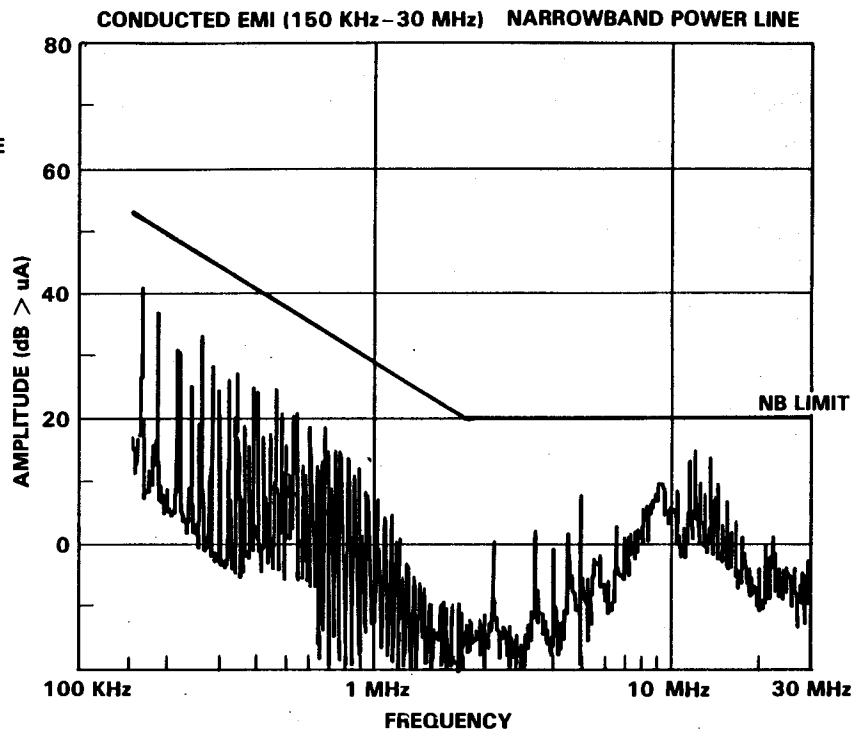
PLOT NO.1A

Figure 12-26.- DO-160A CAT A&Z conducted emissions (current probe).

TEST SPECIMEN

FCC-201

TEST CONDITION OR MODE
SELF TEST**PROCEDURE PARA NO.**

N/A

LINE TESTED

115V 400 Hz HI

DATE

10/09/80

TECHNICIAN

39728

SERIAL NO.

18

NRT ☐**CURRENT PROBE**

GENISCO GCP5130A

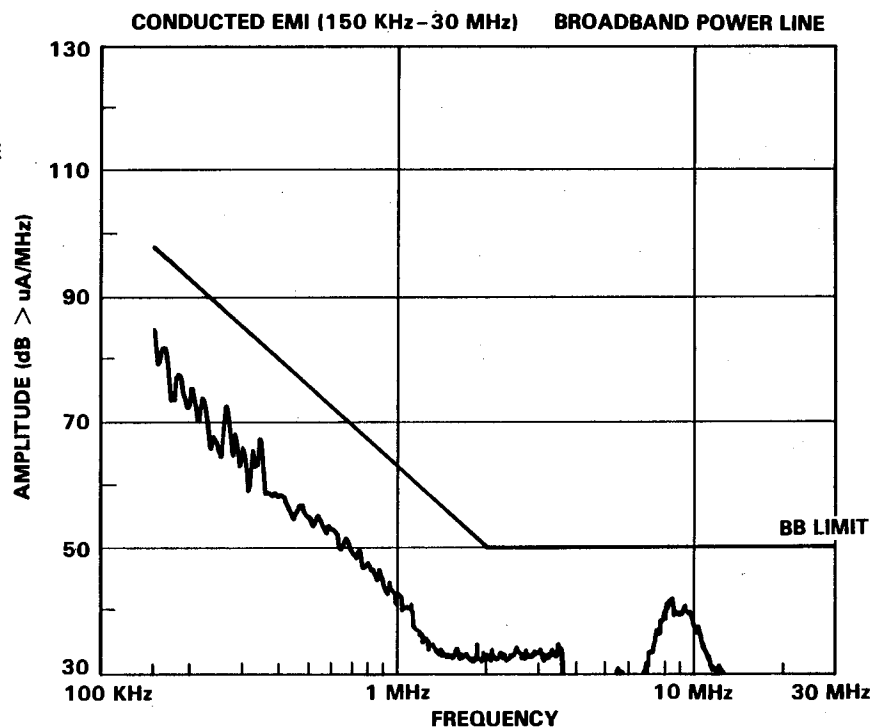
PLOT NO.1B

Figure 12-27.- DO-160A CAT A&Z conducted emissions (current probe).

TEST SPECIMEN

FCC-201

TEST CONDITION OR MODE
SELF TEST

PROCEDURE PARA NO.

N/A

LINE TESTED

115V 400 Hz HI

DATE

10/09/80

TECHNICIAN

39728

SERIAL NO.

18

NRT ☐

CURRENT PROBE

GENISCO GCP5130A

PLOT NO.

2A

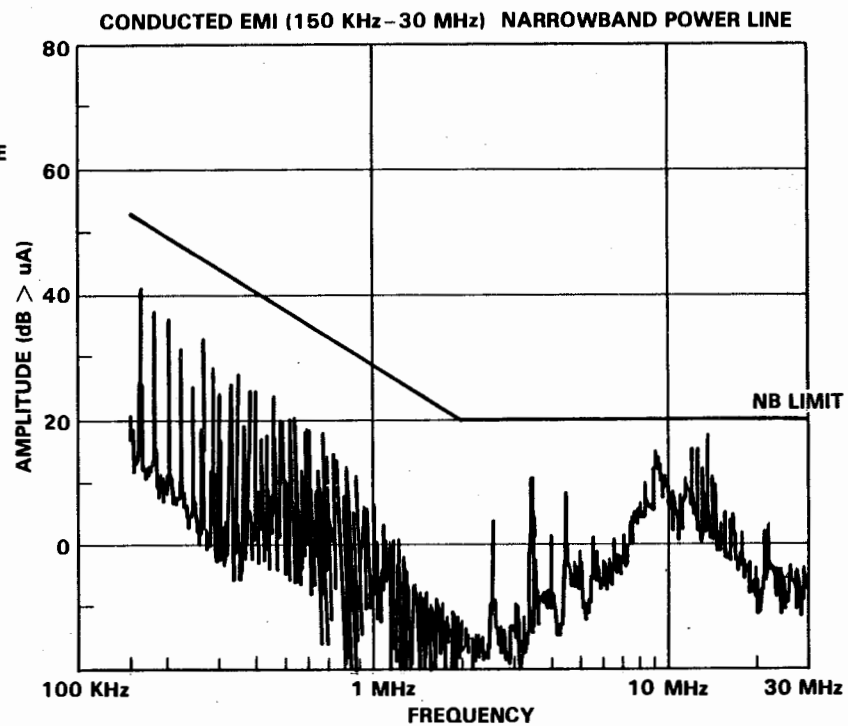


Figure 12-28.- DO-160A CAT A&Z conducted emissions (current probe).

TEST SPECIMEN

FCC-201

TEST CONDITION OR MODE
SELF TEST

PROCEDURE PARA NO.

N/A

LINE TESTED

115V 400 Hz HI

DATE

10/09/80

TECHNICIAN

39728

SERIAL NO.

1B

NRT ☐

CURRENT PROBE

GENISCO GCP5130A

PLOT NO.

2B

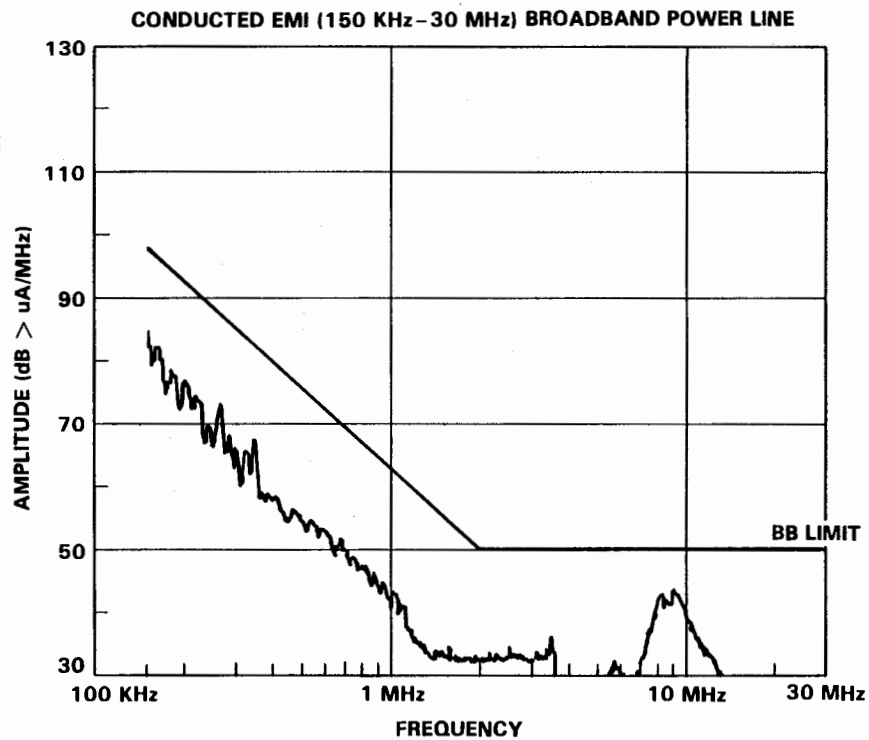


Figure 12-29.- DO-160A CAT A&Z conducted emissions (current probe)..

TEST SPECIMEN
FCC-201
TEST CONDITION OR MODE
SELF TEST
PROCEDURE PARA NO.
N/A
LINE TESTED
P1-A
DATE
10/08/80
TECHNICIAN
39728.00
SERIAL NO.
18
NRT ☐
CURRENT PROBE
GENISCO GCP5130A
PLOT NO.
3A

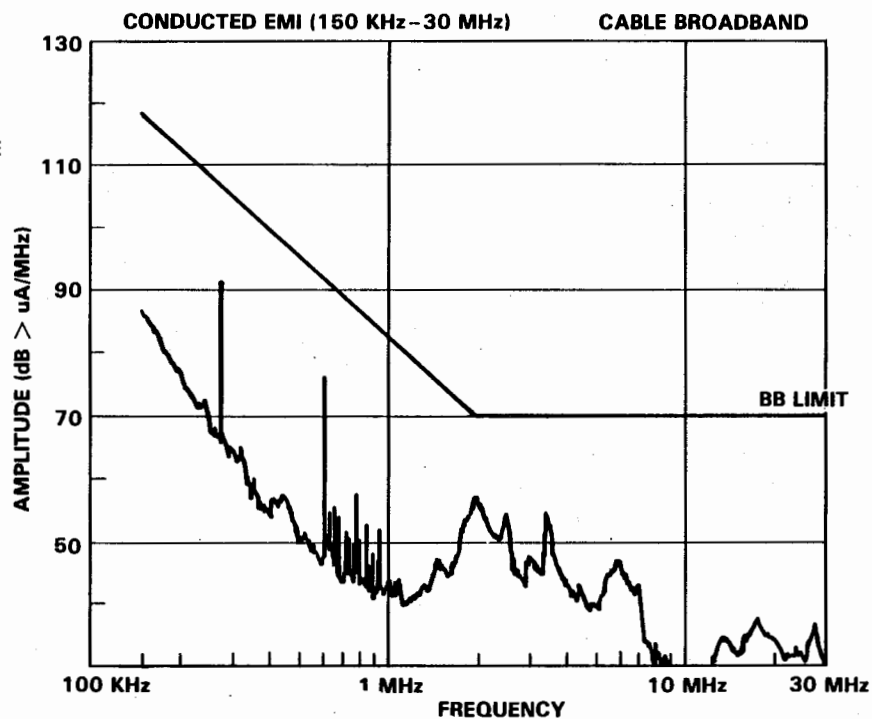


Figure 12-30.- DO-160A CAT A&Z conducted emissions (current probe).

TEST SPECIMEN
FCC-201
TEST CONDITION OR MODE
SELF TEST
PROCEDURE PARA NO.
N/A
LINE TESTED
P1-A
DATE
10/08/80
TECHNICIAN
39728
SERIAL NO.
18
NRT ☐
CURRENT PROBE
GENISCO GCP5130A
PLOT NO.
3B

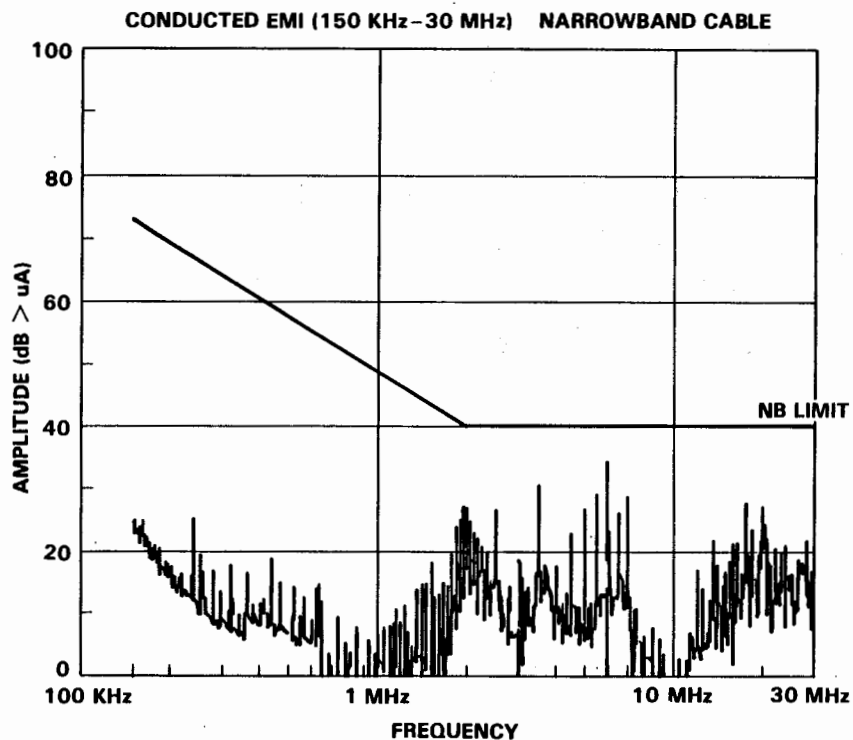


Figure 12-31.- DO-160A CAT A&Z conducted emissions (current probe).

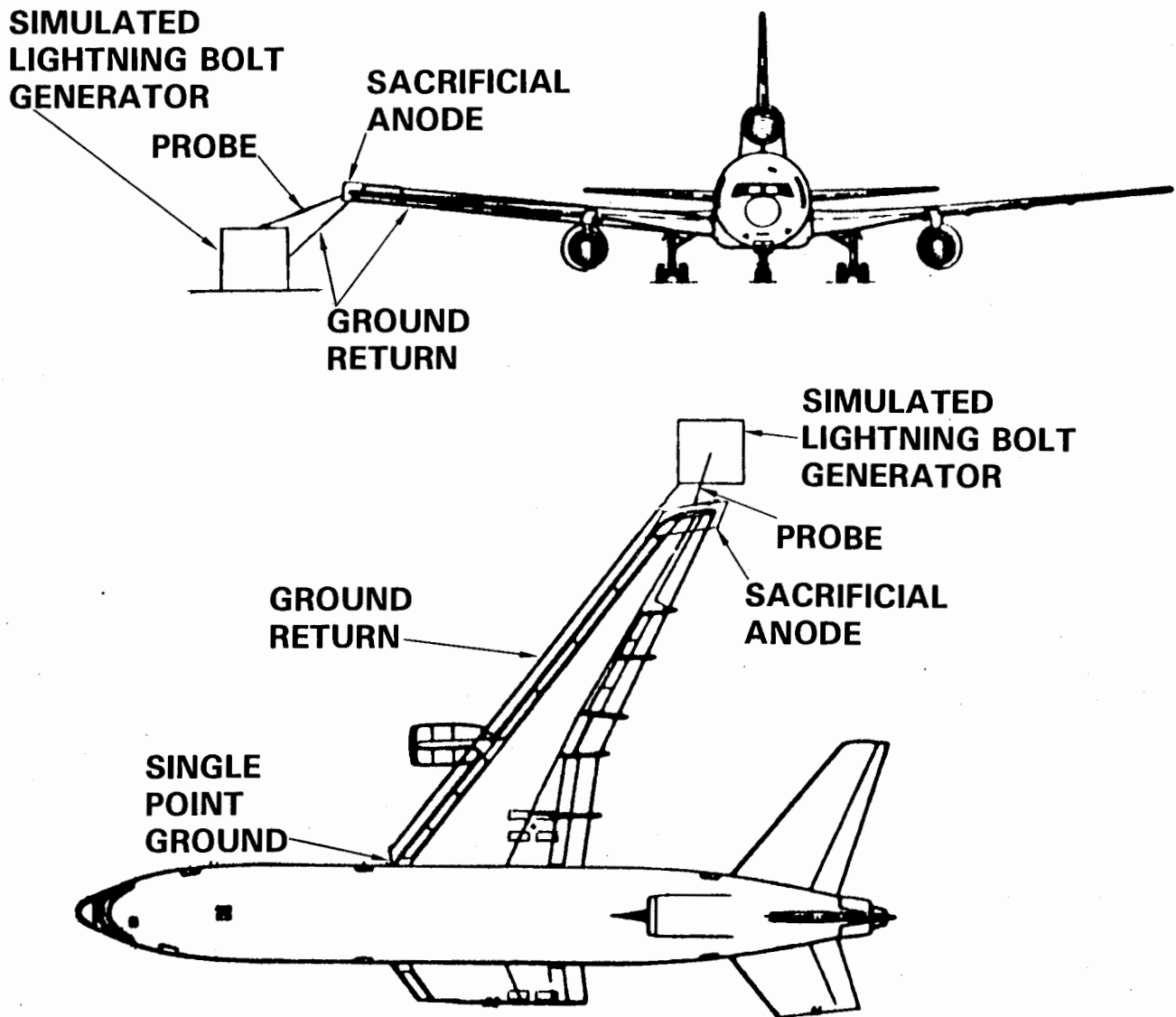


Figure 12-32.- Aircraft simulated lightning strike test setup.

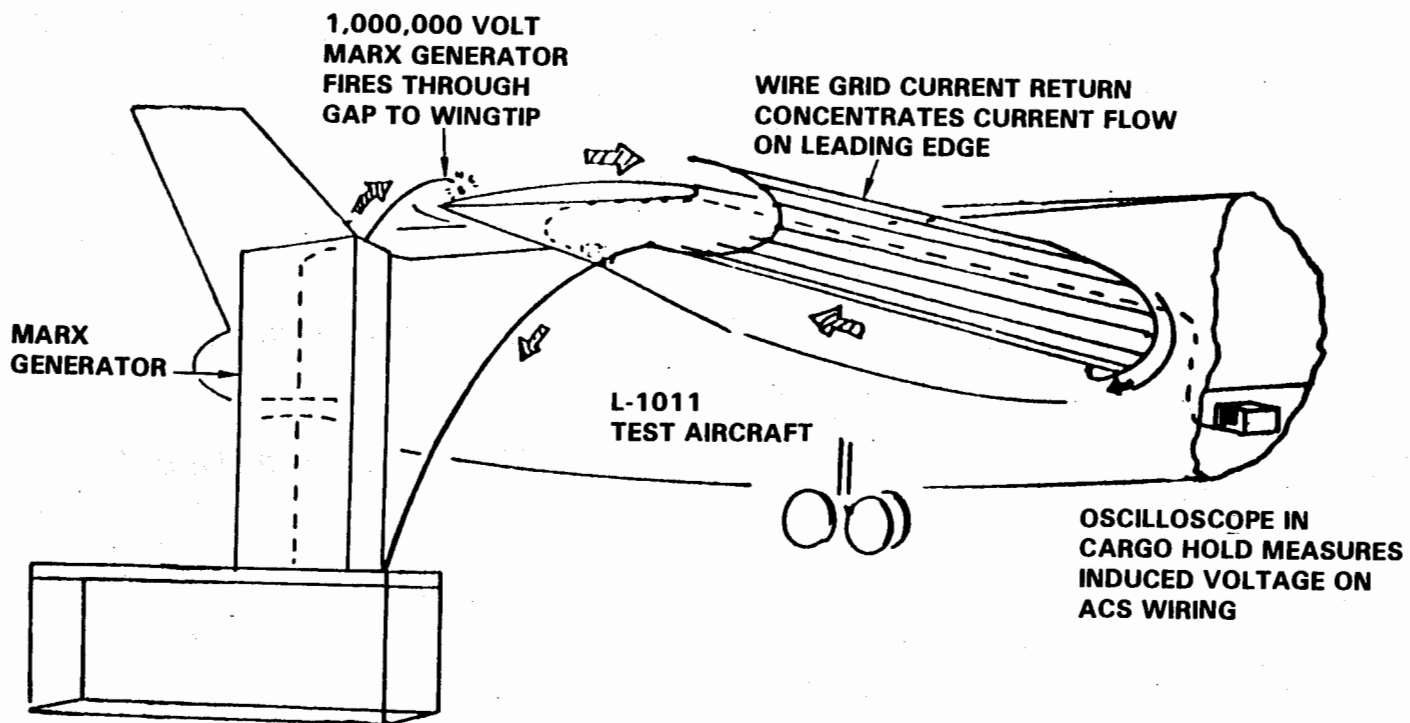


Figure 12-33.- Test arrangement for lightning testing of wing leading edge.

- **TEST SETUP**

- **HIGH VOLTAGE GENERATOR LOCATED AT RIGHT WING TIP ON INSULATED PLATFORM**
- **GROUND PLANE RETURN CONDUCTORS LOCATED IN FRONT OF LEADING EDGE OF WING AND TRAILING EDGE OF AILERON (ALTERNATE PATHS)**
- **ACS COMPUTER INSTRUMENTED IN MESC**
- **TEST COMMUNICATION BY WALKIE-TALKIE**
- **HIGH VOLTAGE DISCONNECTED UNTIL SIMULATED STRIKE IS FIRED AT WING TIP**
- **PROTECTIVE ALUMINUM STRIKE ATTACHMENT PADS ADDED AT WING TIP**

- **CONDITION OF AIRPLANE**

- **UNFUELED — TANKS PURGED AND VAPOR CHECKED**
- **LOCATED IN HANGAR AND AREA ROPED OFF**
- **NO EXTERNAL CONNECTIONS TO AIRPLANE**
- **AIRPLANE INSULATED FROM GROUND**
- **BATTERY/INVERTER POWER ONLY**
- **AREA OF CONCERN — RIGHT WING AND MESC**

Figure 12-34.- Simulated lightning test setup.

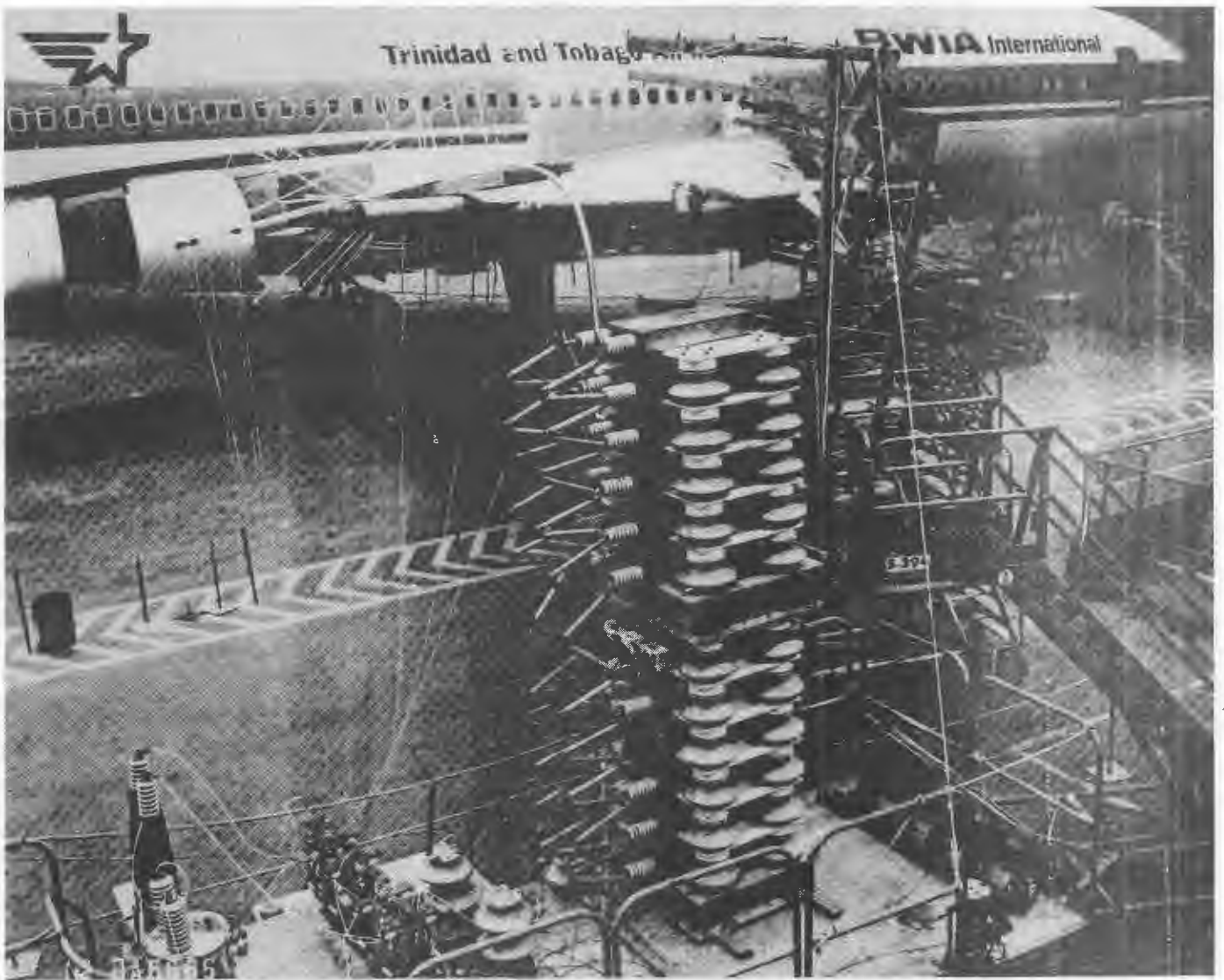


Figure 12-35.- Simulated lightning test setup.

SUMMARY OF ANALYZING AND DESIGNING

Chris Kendall

Chris Kendall Consultants
Mariposa, California

MR. KENDALL: I'd like to summarize. It's been a full day, as far as the information that has been transmitted. I'm not sure I can really do it justice in a summation.

Perhaps we can first start by mentioning the analytical approach to some of the problems regarding the digital avionics threat.

Yesterday we concluded that transients are a threat and a concern to us. This morning we looked at these transients and found that the major threat appears to be in the 5-200 MHz range. Lightning has been well summarized by the various speakers, although there is some conjecture as to what the rise time really is.

The strikes that involve high current are, of course, a little slower than those which are dealing with lesser current levels.

We have found the same to be true for static effects. The greater the voltage, the slower to get from point A to point B, for example, from zero to, say, a million volts. Whereas, if your voltage swing is from zero to 10,000 V, it's going to happen faster. The dv/dt can be the same in both cases.

We recognize that we are dealing with the electrically long phenomenon as the major entry path into our cabling. We talked about types of cabling, alluding to the use of twisted shielded pairs. We also talked about the ARINC 429 bus, and I think John did a superb job telling us about some of the things they did, and some of his conclusions.

One of the things John mentioned, that I wanted to expand on, is the type of shielding efficiencies you can expect from cables. We had talked about shielding cables at one end versus both ends, and the $\lambda/4$ phenomenon, and John had mentioned a new term called the $\lambda/2$ phenomenon.

This particular concept is well documented in various pieces of literature dealing with what happens to a shielded cable when grounding one end versus both ends. One of the conclusions that was reached by investigators was that if you ground the cable at one end, the shield becomes transparent at $\lambda/4$; and if you ground the cable at both ends, the cable shield becomes transparent at $\lambda/2$.

That's the full story, providing we use certain connectors where the shields have to terminate externally, with exposure of leads before connecting to the actual pins, such as the standard ARINC connectors (i.e., multipin, multisegmented connector on the back of a black box, sliding into a register or into a slide).

If you have lead exposure at both ends, then the $\lambda/4$ and $\lambda/2$ are pretty well documented as transparent points for cable shielding.

Fortunately, there are other answers, in that the shielding doesn't have to go to zero at either of these frequencies. It does in the case of single reference grounding, but not necessarily when you ground it at both ends. We have done some research in this area and found exactly what the mechanism is. As you probably have guessed, it deals with the fact that you have lead exposure.

If you have even an inch of lead exposure, with a drain wire attached to the shield through either a pin or some other attachment to ground, then the shielding has a strong tendency to aim toward zero. If that did happen, however, we would have problems that would become insurmountable, except for the solution of some type of further circuit protection in the black box itself.

Generally, with this type of connector, that is one of the only answers. However, I'd like to reference some of the work done on the F-18 that I've been associated with. Here we found that the shielding does not go to zero at $\lambda/2$ if (1) you connect the shield material from the ARINC connector back over the shields connecting to that connector, so that no lead exposure occurs, and then (2) you provide brass or beryllium copper fingers between the ARINC connector that's on the tray and the unit plugging into the tray, so that you have perimeter shielding between the two halves. The shielding then can be improved to a minimum of 20-30 dB. Not a lot, but a whole lot better than zero.

This was necessary on the F-18 because of the very high E-field levels that were required, some of them exceeding 200 V/m.

With this type of arrangement, the only way you're going to improve the shielding quality is by coaxial-type terminations, back shells, and what have you, to prevent the possibility of lead exposure; because it's that amount of lead exposure that can get you into trouble. Let me try to show that graphically.

In the F-18 we had the standard ARINC-type connector, and the inserts associated with that connector. You have your guide pins here. As I recall, it looks something like figure 13-1, labeled "Radiation penetration into improperly terminated shielded cables." This particular connector does not lend itself to shield termination unless you add something to it. A lot of the hope is built into a back shell (made by various companies) that attaches to this connector.

This back shell arrangement is a hood that allows the cable bundle shields to terminate inside the shell. The back shell is a cover with an adaptor. In this adaptor there are different configurations of the back shell. The shield is brought inside, so there is no lead exposure, and then the actual braid is taken to a keeper ring inside the assembly. (See fig. 13-2, "Proper shield termination.")

The unprotected leads are then allowed to make contact to the individual pins of the ARINC connector. In this situation there is no lead exposure at all, and the shielding measurably increases beyond the $\lambda/2$ frequency.

You still have resonance. If I could make a plot of standard braided cables — and I've had an opportunity to test a lot of them lately — we find a shielding effectiveness, and that can even be questioned on test technology and the methodology of testing.

What we find is something that looks typically like figure 13-3, "Typical braided cable shielding effectiveness" — that's the E-field. I'm not talking

magnetic. I'm only talking E-field for the moment. Magnetics have a different effect. The E-field shielding tends to be hovering around 70 dB for most braid cables, and that means cables that have not been specified.

When you go out to buy a shielded cable, you don't ask for a particular braid angle, carrier diameter, finish onto the wires, and longitudinal pressure that make up the cable. Unfortunately, they all affect the shielding efficiency of the cable.

We took a braided cable and made a Chinese finger out of it. We found that if we take a regular braid material and test it, we'd end up with approximately 70 dB. If I put a longitudinal pressure on the cable, of some 20-40 psi, we could raise the shielding from 70 dB to 90 dB.

So there is a lot that can happen in the leakage through those various areas, even when you have no guaranteed contact between the carriers of the mesh itself.

This 70 dB is often maintained, E-fieldwise, up to 1 MHz. After 1 MHz, it gets into a decay that's well predicted by a number of investigators, including Dr. Krugo in Germany. He looked at coax cables extensively using the braid mesh, and found that this decay is typically a -20 dB slope (due to its leakage inductance, as he refers to it) until you hit resonance.

If the lead exposure exists at that point, the shielding goes to zero. If the cables are properly dressed, it doesn't. But it does go into a resonant phenomenon. If you drew a line on the lower performance envelope of this resonant phenomenon, you'd find that you end up with a minimum shielding efficiency in the range of 20 or 30 dB. I think this is a significant factor in dealing with cable shielding.

We can improve the situation if we add foil. But even with foil-wrapped cables, the shielding will go to zero at $\lambda/4$ and $\lambda/2$ if we do not terminate them in a sanitized manner as I've outlined. This, of course, is a problem in our present design, as far as the cost factor is concerned.

There are ultimate solutions such as the technique used on the F-16, which was a rather special back shell arrangement at right angles, made by Ray-Chem. In this instance the cables were brought into a right-angle plate. What was used was a Rayclad terminstor, which is a heat-shrinkable solder sleeve. The individual shielded cables would be brought over to one of the back shell little "fingers." A Rayclad was placed around the cable shield to be terminated and back shell finger, and hit with a heat gun so they would be soldered together. Then the whole assembly was covered so there was no lead exposure. The only problem was vibration. There was a lot of stress at that point, which had to be solved. But technically, that was the approach.

MR. AUCKLAND: Dave Auckland, Syracuse Research. Could you define what you mean by shielding efficiency again?

MR. KENDALL: Yes. That's why I said it's somewhat difficult. Suppose we take a cable harness which is transmitting, say, digital data, and connect it between two black boxes and measure the radiation profile, using methods like RE02 under MIL-STD-461, and its equivalent conditions under RTCA DO-160. Suppose we then

improve the shielding by the methods I've just mentioned -- and remeasure the profile emanating from this cable -- we would call the reduction in radiation detected by the antenna the shielding effectiveness of the added shield. That's what I mean. The actual end results as measured.

MR. ZILLER: Murray Ziller, Sikorsky Aircraft. You mentioned grounding at both ends. We tried grounding multiple points and were very successful.

MR. KENDALL: Yes, you can, if you have a defined place to ground it to, because you're breaking up the standing waves.

If you ground a cable at different nodal points, the standing wave attributed to the original length has been shorted out of these various nodes. As a consequence, the amount of standing wave current has been reduced, and the net RE02, or radiating field, has been reduced.

You're absolutely right if you have some reference. But if you have a composite material, that might be more difficult. It would help, especially if you can get the grounding nodes to be less than $\lambda/4$. Then your shielding will be somewhat enhanced -- unless you started to induce these standing waves on the fuselage member. That would add more complexity.

I hope that helps describe that section more, and resolves some of the concern. I think these are important things to summarize and to look at.

MR. JACKSON: Tom Jackson, TWA. I wonder if John could answer for us whether Boeing used back shells on the ARINC connectors for the 767.

MR. KENDALL: The question, John, is how did you terminate into the ARINC 429 bus connectors. Was a back shell used, or was lead exposure introduced into the termination method?

MR. SMALL: Yes, there is exposure. We don't use the back shell on the tray. The ship's wiring comes up and is exposed for a short distance. Then there's a pigtail that carries the shield to a grounding point close to the connector.

MR. JACKSON: You're saying you did not use back shells.

MR. SMALL: Correct.

MR. KENDALL: Yes. Therefore, his results saying that shielding went to zero at $\lambda/2$ are believable. That's exactly what I would predict.

We've also investigated various lengths and techniques for terminating shields, so that the shield would be allowed to come into the back shell with a pigtail used to terminate it once it's in the back shell. We've experimented with this, and find it's still more viable than the alternative of leaving the cables exposed with no cover. The cover itself helps change the E-field that happens inside the termination sequence.

There is a voltage drop across the braid wire that's used to terminate it. And this voltage drop establishes E-fields between the braid shield and the back shell. However, the smaller that impedance becomes, the lower those voltages become, and the less threatening they become. Therefore, the shield is enhancing the protection level.

We have just run a test on a digital multiplex system. During the test sequence, they used cable troughs. The unit happened to be a shipboard system. The shielded cables would come into the trough, and they terminated the shield in a 1.5-in. length of braid whose width was approximately 0.25 in. They did not comply with the radiated standards. But if they took the braid and pressed it onto the trough directly, without the 1.5-in. braid, the radiation levels dropped by over 8 dB.

That's not significant, but yet it was significant as far as being in or out of spec by 4 or 5 dB. There was a difference — only an 8 dB difference — but it again shows you that even braids contribute to radiation in the higher-frequency regions above, say, 30 to 100 MHz.

Are there any more questions on shielding?

I'm going to change tracks here to something else. Now, the 429 is not a high-speed digital bus. They've done special things to avoid it. I'm sure they were very practical things. It looks like a very good technique, and I was very impressed with John's presentation.

The concerns now are for the future. What's going to happen with these higher-speed buses which use an internal clock on the PC boards much faster than those transferring data at the megabit data rate.

For instance, if you're dealing with a 20 megabit rate, what is the internal clock operating at? Possibly at twice that speed, and being divided down to get a reasonable wave shape for the data transfer.

In these types of configurations, the opportunity for radiation or susceptibility is going to be greater. The reason is that the bandwidth of the logic response is going to be that much greater with that type of bandwidth response.

If I am clocking at 40 MHz, using probably Shocky or Advance Shocky devices, my bandwidths are going to be in the 100- to 200-MHz range, possibly. This is going to create a whole different concern for the quality of that termination.

We have experienced a similar situation on the new high-speed commercial computers. If you look into the central processor of, say, an Amdahl 580 CPU, operating at 41 MHz, 41 megabit rate internally, every cable interconnect in the central processor is coaxial. No exceptions.

If you look at the Craig, the world's fastest computer, the same thing is true. The data lines are matched with time domain reflectometers to make sure the delays are properly controlled for these high-speed computers. We are indeed dealing with transmission lines. A few inches become catastrophic to the transfer of data.

I think they will be fine, as long as we recognize the fact that these data bits are truly RF signals and should be treated the same way we treat any RF signal; paying close attention to transfer impedance of the cable and its terminating impedances, and matching those as necessary. That will be all I'm going to say about cabling.

I was glad to hear discussions of some of the other transient sources (like lightning, and even a little on EMP) to give us an opportunity to see other

fast-rise-time phenomena, and perhaps those which are not so fast. The solutions that most of the speakers gave for dealing with the lightning phenomenon was grounding the cable more often, and breaking up the loop area subtended by the shield itself and the fuselage that it was routed over. This technique was the technique used to harden the system. It shows again the concern for both E-field and H-field characteristics.

Most of the braid materials we use are usually tin-plated copper, and therefore have no real ferrous quality to them. There are some exceptions. Some aircraft manufacturers have investigated the use of Hypernom, and other high nickel alloy steel shields, hopefully for the purpose of gaining some benefit from the permeability of the shield material.

The investigation results have shown that this is very advantageous, because the ferrous content gives you a skin effect much earlier in frequency than the counterpart offered by copper and aluminum, because skin effect is related to the product of the conductivity and the permeability of a material.

But you're subjected to another problem — the saturation of the cable shield. There have been some investigations dealing with the shield saturation.

It's also fun to look at some of the techniques used by people who really have to fight lightning, such as power companies. Have you ever noticed what the power company does for lightning control? (Maybe not enough, since power goes off occasionally in my neck of the woods.) What we find is that on every third electric pole, they run an earth ground from the power neutral down to the earth to break up the loop formulated by the power lines over the earth.

The telephone company, which usually uses the electric poles to support their telephone cables — I meant to bring one of their sample cables — uses a rather thick solid copper foil that's wrapped around the cable that you see running outside. At the alternate pole from where the power company seeks earth ground, the phone people make a ground back to phase neutral of the power distribution. Why? To break up the loop areas during lightning activity because of the magnetic fields involved. These would be the net loop area.

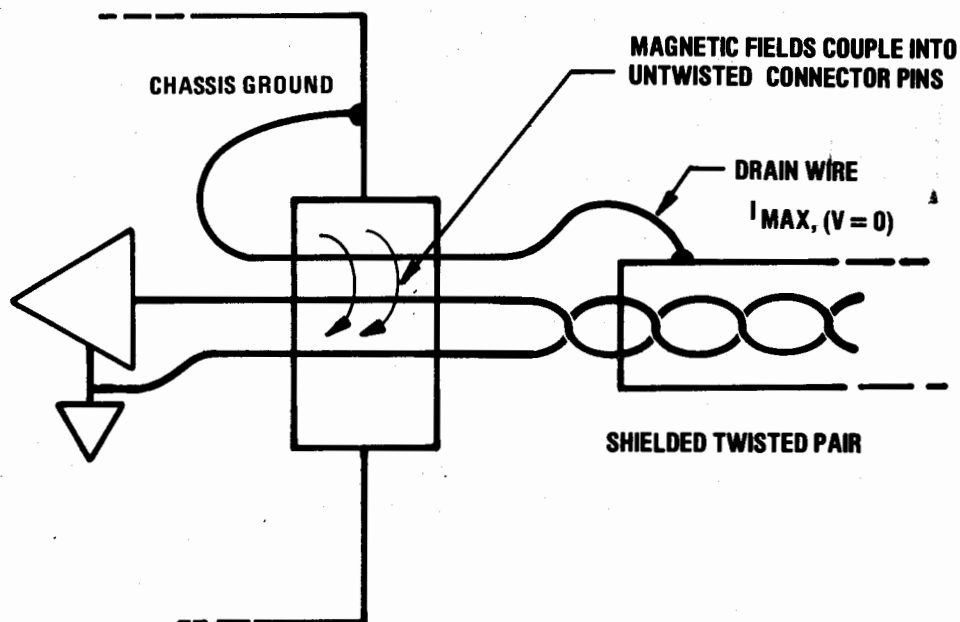
We also recognize that telephone companies tend to favor some type of protection as they come into your house. The old carbon resistor trick had been used successfully for many years, and it would be used to shunt between the tip and ring portions of the telephone line and the water pipe ground.

Newer methods involve spark gaps, where they actually put a spark gap between tip and ring and water pipe ground.

These techniques now have been used extensively for controlling lightning.

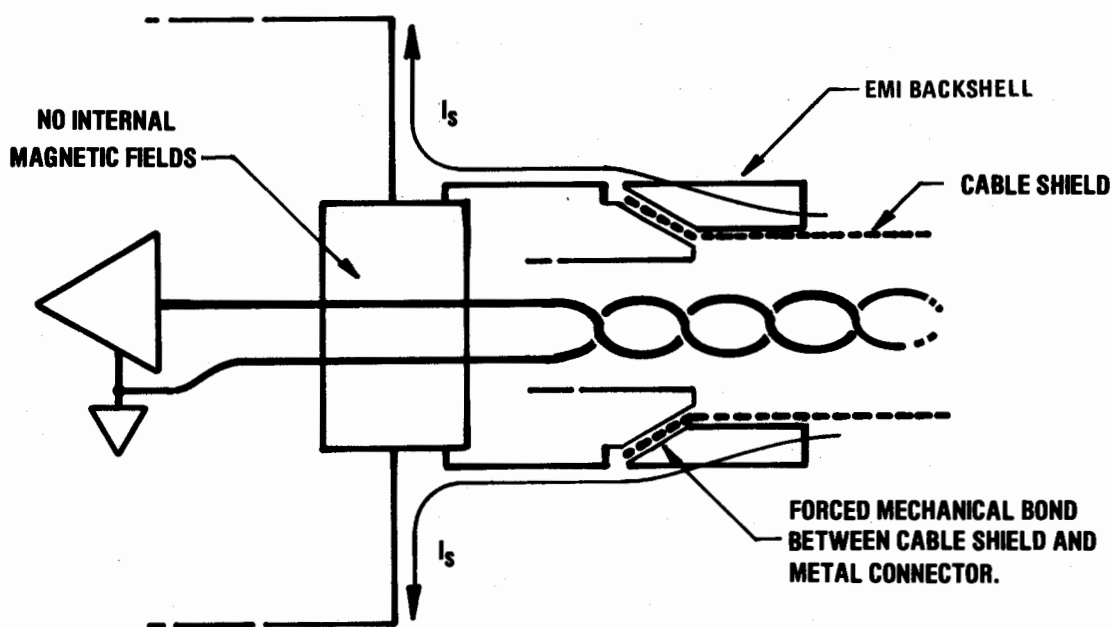
I think that's all a new subject area, but it is interesting to look at what has happened.

I guess, unless there are some questions that I or someone else can answer, this should conclude our afternoon.



- ALL CURRENT HAS TO FLOW ON DRAIN WIRE.
- MAGNETIC FIELDS COUPLE IN CONNECTOR FROM DRAIN WIRE ONTO SIGNAL PAIR CAUSING EXTERNAL FIELD PENETRATION.

Figure 13-1.- Radiation penetration into improperly terminated shielded cables.



- I_s IS SPREAD OVER ENTIRE CONNECTOR SURFACE AREA REDUCING MAGNETIC FIELDS SINCE NOT ALL FLOWING THROUGH ONE DRAIN WIRE.

Figure 13-2.- Proper shield termination.

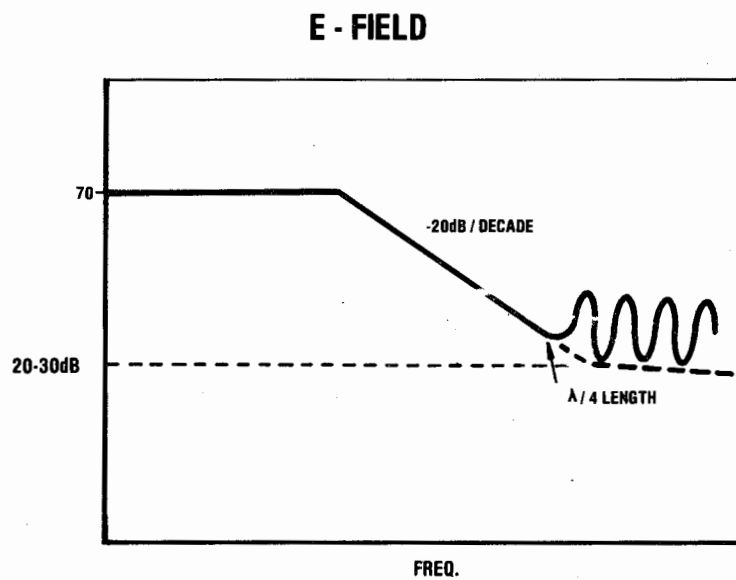


Figure 13-3.- Typical braided cable shielding effectiveness.

TESTING TO THREAT

Methodology of Validation

Chris Kendall

Chris Kendall Consultants
Mariposa, California

MR. KENDALL: Because this is the last day, are there any questions -- something that has bothered you about anything, or comments you want to make before we start? This is a good time.

A QUESTIONER: Back to the first day; you were talking about T^2L couplings between lines and having sufficient energy levels to cause logic gate switching?

MR. KENDALL: Yes.

A QUESTIONER: I pulled out my calculator last night and ran a few numbers. I was wondering if there is sufficient energy in that coupling signal, at 15 or 20 MHz, to allow the signal to remain above that level through the gate transport delays and setup delays. Have you looked into that?

MR. KENDALL: Yes, indeed. It's a good question. The question is, how long does the pulse last (what is the time domain pulse width of the pulse) induced through inductive coupling. This is why we have mentioned special cable routing techniques where every other lead in the ribbon cable is ground or multiground twisted with the high side to reduce the effects of logic-to-logic coupling, which is indeed a concern. Because of the capacitance between the two circuits, as the first circuit toggles, the second circuit (because of capacitance) follows. Then as soon as the voltage is reached in the culprit circuit, the time constant formed by the capacitance between the two, versus the circuit impedance, allows the exponential delay. In most situations where we're just looking at capacity coupling, start in time domain situations, the logic itself creates pulse widths in the 2- to 3-nsec region.

Now, if you look at the logic noise immunity, there are two parts of the equation or two parts of the concern. There's what we call the dc noise immunity, and there's also an ac noise immunity term. We find that in the ac noise immunity term, it takes higher voltage levels to create the same disturbance. In most cases of T^2L , the ac and dc noise immunity levels become the same with a pulse that's approximately 20 nsec wide. So now we find that if the pulse width is like 2 or 3 nsec, it may take 10 or 12 V to upset or change a zero to a one compared to, say, a 20-nsec time interval. So we know that once the pulse width is on the order of 20 nsec, we are in trouble.

Now, let's look at this in terms of coupling from electrostatic effect, P-static effect, or a lightning strike of many, many thousands of amperes, where the rise time can be substantially faster than the ones we've been talking about. In this situation what our concern is it's going to take a hit first, especially when the cables are electrically long when the pulse occurs.

Now, the pulse of an electrostatic discharge (ESD) is generally 400 nsec long, but we look at the rise and fall as the critical item here. Though, in a standing wave situation, you get the first pulse, then the second pulse, and then the third because of reflections. This pulse is reflecting back and forth because of mismatched impedances. You get the composite of a damped sinusoid induced in the circuit, and duration of the damped sinusoid is critical to this failure mechanism. In most cases it's far in excess of 20 nsec and, therefore, it's a serious problem.

Now, if we integrate only from 1 to 5 MHz, you may not have a sufficient pulse width. But that isn't really where you stop. You have to integrate (which I didn't do, and I said you should do) all the way up to maybe 100 MHz or so. But even there, in most cases if it's a damped sinusoid, that doesn't tell the whole story. In most cases you'll exceed that 20-nsec situation. But you're right. You have to look at it; there are other benefits that can be derived also.

That was an excellent question. I think it's something again we have to throw into the equation.

Any other questions?

A QUESTIONER: I'll ask another one. There is a test that Boeing has, and I don't remember what document it's in, about PF radiation. Maybe Keith could comment on that.

MR. KENDALL: For susceptibility, you mean?

A QUESTIONER: How we handle things like that.

MR. KENDALL: Radiating as a circuit?

A QUESTIONER: Well, radiation coming from all these black boxes. Is there any hierarchy or any logic that says we've looked at this and it has to be some level?

MR. KENDALL: I think I saw a chart yesterday or maybe the day before that talked about a 100-V/m radiation level. Maybe it was the Lockheed presentation . . .

MR. KALANQUIN: I don't fully understand the question. The hundred you are talking radiating susceptibility; what a box will emit?

A QUESTIONER: What a box is permitted to emit.

MR. KENDALL: Oh, emissions from the box.

MR. KALANQUIN: You've got to consider the location of the box within the air vehicle; the locations of antennas; and what kind of leakage capacity you would have between the box and the equipment or the wiring from that equipment, where it might couple into antennas outside the airplane. You've got to assure yourself that radiation from the box or wiring does not get to your antennas at sufficient strength to cause an antenna problem. That is your first concern. And then, of course, your second concern is box-to-box radiation.

But generally the first concern is an overriding concern. You always have wiring that is exposed outside the fuselage that can couple directly into, for

example, your ADF antennas, and also directly into your antenna leads. We've had problems on past airplanes, for example, in the mid-60s, when the airlines were playing games with VHF satellite communications, and they increased the sensitivity of their VHF transceivers in order to do that. Our immediate problem was that every time we operated a little dc motor, it would cause a squelch. That was a direct radiation problem. And we had to compute the coupling path. And so, particularly in those areas, your ADF and your HF (HF has not ever really been a problem), but also your RHF band; those levels are closely related or should be related to your receiver sensitivities. They're probably the most appropriate. They operate down in the microvolt region as does some of your digital equipment. You talk about volts in order to get above a logic level.

MR. KENDALL: Thank you, Keith.

MR. KALANQUIN: The 100-V/m figure was at that susceptibility

MR. KENDALL: I had the same problem, exactly the one he was referring to.

It is a concern because we don't really know where a receiver might reside frequencywise and locationwise. Therefore, radiation (such as a computer might generate, which is nothing more than an unsuppressed harmonic generator in many respects) has a spectral line of emission associated with virtually every harmonic of the digital clock.

Yes, Keith.

MR. KALANQUIN: On the new 757-767 program, we found that we've used a lot of digital equipment. The spectrum we're seeing now is a lot different from past programs, in that we do see all of these harmonic clock frequencies, and you do see harmonics in switching regulators. The thing that is particularly significant is that equipment manufacturers will commonly use 2 MHz for a clock. So you would think by the time you get up to 30 or 40 Mc, they would have those adequately squelched. But they have a very difficult time doing that, and we've had signals way up into the VHF bands. We have had some problems there that have caused us to insist on compliance with the spec requirement in the VHF band.

It was very difficult for a couple of equipment manufacturers to meet that, but they did. But there is no margin in a certain frequency range. Personally, I'm not particularly in favor of lowering the limits any more, because it is difficult for them to meet them. Every time you pull the levels down, you cause the equipment manufacturer to go to a more exotic design. Maybe if they'd had a good design to start with, they would have been all right; but every time you lower the limits, you cause them to put in more components. Reliability, and weight, and everything else adds up.

MR. KENDALL: Thank you. Anyone else dare ask a question?

A QUESTIONER: You'd recommend you internally tie your grounds to test ground, internal to the box?

MR. KENDALL: Yes.

A QUESTIONER: We have some concerns on the differences in potential between one chassis ground on one box and another chassis ground on another box. I'd like

to hear from anyone if that's the way they've set up any of the systems in the past — actually internally tying the grounds inside the box to chassis.

MR. KENDALL: One comment before you raise the question, and that is when I'm talking about tying chassis to ground, I'm not necessarily talking dc. Although generally that's possible, too. I was impressed with the paper that Dr. Hussein Youssef, of Lockheed, gave yesterday regarding the lightning threat. They insist their boxes dc-wise, I believe, remain floating from chassis — is that correct?

Now, go ahead. I didn't want to be misquoted.

A QUESTIONER: Is there anybody who's internally tying the boxes to chassis ground, directly, dc-wise? Or do they recommend ac-wise, or are they just bringing out a wire and doing it internally in the airplane? Are there any comments on that?

MR. KALANQUIN: You get into these computer boxes where you've got a computer system — all of those boxes generally have cooling air. When you put those on an aircraft, you've got to supply them with cooling air, and that generally comes in through the bottom of the box. Right above the bottom of the box you've got a little neoprene or nonmetallic gasket for air sealing. So the bottom of that box is generally set off the shelf in order to maintain the cooling airflow. But that back connector on the boxes is a mechanically floating connector. You push the box in so that the connectors will mate.

The front tie-down holds the connectors in place. You would not believe what you are seeing at the present time, but they are not a good bond. So when you put that equipment on the shelf, unless you take some very special means to assure that your box is grounded, that box is very likely going to float. The only way your case is grounded on the box is to bring the ground wire out . . .

A QUESTIONER: Through the connector?

MR. KALANQUIN: Yes. With respect to circuit cards to chassis, I think all circuit cards (Chris has talked about this before) need a good low induction capacity; all circuit elements in it, so that it may come to some common point in the box. I'm not an interior-box-design person, because I've never gotten into that side of the house, but I do know they need a very low impedance tie-in.

The point I wanted to make is that if you want a chassis ground, the only way you're going to assure that in an air traffic environment, particularly if you've got cooling air, is with a dc ground.

MR. KENDALL: One thing I think we have to consider (fig. 14-1) is that if the box is indeed a Faraday cage, the main concern we have with impedance from the box shell through the chassis is of course lightning considerations. As I understand it, you'd want this box to be at the fuselage potential.

Now, also the box does have capacitive effects to the fuselage, and you would like to short out those unknown effects, perhaps, by putting some type of dc shunt between the two. On the F-16 and F-18 programs, there have been requirements for a MIL-B-5087 connection between the black box and the "tray." They did put in special provisions of beryllium copper finger contact between the tray and the black box itself. There, they would have a tin-plated surface on

the aluminum used as a mechanism to achieve electrical bond between the tray and the unit. This was a special added feature to achieve that MIL-B-5087 criteria. I don't think it's universally used.

There are no electrical provisions used to achieve that goal, and the dagger pins on the connector are not very good at it. One manufacturer came up with a new type of dagger pin that would achieve better bonding as you shoved it in. I don't know whatever happened to that. I don't even know if it's being used. But about 10 yr ago I did see a special dagger pin arrangement for electrical bonding. We've looked and relooked at this problem of grounding a black box to the tray, and there are certain provisions. But even I know from the F-16 days (when we were able to achieve 0.0025 ohm, and send it through vibration and salt spray, and this and that), that we were lucky to see an ohm after testing. There is a problem of aging even with the best of grounds. I think Keith's right in the end. Probably it's that silly little wire that's going to be your saving grace as far as ground is concerned.

Now, let's talk about the circuit. I had mentioned yesterday some of the simple examples where we have a two-box situation, where the ground plane was referenced to chassis in both boxes. Concern was raised about the difference in potential between locations of two boxes separated in the vehicle (for example, in the cockpit versus the electronics bay). What I'm saying is that if you do use this technique, you must use signal reference grounding. Therefore, if one grounds both boxes, there's a demand on the system that the boxes be isolated electrically. That would imply differential isolation, optical isolators, and that refers back to John's previous comment about bringing wires off both ends. The other technique is to isolate the two boxes.

But one thing I did want to mention is that there are two modes of isolation. There's dc isolation. At dc frequencies I don't know what the difference in potential is across a fuselage, or even 400 Hz. I'm sure Keith can comment on that. But it has to exceed the threshold of the noise immunity of the logic.

Now, addressing just logic, not analog. If I have two boxes and they exceed a volt potential difference, then I could have problems on a single-ended drive situation. On the other hand, if I ignore the dc and say that's not too bad, and that the only problem I'm going to have is at higher frequencies, then that's a different ballgame. For instance, remember the very first example I raised of the floor of this room being copper, silver-plated, gold-plated, or what have you? Dc-wise they are extremely good but RF-wise there's a problem as soon as you get to $\lambda/4$.

The same thing could happen in the fuselage of an airplane. You may have the best of all skins, but as soon as you have $\lambda/4$ it doesn't matter anymore. There is no such thing as ground in the electrically long region, and that's something I really can't stress enough. So the only way that you could communicate is through transmission lines. The transmission line itself becomes an isolator. The mutual inductance in the coaxial cable between the center pin and sheath is what separates it from just a plain old twisted pair. That mutual inductance is the equivalent circuit of a common mode choke, and a common mode choke is the equivalent circuit of an isolation transformer at high frequencies.

What happens is that you are isolated through the coaxial cable itself; the actual data cable becomes your isolator from box A to box B at RF frequencies.

Where you really have the problem in high-frequency situations and bandwidth situations of digital electronics, the answer has to be in the form of the cable you're using, or in optic isolators, or in differential line drivers and receivers. There is a concern that there may be coupling around these particular features. We may not have achieved the isolation we thought we had at high frequencies because of the way we located them in the box and/or how we routed the inputs to the outputs of these isolators. These are things we have to address.

That gets into the bowels of the design of the black box itself. There are problems there, too, because the box has one connector which everything comes through, including power. The problem is how do you keep isolation through that connector? Sometimes it's not easy.

So those are the things we have to address. There's a lot that can be done at the black box level, but we have to make sure that the person who is building the black box has a sufficient concern for improving the situation.

On the F-18 there was a design requirement for every pin in the connector to be filtered. They didn't say how that was to happen, but it was a basic requirement on the F-18 avionic systems. What that meant was not well defined, but it did evolve over the years. Now virtually every box on the F-18 has a filter pin connector or some other filter mechanism to filter every pin; not just one or two, not just ac power. It was required that every pin be filtered.

That might be a little tough on a 20-megabit data channel. It's acceptable on something like 1553 at a 1-MHz rate. But what do you do at a much higher data speed where capacitance becomes a greater issue? One thing I might mention, too, is the advantage of coaxial cable among all its disadvantages — cost and size. It has a lot less capacitance per linear foot. The design of the cable generally lends itself to a much smaller percentage or a much smaller amount of capacitance between the center pin and the sheath on coax, compared to its counterparts in, say, a twisted shielded-pair cable, where you have more capacitance per linear foot.

Another thing you might ponder in relation to coaxial cables. How many conductors does a coax have? Generally we have two, a center pin and a sheath. There are three conductors to a coax: the center pin, the inner surface of the shield, and the outer surface of the shield. At high frequencies, the RF currents do not flow in conductors but rather on the surfaces of these conductors. This is because of the skin effect, which is a magnetic phenomenon of current flow. And this gives us virtual isolation within the design mechanism of the sheath to do this between the inner surface and outer surfaces.

On braided cables there is a lot of leakage (called leakage inductance) through the shield, which does not give us as much isolation as we would like. But in the foil-wrapped, shielded cables, this isolation is improved upon, depending, of course, on the thickness of the foil and its ability to keep this isolation maintained. So there are some excellent reasons to use a coaxial cable. But the coax cable demands single-ended circuitry, which now brings the issue back again. What happens if my dc resistances or low-frequency resistances cannot maintain the 1-V noise immunity level? Or if I use high-level logic (HTL)? Maybe I can even have more than 1-V noise immunity. Maybe that's what I should do. There are choices to be made. We have to look at all the options, and

decide which is best for our particular application. My feeling is it's best to locate each chassis to ground, because at the high frequency it's going to be grounded anyway.

Let me give another example (figs. 14-2 and 14-3) in terms of low-frequency conditions. If we take the mother board, which is our central ground reference, and keep it off chassis, we feel we've got isolation. That's indeed true at 400 Hz and It's true at dc, but it's not true at 10 MHz. So even if you try to follow principles of single-reference grounding, you cannot maintain it in the high frequency. You have a situation where this is the mother board and this is the chassis, and then they may have cables coming out. I would have a box in which there would be a PC board, a logic board, and a signal.

Maybe these would be coupling between the two boxes. At 10 MHz, especially now that weight is so critical and space in the cockpit so critical, there can be stray capacitance between the boards. Most of these boards are multilayer boards. Some are 18-layer boards. I've heard some are even 23 layers. There is a point of no return, I think. All this is within a fraction of an inch. When I say 18 layers, these 18 layers are 1/8 in. thick. It's an amazing feat, and there's a high reject ratio. In the high frequency, let's assume that we do have some type of ground to the fuselage and through the fuselage. Even though it has some impedance, we have some connection.

If this is what we've got, we have to recognize that even our circuits are going to see capacitance; they are going to see a short at some frequency. We can't prevent the ground loop. So when we look at the ground and its high-frequency characteristics, and at this net loop area, we've got a problem. This is exactly what happens with digital transmission. When we tried to send 32 signals down a digital cable and then connect the return to some central tie point through the chassis, we just couldn't operate because the capacitance completed the circuit for us, even if we floated one board. This stray capacitance is not on your schematics. We often think EMI is a study of what is not on the schematics as opposed to what is. We often concern ourselves with the stray effects as opposed to the actual things on the schematic. If you added them to the schematic, I think a lot of these problems would have gone away years ago.

This capacitance now creates the completion of the circuit, and there's only one way we're going to break that circuit up and get rid of that loop area. That's through transmission line principles. If I take the return wire and twist it, even though it adds more cables, the presence of that wire forces the electrons to flow either through this path or back on the return wire. And the electrons will flow through the return wire when the mutual inductance between these two is high (you'll see this done now in many digital cables).

Now, we want to get high mutual inductance between the signal and its given return. Even if we take 32 signals and 32 returns, twist one of the returns with each signal, and short together all the returns prior to going through the connector, we still get a tremendous advantage. Even though a twisted pair is sitting here with a return, and the two grounds are tied together, the electrons have two choices. They either flow through the ground plane, back through this wire, or back through that return wire. If I continue I'll get more choices. But they become insignificant because in the higher frequency regions the currents are going to flow back on the wire that has the high mutual inductance.

There are some limitations, of course. And that's why when we start pressing the data transfer on these cables higher and higher we cannot live with just twisted-pair conditions because they will begin to have some mutual inductance and crosstalk between them. These twists are not homogeneous, they are not perfectly canceling, and they are not transmission lines.

A twisted pair is great when you're sending 1-megabit data, but if you send 10-megabit data down the cable with edges in the 2- to 5-nsec region, a twisted pair reaches its limitation. Any slight mismatched impedance along the twisted pair shows up as a reflected part of the signal. When the pulses come through and there's a slight mismatch, part of them are reflected and the rest continue. That happens at every little junction point until the noise buildup becomes very serious and the data transfer becomes quite a problem.

As I said, twisted pairs are great for certain speeds of data transfer, but when you get to 10 megabits, or higher, you have to go to coaxial cable. There is no choice. If you look into an Amdell 508 or a Craig super computer, all the interconnects are coaxial, without exception. Everything is coaxial in the high-speed processors even though the distances are not that great. In Craig, all the boards are built in the round, with all the cables in between to keep the links down. But even there, they're all coaxial; it's impressive. We see that we have to consider transmission lines as the data rates increase.

So there is some isolation achieved. In some of the earlier commercial computers, they would actually add a common mode choke to improve the rejection of the currents that might be induced. The choke would reject it, and also enhance the flow of the actual data. So these are other ways of doing the same thing.

We had an interesting problem not long ago with an AM radio station that moved to another location on the outskirts of town. The station had an antenna put up so they could still broadcast to clients in the old area. They put the antenna right next to a telephone company building.

What happened was amazing. You could make a phone call in that town and hear music, or what you thought was music, played on your telephone lines. The phone company didn't really care for this, so they asked us how we would solve this problem. Our solution was to take large ferrites and put them about every 10 ft for a distance of four or five telephone poles, and it solved the problem.

Why? Because the AM radio station had induced (it's a ground wave) common-mode currents to flow into the sheath of the telephone lines. By putting the ferrites on, we added impedance to that flow of current. The current was reduced, and the coupling between the sheath and the inner conductors was reduced, causing the problem to go away.

You can do this type of thing. The common mode chokes are very helpful when you're faced with this type of dilemma.

There are, of course, limitations. The common mode choke in the high-frequency region is limited to around 15 or 20 dB, because of crosstalk around the ferrite block.

In the lower frequencies it's far more effective, where you don't have as much crosstalk across the input to output of the balun or common mode choke. So we have to devise a plan recognizing that this capacitance is real. If you ask me

if there is a mismatch in impedance between these two boxes, I'm going to say, "Absolutely," especially at $\lambda/4$. There's going to be almost an infinite difference in impedance. The system has got to work. Performance must go on, and the only way is through a transmission-quality termination. It's against everything we've ever thought of to this point. We've been very cautious of ground loops and multiground paths — and those are real threats, by the way. I don't want to ignore the low-frequency problem. This technique I've just shown you does create a low-frequency concern. It was well demonstrated yesterday. You have to wed this system with all of the other principles to make it work. But if you don't do something like this, you're not going to transfer data.

In the end, whatever technique you come up with, you have to test it sufficiently. I look at DO-160 as being a reasonably good method of testing for the low-frequency phenomenon, of making sure that your grounds don't float, the low frequencies are stressed, and your tests have pulled so many amps per foot and are stressing the low-frequency coupling. But I do have some concerns about the high frequency.

Those are the methods I'd like to share with you this morning. I want to talk a little about what can be done to make sure the high-frequency phenomenon has been well addressed.

First of all, we could certainly take an RFCW signal and radiate at our boxes, and if we can pass that test we should have no problem in passing transient phenomena. I've heard this argument a number of times.

The problem with that is that it still dumps energy at one frequency. And it isn't necessarily true that a CW test is a good substitute for a transient stress.

The problem is that the CW is scanned. Generally when you're doing the test, you are starting at one frequency and slowly scanning to another frequency. In this process you're radiating at the system.

Granted at $\lambda/4$ frequencies, if your frequency of radiation is held for a moment, or if you get close to it and you sit there for a while and ponder, you may then get the true effect of the standing-wave coupling.

But that again depends upon the criteria for the field intensity. If your criterion is 1-V/m, then you're never going to get into logic. Suppose I use a 1-V/m as my criterion for radiated susceptibility, and I'm dealing with logic with a 1-V immunity, and the best transfer function I can hope for is 0-6 dB as the maximum. Typically I'm not going to see more than half of the field intensity appear as a voltage in that circuit. That is if I radiate at 1 V/m, the most I can see is 1/2 V/m introduced into the logic gate, totally unshielded — no shielded cables, no shielded cases. One volt per meter usually passes through logic. That wouldn't be true for analog necessarily, but it is reasonably true for digital. Typically, we have found that to have any threat at all, you have to exceed 3 V. Once you get to a field intensity in excess of 3 V, you can couple some induced effects into the logic itself. As you go beyond that criterion, it becomes more and more real.

If we have a situation like this, it's certainly possible. But we're trying to do it all at one frequency. We are not looking at any integration process with

that type of stress. With a transient effect, on the other hand, we do have a broadband spectrum generated, and we do have the resonant conditions and the concern about reflections. Finally there is the integration of this threat across the device itself.

Therefore, many of us still prefer some type of transient phenomenon to test the high frequency. For example, suppose we run the DO-160 tests on an on-board computer. I would feel reasonably sure that questions dealing with dc resistance from point A to point B, or the low-frequency resistance, or the magnetic coupling have been addressed. If it passes these tests, I think you've got a reasonably hardened box for the low frequency. However, I don't feel as comfortable for the high frequency.

Let me relate what we have done on some of the computers to help this problem along. The most helpful test, I think, is the relay transient test, but we've had some concerns about that, too. We recognize that not all the relays are the same, but someone might select a relay that would give a little better profile than some other relay (I know none of you would do this), but we've heard this as a possible argument.

Assume we remove the relay and go back to the test we proposed with the two boxes interconnected by a cable of some consequence. We'll assume there's some type of ground between them. In the relay transient test, a wire is taped to the bundle for some prescribed distance. Let's assume the distance is at least a meter. There should be some minimum distance callout between the connector of the unit we're testing and where the wire begins. I'd like to keep this within at least 6 in. I couldn't tell you if it made a difference if it was 1 in. or 6 in., but it should be fairly close, not far removed. We recognize the connector as one of the weak links in the penetration of RF to a box where standing waves occur, so we do not want to ignore the connector region; 6 in. would be a maximum separation. In fact, if you put the test conductor right next to the connection, I wouldn't feel bad, either.

Let's assume the test wire is 1 m in length. It should be long enough to be a standing wavelength for the band length of the logic family being stressed. I would say 1 m is an absolute minimum for this test; 3 m might be a maximum.

I'm especially concerned if you get it too long in the high frequency. It's okay in the lower frequency because the rise time we're using is going to be perturbed by the length of the wire you're adding. If you get too much L in this wire (too much inductance), you're going to slow the rise time, and the stress is not going to be what you want it to be.

So here we now designate a loop. I usually keep this about 0.5 m away, and I bring it back to this location over here, or on one of the corners we've moved. At this location we usually connect a high or fast rise time electrostatic discharge simulator (see fig. 14-4). We take one of the leads and tie it to the ground terminal on the electrostatic simulator, and the other lead comes out. (Incidentally, the tested I prefer is where the discharge occurs in the probe itself, not back down in the case. I would recommend the new, and I cannot stress enough "new" Andy Hish simulator, in which the probe (not the box) is the point of energy storage and discharge. In one of the earlier models manufactured by that company, the capacitor resided inside the box. I don't think that's good.) So now it discharges in the probe. It has various tips that you can select, but let's assume we select a round ball for the first test. This

lead is usually 1 m long, and it receives power. Therefore, as we arc to the lead and the voltage is below about 2 kV, you physically have to touch the probe to the lead because there is no real arc that you can see. In the lower voltage, you simply touch the probe to discharge and the higher ones will arc. If you're down to 100 or 200 V, this should be a direct discharge.

In the lower voltage regions, as you discharge, you have first the ability to vary the voltage. (You're dealing with a tester that's relatively inexpensive, around \$3000.) The instruments having high discharge rate probes are rated, in some cases, to be as fast as just under a nanosecond. Some of these are in the picosecond rise time for the low voltages.

You have an extremely fast rise time within the confines of this loop to cause the arc.

An improvement of this technique might be a transmission line, where we actually set the lead in a little more of a trough, and try to match the impedance better. We can even get higher frequency stress (but I didn't want to get too exotic, and I wanted to see how this worked anyway), where we just change out a chattering relay for a rather inexpensive fast-rise-time generator where we have control of the voltage.

In some of these more exotic ESD test simulators, you even have a timer and a counter that tells you how many discharges occurred. These models will stop on count, or stop on time. You even have the ability to change the discharge rate from one every 4 or 5 sec to, maybe, three or four a second.

You are getting an extremely fast rise time or broadband stress with this system as you discharge, and we find this to be very useful, not only as a good ESD test, but also as a tremendous troubleshooting aid. Suppose I've got four or five cables, and I don't know which one is weak. By going from one cable to the next and looking at the compared level of failure from one cable to the next, I can get an awfully strong clue as to the level of stress at which the cable fails.

We did this, as I mentioned, in Berne, Switzerland, when we were troubleshooting a computer. We found that the one cable that failed, in this case, failed at 500 V where the rest of the cables could take 25,000 V stress and not have a failure.

There are some limits. An example might be if all the cables are close together, it's a little harder to separate the cables out. But where you have the ability to separate the cables, it's very useful. This is one test I would propose: fast rise time, controlled amplitude, and fairly well documented waveform. Except for the way we perturbate it with the test loop, the test could be improved upon by some type of controlled impedance network.

The other possible threat is a direct discharge to the unit itself, especially in the cockpit or areas where it is possible to make direct or intermittent contact with some other object, such as the pilot or possibly even metal. In that situation, any place that normally would be touchable by the pilot should be tested for a direct discharge. You run an arc and discharge directly to the unit under test, and that is usually done by connecting the ground to some part of the unit.

You have the simulator again. Then it comes out to its probe and you can discharge directly to whatever could be touched by the pilot or any of the crew.

In this situation you have the ability to test for directly induced transients. This threat is most likely to occur in very dry atmospheric conditions where a Tribo electric effect can occur.

MR. SMITH: On this test you have plenty of rise time

MR. KENDALL: Oh, yes. What is the rise time? Typically this could be around 2-3, maybe 2-4 nsec, depending upon the voltage.

MR. SMITH: Are you going to develop a pulse that's long enough?

MR. KENDALL: Wide enough. Indeed you will. Only because I've done it so many times.

Typically the waveform is 400 nsec wide. So you're dealing with a 102, 105 nsec rise time with a 400-nsec duration. And this is indeed what the human body looks like during a discharge cycle.

MR. SMITH: (Unintelligible.)

MR. KENDALL: But that's real. Because if it's caused either by a human, or static on the fuselage, you're going to have very short, very fast rise times, and you're going to have very narrow pulse rates because of the energy content. The possible exception would be lightning. We're not trying to use this as a lightning simulator.

MR. SMITH: Is it primarily for . . . (Unintelligible).

MR. KENDALL: That's right. Now, it can be modified, you're right. If you want to create something with more energy, we simply have to increase the value of the capacitor.

MR. SMITH: (Unintelligible.)

MR. KENDALL: The chattering relay is more realistic for simulating chattering relay situations, but it's not very realistic in simulating fast rise time P-static, or E-field generated from precipitation static, or static discharge inside the cockpit.

MR. SMITH: A place like the . . . (Unintelligible).

MR. KENDALL: Very seldom. In the cockpit with new digital controls there's a lot of button pushing, I understand, selecting frequencies for radios, selecting headings, and inputting data to the computer. In those modes there's a lot of human contact involved.

MR. SMITH: Realistic for cockpits to . . . (Unintelligible).

MR. KENDALL: Exactly. The black box that might reside in the electronics or avionics bay would not necessarily have to be tested for this. This would be something that would be simulated. You would have to do the induced test, because cables could see this transient on them and would stress the adjacent cable. But as

far as a direct discharge to the electronics in the avionics equipment bay, it wouldn't have to be stressed, only where you're going to have physical contact with the equipment for lightning or precipitation static. Those might be exceptions.

A QUESTIONER: Do you do any test at all by varying the ground potentials of the two boxes?

A QUESTIONER: It won't make any difference?

MR. KENDALL: No, we found this is too fast that the grounds are already infinite. They're already electrically long in separation, so whether you bond them or not is immaterial.

A QUESTIONER: Is there any particular manufacturer that makes the type of equipment used to generate the arc?

MR. KENDALL: I suggested three. One is the new Andy Hish simulators, called the electrostatic simulator. He's, I think, in Chatsworth, California. I think his is the least expensive. It's around \$2000. The other company is Experimental Physics Corporation. I think they're in Sunnyvale now. EXPX is their abbreviated company sign. And then Schraffner, a German company. There's also another company's simulator that the IBM Company uses for large equipment, which isn't exactly applicable. It's made by the Zapper Company in San Diego.

Is there a question here?

MR. THOMAS: Ron Thomas, Sperry. Can you control the source impedance of this simulator?

MR. KENDALL: Yes. We'll get into that now. These probe manufacturers will build just about anything you want, as long as the price is right. They use a good-quality, high-frequency-rated, high-voltage capacitor, or capacitors, in the buildup of the generator. Then the output goes through a resistor for which you can select different values to the point of discharge of the probe. One side of the capacitor goes to ground - the high-voltage charging source connects to the other side of the capacitor through a large valve resistor.

The charging supply is a variable power supply. They vary the voltage. They take a very high resistance value and they charge the capacitor. Then the discharge resistor varies from 100 to 1500 ohms, depending upon what you're trying to simulate. This is now the commercial type of test. That is because there are different resistances to the human body. Some of you are "saltier" than others, and your resistance is either lower or higher. The human body typically has a high resistance value. But when you take a key out of your pocket and discharge through a key, then things change drastically and the resistance becomes lower.

The concern is that the value of the capacitor in most of the models used is based on the human body, or that which would be charged in a piece of furniture. In the case of an aircraft, it would be the seat that the pilot or crew sits in. That represents a given amount of capacitance. Typically the value of capacitance used today is about 150 pF.

That also varies a little bit, and usually is selectable from about 100 pF to as high as 500 pF.

Some static discharge tests are required by the military for electro-explosive devices, and they use 500 pF. There's a difference, of course, in the commercial sector. They're not looking for a 100% cure. They're interested in maybe 95% of their products not having problems. In the commercial world, they're running a probability game that might be different from yours, and they may use different values which will not result in the same stress levels. They're looking for the average probability distribution for discharge from the human body, or a cart, or furniture.

With 150 or 500 pF (again with 150 being the more common value) as the discharging capacitor value, and with the 100- to 1500-ohm resistor, these two parameters affect the stress that you will put on a particular system. In avionics systems, these will have to be reviewed in terms of the P-static and electro-static discharge conditions normally seen in aircraft. With these parameters in mind, we can find a reasonable value of capacitor and resistor that would represent a true situation and a true simulation.

The main thing is rise time. You have to concentrate on rise time, and that's going to be determined by the quality of that capacitor and the way it is built into the probe. That will be a very important part of this stress.

As you do this test, you want to maintain that rise time. You also want to maintain a reasonable energy level of stress that's realistic, so that you are properly testing. Voltage also is going to be a key issue.

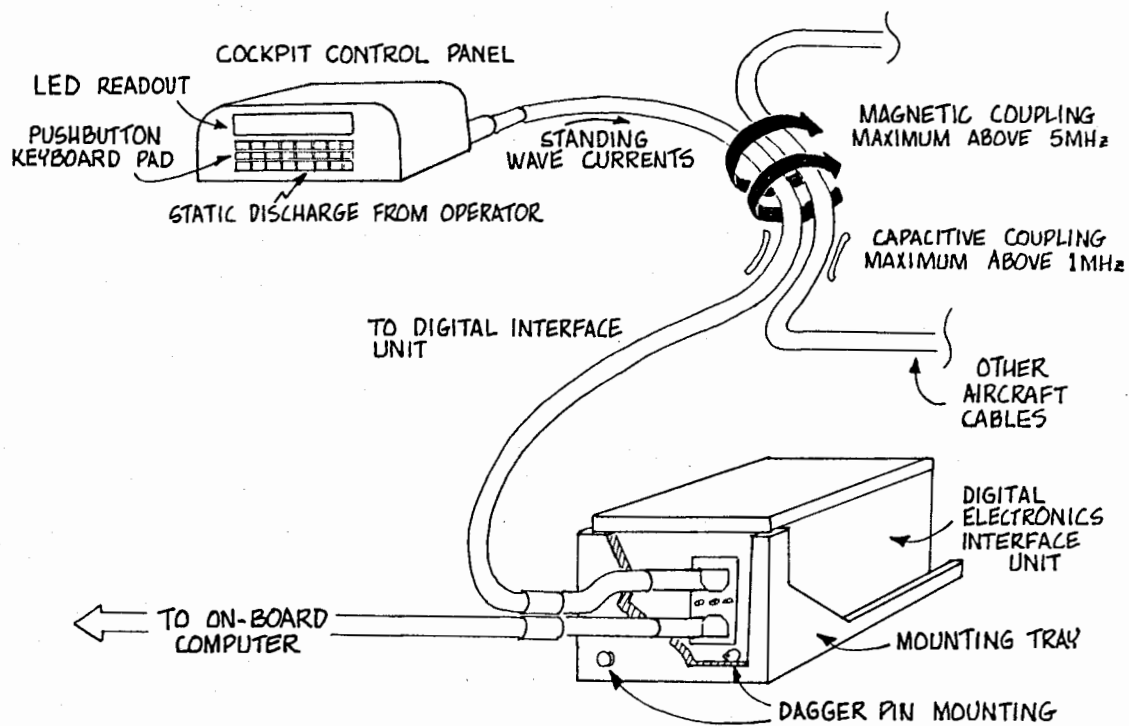


Figure 14-1.- Example of concerns for digital avionics.

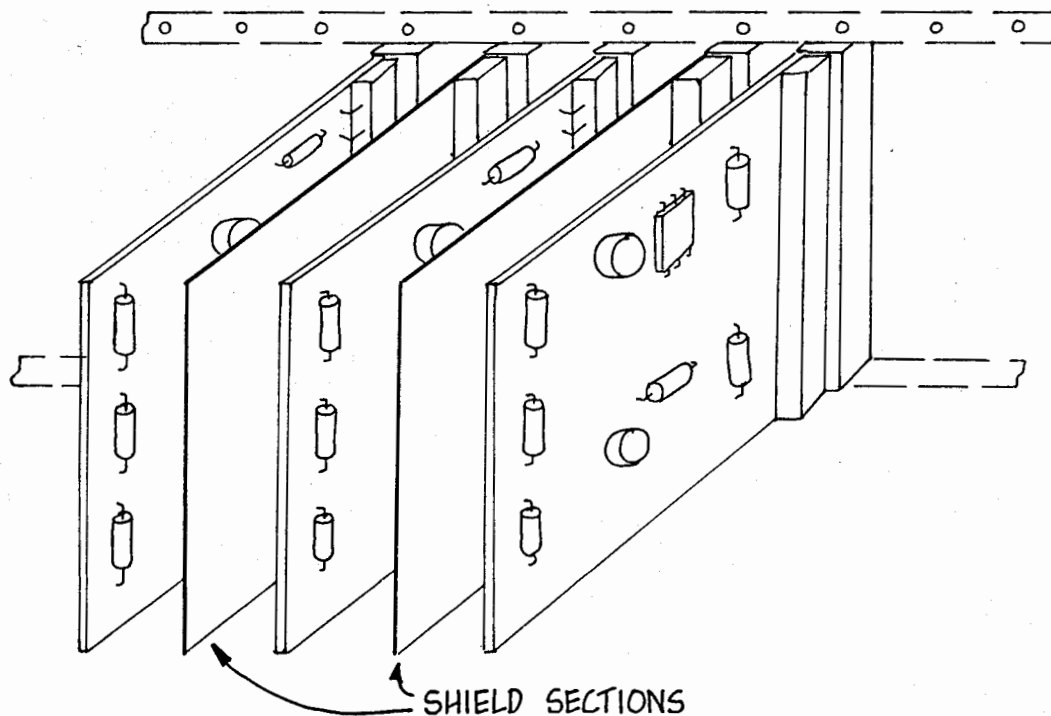


Figure 14-2.- Protecting against board-to-board coupling.

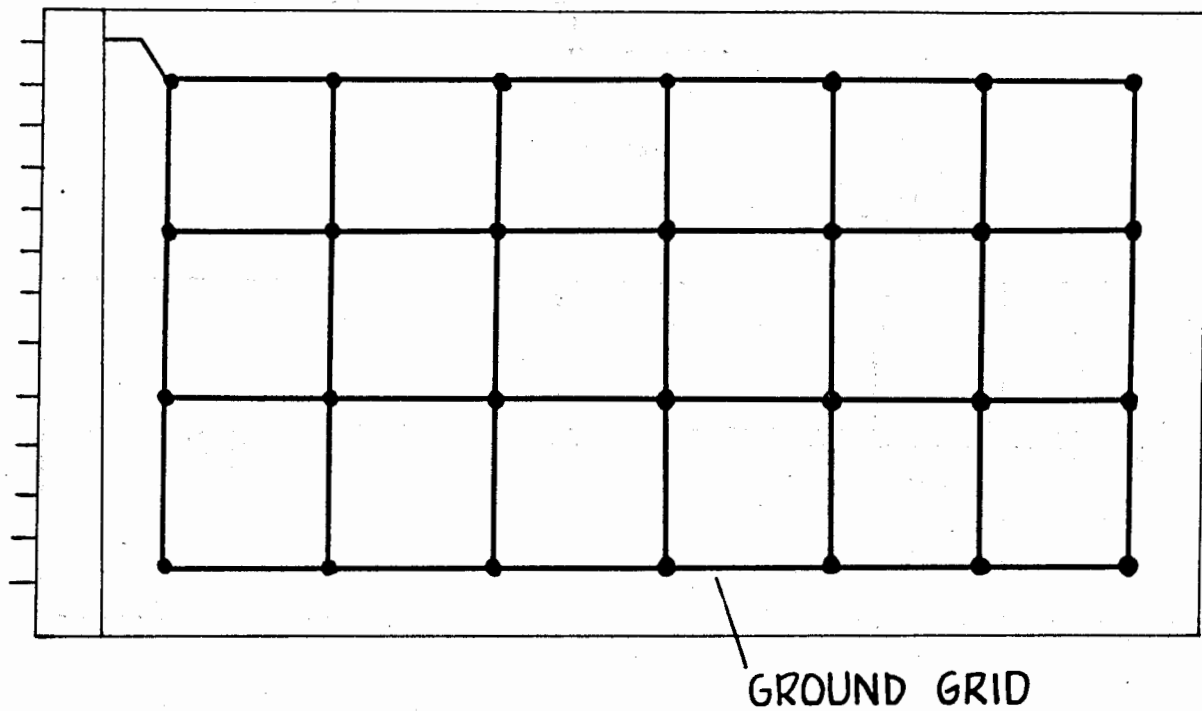


Figure 14-3.- Typical PC board ground plane.

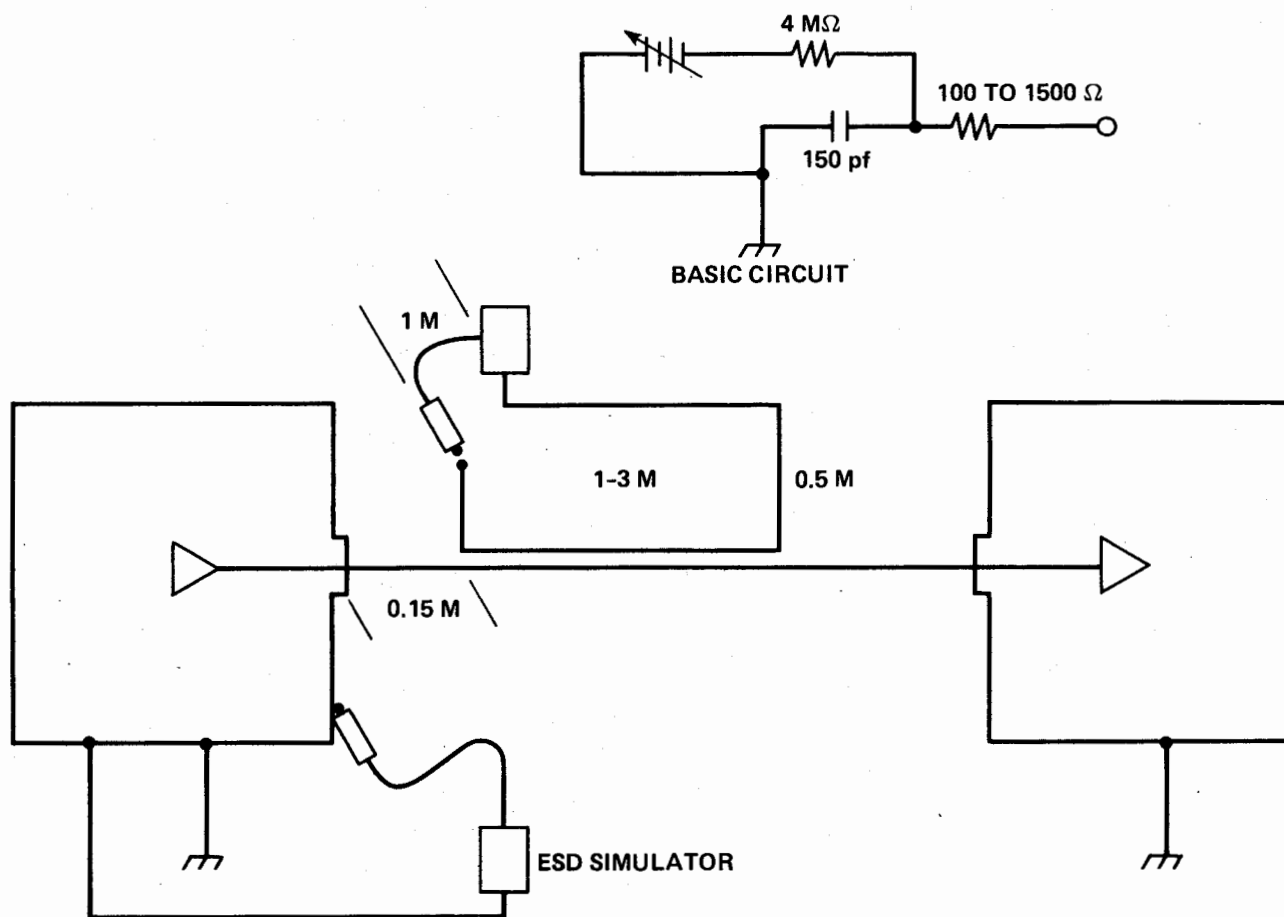


Figure 14-4.- Fast rise time electrostatic discharge testing.

EMI HARDENING CRITERIA

Developed for Aircraft Including a Transient Study of the MIL-STD 1553 Data Bus

Cliff Scouby

McDonnell Aircraft Company
St. Louis, Missouri

MR. RASCH: The next presentation will be EMI hardening criteria, and it will be given by Dr. Cliff Scouby from McDonnell Douglas. Dr. Scouby received his Bachelor's, Master's, and Ph.D. degrees from the University of Missouri, where he specialized in statistical communication theory and system modeling. He served as a member of the faculty at the University of Missouri in Rolla for 5 yr prior to transferring to the McDonnell Aircraft Company.

For the last 10 yr, Dr. Scouby has specialized in electromagnetic analysis and system modeling. Dr. Scouby has applied computerized models to solve various EMI problems in the area of EMC, lightning, and EMP. He conducted investigations on the EM effects of composite materials, which include EM shielding, lightning damage, and triboelectric phenomena.

Dr. Scouby is presently directing his efforts on design concepts for the next generation of fighter aircraft. Dr. Scouby.

DR. SCOUBY: Thank you, Nick.

As Nick said, I'm filling in for Gus Weinstock rather suddenly. Gus is Mr. EMC at McDonnell Aircraft, and I wouldn't presume to be able to answer all the questions that he might be able to, with regard to the details of EMC design that we do.

These are his charts,¹ and I had a chance to look them over and I think I know essentially what he wanted to say.

What I'll do is go through Gus' charts, and if you have any questions, feel free to ask at any time.

I'll start by talking about the antenna-to-antenna coupling and then get into air-frame shielding. The air-frame shielding is one of the big items that we have worked on in recent years (particularly since we've gotten into composites on the newer aircraft) and then proceed on down the line to — I don't have anything on aircraft demonstration insofar as the presentation is concerned, but that is the last item of the EMC program that one has on an airplane.

Several years ago McDonnell had an antenna-to-antenna analysis program, a computerized program that was developed, and subsequently was enlarged to a more general program which the Air Force now calls IAP. The part of intrasystem analysis program function that we generally use within the company is antenna-to-antenna coupling.

¹This speaker's vugraphs not available at the time of publication.

I'm told some of our airplanes, and keep in mind they're pretty small, have some 65 antennas on them. So it's a considerable problem to keep them from interfering with one another.

And the way that's approached is, not only using previous designs, but also using the antenna-to-antenna coupling analysis program to calculate what kind of power densities or the actual amount of interference that would be expected between systems that are antenna-to-antenna coupled.

There are other aspects to this generalized program, but by far the most useful in our experience is the antenna portion.

The second element that we get into is fuselage shielding. I don't suppose this is any different from how anyone else does it, but generally you start in the process of systems EMC design with deciding what your external environment is and what kind of shielding you can expect to get out of the fuselage. Then get down to what levels the boxes see and so forth.

Now, this has been an area of considerable concern, and the subject of extensive efforts at our company over the last few years, primarily because of the composites that we're putting on vehicles.

On the F-18, a graphite/epoxy composite covers the avionics bays where the equipment is located. Pretty much all of the avionics bay doors are graphite composite. Before we went through this program our concern was just exactly how much additional problem was that going to cause, particularly since this is essentially a fly-by-wire aircraft.

The AV-8B has considerably more graphite/epoxy than the F-18. Part of the difference in terms of percentages by weight is that the AV-8B has a large composite substructure, whereas on the F-18 the composites are essentially just on the skins. For example, the wing area is completely composite, with just a few exceptions; certain parts like the pylons mount are metal, but for the most part the wing is one composite piece.

MR. SMITH: What are the other materials . . . ?

DR. SCUBY: A combination of things.

MR. SMITH: Of fiberglass and . . .

DR. SCUBY: Well, I don't think there's any fiberglass included because this particular vehicle, at least the current model, doesn't even have a RADOME.

There are several pieces that are steel, and there's a little bit of titanium in a place or two. I really can't tell you what those things are. You're asking hardware questions now. I don't know about hardware.

A QUESTIONER: Did you do any conduction tests on that wing?

DR. SCUBY: Yes, we certainly did. But I hesitate to get into that at this point. If you want to ask that question at the end, I'll be happy to outline what we did.

There were fairly extensive lightning tests done both on the F-18 and AV-8, and there are some things that I think very much need to be done that I don't know of anybody doing. In fact, I'm on a little bit of a campaign to get somebody to do some of those things. So I'd be very happy to talk about that a little bit later. Yes?

MR. ZIGLER: Murray Zigler, Sikorsky Aircraft. I just wondered how you got continuity from the graphite to the aluminum.

DR. SCOUBY: Let me defer that to later. I have some slides that address that topic.

MR. ZIGLER: Great.

DR. SCOUBY: Anything else?

Okay. I'm not sure why this particular chart was included, except it goes back to the beginnings of when we started doing work on composites and we wanted to know what the performance of the material was, irrespective of the way you put the thing together. It turned out to be a considerable problem, but one of the ways we found that worked pretty well was to build a coaxial fixture and make up what amounted to washer specimens and mount them in the center. By doing this you can get what is the equivalent of plane wave shielding effectiveness of the graphite. This was about 1975.

It turns out, as most of you have probably seen, that the performance of a graphite/epoxy, which is the primary material that we used (I should qualify that, because there's clearly a variety of possibilities, depending on the details of the composite) has conductivities that average around 10^4 in MKS units; 2×10^4 is an often-quoted number, and that is sufficient for shielding performance in the neighborhood of, say, 60 dB or better for the typical kinds of skins you may use. It's more than adequate, generally, for what we're looking for, insofar as the performance of the basic material is concerned. But the real problem comes, as alluded to by your question a moment ago, in how you get continuity between panels.

Speaking of panels, we tested a large number of panels of various forms, and this happens to be one of them. This may not be a good example. But the panels we tested utilized all kinds of joining methods. We tested them for several things, including shielding performance and joint impedance.

Since we've already mentioned transfer of lightning currents, here is a list of panels we did in one particular test series. This happened to be a test series that was done for the AV-8. We did a similar series for the F-18. This will give you an idea of the configurations that were tested.

Generally speaking, what was done is shown in this vugraph. This example is aluminum/aluminum.

It's very difficult, depending on the kind of tests that you're doing, to get absolute numbers, because things tend to become dependent upon the particulars of your test setup. So what we generally did was to compare performance to something that we were familiar with, and that usually happened to be aluminum. That's what we did here.

There was an elaborate data reduction performed on the data for these sets of panels. The bottom line was that the performance on almost any of the tests depends on the joint impedance, the bond from one part of the panel to the other.

Here is one example of a panel that was mounted on a box. There was a source inside the box, a receptor antenna that was moved about on the grid on top. There was a seam across the top, and the readings were plotted as a function of position across the top. As you would expect, the highest readings occurred in the area of the seam.

A QUESTIONER: What frequencies were these experiments done at?

DR. SCOUBY: I can only guess at the frequencies now. I remember there were test data taken from about 100 kHz to 18 GHz. However, that's not to say that's what was done in the test setup I just showed you. It was over the primary frequency range of concern, though.

A QUESTIONER: Will the relative performance of these composites essentially be better at low frequencies?

DR. SCOUBY: It's not constant with frequency. It's hard to make categorical statements about that sort of thing, but that tended to be the case. What we're talking about here is the situation in which the predominant reason for leakage, we're talking about EMI problems, is the relatively poor bond at the seam. The only conductive part of the composite are the fibers, which are difficult to connect to electrically, difficult to make a bond to.

Ordinarily the ones that did well did relatively well over the entire frequency range, although of course it wasn't constant in frequency. But as I understand your question, you wanted to know whether ones that did well at low frequencies also did well at high, and yes, that was generally true.

MR. SMITH: How about the higher frequency?

DR. SCOUBY: Well, that sort of thing, if I understand you correctly, is more or less what you would expect.

In the cases in which you are relying upon conductive connection, now you use rivets or fasteners of some sort. That is, if you take two panels that have conductive connections and one has fairly good connections and the other hasn't, the one with the good connections will do better across the frequency band. If you are dealing with conductive connections, but you have a considerable overlap in the panels so that at high frequencies you have a considerable capacitive coupling between the two panels, then you find that the capacity of the coupling becomes the dominant factor at the high frequency. So while it might be poor in low frequencies, it may do quite well in high frequencies. In fact, on some of the F-18 avionics doors, we relied on this capacitive coupling effect to achieve high-frequency bonds.

I had that for the F-18. I can't give you a general answer, because it depends on the application. But I have some that I can show you for the F-18. As for the structural joints, we have found the best electrical joints are simply those that have very close tolerances on the fasteners.

What you really like to have is interference-fit fasteners in the holes. Since you can't do that with the composite material, you want them simply as tight as you can get them. You use lots of fasteners that fit as tight as possible; that gives you the best structural joint.

Now, that's not to say that it's not possible with laboratory kinds of joints to do better, but in terms of any actual manufactured items, we've never been able to do better than that. It's even hard to do better with coatings than it is with a tight fastener through the hole. So good structural joints is the general answer to the question. When you talk about bonding doors — well, that varies somewhat depending on what it is you're looking for and what kind of restrictions you have.

MR. SMITH: Thank you.

DR. SCOUBY: Here's a list of the same panels for a different test series. These panels were tested for joint impedance, essentially by running a current from one side of the panel to the other and looking at the voltage profile across the panel as you did that. And as you would expect, the profile was a gentle slope over the graphite section and an abrupt change at the joint.

The idea was to quantitatively distinguish between the performance of the candidate designs for the joints. That turned out to be a difficult job, because there was similar performance for a variety of the joints. There were also a lot of other factors — I can sum it up by saying it's hard to define performance ahead of time.

A real problem area is the joint that is susceptible to corrosion. By the time you're able to achieve appropriate corrosion protection, you can't get the kind of bond that you wanted to get between joints. At any rate, we ran this test so we could get a quantitative measure of the performance of the different type of joints.

Here is something similar to what we've been talking about. It's a sketch of things that were done for the AV-8. The AV-8 forward fuselage is essentially entirely composite material: the skin, the substructure, and the stiffeners are. On the F-18 we had avionics bay doors that were composite. (I'll get around to some of the details of how those doors were bonded in a few moments.) On the AV-8 the entire structure was composite.

Before finalizing the design, there were a number of tests that were done, and this is an illustration of one of them. A facsimile of the lower portion of the fuselage was built, except, for economic reasons, it didn't have the curvature of a section of actual fuselage. It was built out of graphite/epoxy in the same way that was intended for the forward fuselage, and there was a corresponding mate fixture that was built out of aluminum. Then a number of tests were performed to determine their relative EMI performance. Here is a picture of that composite box.

There is a door along this side, and there is also one in the bottom. I believe there's also one on the other side. There's a group of connectors and switches along the end that enabled us to make connections to cables. I don't have a schematic to indicate exactly where they ran, but there were a variety of different cables, or wire bundles, that ran around on the inside of this box, some of which ran right beside the seam that was formed by the access panel. The

idea was to find out how much pickup could be measured for the graphite box, for these various wire configurations inside, and how it compared to corresponding measurements that were made for a metal box.

This is a comparison of the test results of the test in terms of shielding effectiveness. This is a composite fixture here and a corresponding metal one here. These were from earlier tests. But the results are comparable in that the measurements indicated that there is relatively little difference in shielding effectiveness between the aluminum and the graphite structure.

Keep in mind that what dominates these data is the leakage around the access doors. Whether these two correspond will depend on whether there's comparable leakage, which in turn will depend on whether there is comparable bonding.

Basically, the metal structure was built without concern for the bonding, whereas the graphite structure was built so as to achieve as good a bond as possible.

With that stipulation, you end up with shielding performance that's comparable, which is not to say that if you bonded the metal as well as possible, it would give comparable performance, because it won't. Or that if you put them together the same way they would be comparable, because again they won't. If you expect comparable performance, you must take pains to bond the composite, whereas in aluminum construction, or metal in general, you usually don't have to be so careful about bonding. Except in cases where you have anodized coatings; that certainly can cause problems.

A QUESTIONER: Could you show that again, please. I'm just curious, above the 1000 MHz, what's the reason for all the vagaries on the other aluminum?

DR. SCUBY: The way I recall this was that there was a measurement made on the pickup of a corresponding wire. I think these were actually individual wire pairs. I think there're probably twisted, shielded pairs. Whatever kind it was, there was a measurement made for pickup on the outside versus pickup with the things inside the fixture. That's what you're looking at.

A QUESTIONER: Fine. And then I'm sure . . . how many gigahertz there . . . or is that epoxy fairly large . . . (unintelligible) . . . of weight . . . or aperture considerations . . . I'm wondering, what's the reasoning for all that?

DR. SCUBY: I really can't answer that question. In the first place, I don't know that I recall the particulars of this one. In the second place, I do recall specifically that we conducted a variety of tests that were comparable to this, with different fixtures. This is characteristic of what you get. If you do a good job of bonding the composite, you get curves that do pretty well, particularly if you're talking about a pickup medium that's sensitive to the electric field portion. However, someplace up in the gigahertz region, you start getting all kinds of variations.

Those variations depend upon the test setup. Very distinctive. They're going to be different for each setup that you have, for each fixture. So if I take these particular ones and I look at this variation, it won't be the same as it was for the other box.

In a general sense, it has the same characteristic form, but those parameters are clearly dependent upon the details of the structure.

A QUESTIONER: It's probably just reflections of additions and subtractions due to the inclusion. You have that no matter what. But the size of the enclosure probably incorporates the effects of the higher frequencies.

DR. SCUBY: Clearly when you get up to this frequency regime where the thing begins to appear relatively large, you expect to see some phenomena of this sort.

The details of precisely the fields inside these structures are hard to evaluate, and no attempt was made to do that on any of these structures, primarily because it was just too big an effort. What was intended was to get a general comparison between the performance of the metallic aluminum structures and the composite structures, putting the aluminum structures together in the usual way and taking pains to bond the composite structure.

That's clearly the general reason. The specifics of it, as to the molding inside, the field configuration — who knows? It's undoubtedly complicated.

A QUESTIONER: The only thing I have to ask is, you're not really trying to make a hard comparison between one box and another box?

DR. SCUBY: That's absolutely right. In fact, you can't do it.

A QUESTIONER: Okay.

DR. SCUBY: At lower frequencies you probably could do that reasonably well, but you can't at the higher frequencies, which is one of the big reasons you have trouble with the designs. In general, it's not possible to build the exact structure in the desired configuration ahead of time, and it certainly is going to depend on those details. So you can only draw general inferences about the kinds of things that you need to do in order to get good performance out of the composite and good guesstimates, perhaps on the region of shielding under test that you expect to get.

But you can't depend on what the specifics are going to be on the test articles that you do ahead of time. If you really want to know what it is, you have to test the actual thing. Even then you get in trouble, because things like whether or not a box is in place in an avionics bay makes a difference on the pickup on a particular wire. So there are just too many factors that relate to geometric complexity that cause you to be unable to get exact numbers. That wasn't what this was intended to do, particularly not in the high-frequency regions.

MR. KENDALL: I notice that in the 10- to 20-MHz range, there appears to be a definite degradation appearing. Do you know this since you ran the test at only 4 MHz?

DR. SCUBY: You are talking about downward in frequency?

MR. KENDALL: Yes. The lower end looks like it's heading down drastically.

DR. SCUBY: Well, these particular tests were not conducted at those frequencies, but to give you a general answer to that question, if you're talking about a

sensor which is an electrically dependent, high-impedance type of antenna, electric field shielding effectiveness there, then it does not significantly degrade the frequency. Quite the opposite is true if you're talking about magnetic shielding effectiveness; I think that's clearly the case. If you get low frequencies . . . if you had the frequency scale shifted and you're looking at magnetic shielding effectiveness, even for aluminum, it's going to do like that.

MR. KENDALL: I'm assuming the . . .

DR. SCUBY: Well, this was not either, although it's more E-field-dependent than anything else.

MR. KENDALL: (Question unintelligible.)

DR. SCUBY: There were three different antennas used in this particular one. I'm not sure which one this represents, but they are more high-impedance than anything else.

MR. KENDALL: Do you find, then, this was a magnetic test?

DR. SCUBY: No. This was done to find the relative performance of the two fixtures, and the antennas that were used were ones that we could fit into the structures, and that gave good sensitivity. I think there was a disk combination antenna that was used, and I'm sure one of the tests used a rod antenna. I'm not sure on this set of tests. It's clearly not this one, but there was a loop antenna used on some of the tests. But this is not magnetic shield effectiveness at all. If you can say it's one or the other, it's electric.

MR. KENDALL: Okay. That's why I was concerned. Is there any chance for that, other than what you're trying to say now?

DR. SCUBY: I don't know specifically why it looks like that. On the test in which we went down through 100 kHz with antennas that I think would be comparable to what we have here, I don't recall any significant degradation at lower frequencies in shielding effectiveness.

Okay. I mentioned the AV-8 composite wing earlier. We used the actual hardware as a test article. We took one of the earlier wings and did tests on it; you can see the radiating horn in this case. There were sensors and wires inside the wing. This is one side of the thing. This is a one-piece wing that goes across the top of the airplane; what you see here is essentially half of a wing.

This is in regard to graphite/epoxy performance, and doesn't say anything about lightning. I'll try not to get into lightning right at the moment. We can talk about it later if you like.

The inherent shielding effectiveness is quite adequate. By "inherent," I mean that it is independent of the joints and seams, considering it to be in the context of a plane wave shielding of a panel with no seams.

The fixtures don't show any significant reduction of shielding effectiveness due to the seams other than the stipulations I've already given.

The structures we found that we can put together with the graphite give adequate performance. One illustration of this is the F-15; it's got some composite on it, but it doesn't have any in the avionics bay. It's back in the tail section mainly, and on the speed brake.

The access doors are all metallic, and we found by actual measurements that the performance of those doors is not as good as it is on the F-18 designs. The F-18 doors are composite for which a considerable effort was made to bond the joints. I'll show you some details on there in a moment.

MR. VENUTI: Are you looking at any composite material other than graphite/epoxy?

DR. SCUBY: Not really. The graphite epoxy is the one that we expect to be using almost exclusively for the foreseeable future, and we haven't looked at any of the others. We don't, for example, get into KEVLAR or any of those sorts of things, as missiles or helicopters (for example) do. We don't see any significant application of that, and so we've really restricted ourselves to the graphite.

MR. SMITH: Does the last statement include lightning occurrence on the seam of the aircraft?

DR. SCUBY: This was not intended to include lightning.

I don't like to give a general answer for lightning currents, because I think we've done enough testing to know where that sits, and we have answers to most of the problems with regard to lightning. There are some answers that we don't have — those pertaining to the specifics of some composite designs. So there are some areas of lightning that I think need some additional work and this is not meant to include that.

MR. SMALL: John Small, Boeing. Do you use conductive gaskets around access holes with graphite/epoxy to provide additional shielding?

DR. SCUBY: Yes, to some degree. Although the problem with conductive gaskets is essentially no different than it is with any other kind of EMI tight bond for composites. The problem is, how do you bond the gasket to the composite? We found this to be a significant problem, particularly to a gasket that will remain a good conductive bond over whatever environmental conditions the equipment may happen to encounter. I should qualify the "yes" by saying the EMI gasketing has evolved down to finger stock rather than more sophisticated gaskets. And that's not meant to imply that it's exclusively that. But that seems to be the most practical, both in terms of doing a good job initially and remaining pretty good throughout a reasonable lifetime. I'll add just a little bit more on that in a moment or two.

Now we're back to a general concept of EMS for aircraft design, which is to say that we're back to the fuselage shielding idea. What I've said up to now is essentially aimed at the specifics of how we decided what kind of designs to use that would give us adequate shielding for the composite joints.

For areas that are unavoidably open (the wheel wells, for example, when the wheels are down), there were careful measures taken to make sure that we get good shielding out of the fuselage over all of the area. I will now address the screening of the areas that are exposed, and overbraids or extra shielding

(of some sort) on the cabling that runs through the areas that are not EMI tight, for example, the wheel wells.

That screening takes forms I'm sure you're already familiar with (at least it does except for composites). We've done some extra things for composites. This shows an example of screening that is put over what could be an EMI aperture.

This slide gets us into the composite door bonding. It shows a little more detail on what was done (this was essentially an F-18 design) in terms of this particular configuration.

The difficulty with bonding access doors was (1) making good conductive contact with the composite that forms the door, because these doors are thin; and (2) maintaining something over the lifetime of the vehicle.

In this particular case, beryllium copper spring fingers were used -- shown here and around the periphery. This combines with a silicon rubber form-in-place seal as an environmental seal. Then you have the beryllium copper spring fingers with the compression stock. Aluminum tape is then laid over the composite, which enhances the high-frequency capacity coupling between the spring fingers and the composite.

At high frequencies, well, at all frequencies, you have a problem with adequate conductive contact with rivets (or whatever you put through a thin structure like this) bonding to the spring fingers.

A way to circumvent this particular difficulty of bonding, which seems to work very well, is to put a 2-in. strip of aluminum around the door. This forms a capacitive coupling between the conductive part of the composite and the spring finger strip. This design, or some variation of it, is essentially what is used on the F-18 doors to achieve bonding.

DR. AUCKLAND: As I understand it, the door panel itself is about 5 mils of composite sandwiching honeycomb

DR. SCUBY: It's not 5 mils; 5 mils is the thickness of the tape that's laid up to make up the door panels. The door itself

DR. AUCKLAND: I was going to say that there's an aluminum honeycomb, I think, inside two of the composite panels, inside and outside, that make up the door panels. Is that correct?

DR. SCUBY: No. Not for this. There's no aluminum honeycomb there. We've stayed away from aluminum honeycomb for a variety of reasons, partly because of lightning. If you have aluminum honeycomb and get hit by lightning and it punctures the outer skin, the aluminum honeycomb will be a preferential current path for the lightning, and it can vaporize a considerable portion of honeycomb. The outgassing from that vaporization can blow through into the inside.

There are other problems, but the lightning is certainly one of the worst as far as aluminum honeycomb core. You have to be careful where you use the honeycomb.

DR. AUCKLAND: This current is pretty much capacitive coupled to the inside surface of

DR. SCOUBY: It's both. The fasteners aren't really closed, but for high frequency it's primarily capacitive coupling, yes.

MR. BOTOCKI: Botocki, Airbus Industries. Do you end up with any corrosion problem between the aluminum tape and the carbon fiber door?

DR. SCOUBY: No, I cannot recall any specific provisions that were implemented on the F-18 door for corrosion protection. That is a problem if you have moisture intrusion, because you will certainly have corrosion.

We've done a number of tests, and other designs that we've considered have been eliminated because of that very problem. In this particular case, I think the intent was to seal the thing off.

The aluminum tape is also meant to be sacrificial, in the sense that it can be replaced. The compromise — the end design — was to try to seal the thing off and make the aluminum strip replaceable, so that if and when you have problems, you simply replace the strip. I don't recall any other specific provisions.

You realize I was not one of the designers and I don't remember the specifics. But there were no provisions other than the seal, and making it sacrificial. In this case I would expect that you'd have problems if you get the door wet a number of times, especially if it's a salt spray.

DR. AUCKLAND: I may have wrong information again, but I also thought that there was a thin layer of fiberglass underneath between the aluminum tape and graphite epoxy.

DR. SCOUBY: On doors, all right. That depends on where the application was. On doors that were considered thin enough to be punctured by lightning, let me be a little bit more specific. We did a series of tests to determine how thick the panels had to be in order to prevent lightning puncture. There were some doors that were marginal, on the borderline of expecting puncture for the severe restrike situation.

The tests also indicated that if you put a fiberglass layer on the inside of the surface, it prevented puncture. The primary cause of puncture of the thin panels was (1) the heat from the lightning current itself, and (2) the shock the area took because of the acoustics, and the outgassing of the material when it heated up. Some of the thin doors do have fiberglass on the back of them.

If you have fiberglass on the back of the doors, you have to decide whether the fiberglass layer is thick enough to degrade your capacitive coupling sufficiently to cause problems, or you have to put the fiberglass only in the center area and not have it on the edge. The edge lays over the sill anyway. But that's the way it was done.

I think in most cases the fiberglass was extended on out, and the thickness was found not to be too significant in terms of the capacitive coupling.

MR. EHRET: Is that substructure graphite/epoxy?

DR. SCOUBY: No, the substructure is aluminum.

MR. SMITH: (Question unintelligible.)

DR. SCUBY: We're getting into lightning again.

All right. On the F-18, the answer is no. And that came about this way. I don't know how to answer your question without telling you the test. There was a facsimile of a fuel cell (a wet-wing fuel cell) built, and lightning tests were conducted on it. There was neither any significant structural damage to the skin nor any internal sparking which would cause fuel ignition for the F-18.

Now, what you're talking about is the structural skin. I don't know what the average thickness is, but it's ordinarily not thinner than a quarter of an inch and in a lot of places it is thicker.

The lightning penetration damage is confined to the first few layers, and we're again talking about 5 mils per layer that's essentially formed up from the tape.

The current transfer through the fastener to the substructure is probably the biggest threat. Certainly that's one of the problems that exists for all composite substructure. There was not found to be any internal arcing when fasteners were attached directly on the F-18 designs.

Testing indicated no threat to flight safety and, in fact, no significant damage. Although certainly if you got hit by a very large strike, you would need some surface repair. So there is no protection on the F-18.

MR. SMITH: Has that been changed for the AV-8?

DR. SCUBY: Well, that's another matter. Let me defer that until I finish this section. There were some other questions on lightning, and I'll also give you a bit of a pitch for some work that I think needs to be done. But yes, it's different for the AV-8.

Let's see. What you have is an access door with a hinge here in this region, and the beryllium copper finger stock around the edge. You can also see the tape on the door. It's difficult to tell exactly what this is, but it's an F-18 door.

Here is another view that shows a detail of the door up in one corner. You can see the finger stock a little bit better, and the tape around the edge.

Most of you are undoubtedly familiar with the process of overbraiding the cable. We've gotten off on various tangents, and so the continuity of this presentation leaves a lot to be desired. But keep in mind that we started talking about the fuselage shielding, and the screening of the areas that you expect leakage, and of the overbraid on cables that are exposed. This is just showing the machine that puts the dacron, or whatever, overbraid on the cables for those cases where you want shielding on cables.

Okay. That is essentially all of the charts on composites and their application, and now we're back to the original chart on subsystem EMC control.

Subsystem EMC control is essentially accomplished by these items. First of all, 461 and internal environments which we generally have set between 20 and 100 V/m (depending upon where the item is located and what the frequency range happens to be), and the external environment over most of the frequency range. On the F-18 it's considered to be 200 V/m.

Ground plane noise immunity between WRAs (that's weapon replaceable assemblies) is 600-V coupled relay transient immunity. That is a test similar to what Chris described earlier this morning. You have a relay that's wired back on itself and sits there and chatters, and generates spikes which run in the neighborhood of 600 V, generally higher. I guess this is the minimum.

Spike emission control on power lines. MIL 5087 on electrical bonding with interface filtering on all ports of entry.

And again, as Chris mentioned, the F-18 used filter pin connectors on all those places that were considered to be vulnerable. And interface circuit control grounding at the boxes, rather than WRAs.

Balanced signal circuits. There were an awful lot of balanced circuits that were used in the F-18. What was done was that early in the avionics systems layout, somebody went through and decided which systems were likely to be sensitive, and made some rough categorization of what that sensitivity was. Depending on what that happened to be, you ended up with twisted pairs, or twisted shielded pairs, or twisted balanced shielded pairs, or whatever. It turned out that on the F-18 there were a lot of circuits that were balanced.

There's discrete signal thresholding and finally there is a large amount of developmental testing.

Now, I've already mentioned, in some fashion, a large portion of the developmental testing as far as the composite EM performance was concerned. There were also large numbers of developmental tests that were conducted for wire coupling, and decisions were made based on those test results. That's essentially the basis of the subsystem EMC control.

Okay. Down to avionics installation — this chart lists reasons for concern (say, on aircraft like the F-18 or the AV-8) above and beyond what the concern might have been for a previous aircraft (such as the F-15, which was pretty much designed in a traditional fashion with essentially an all-metallic structure).

The digital systems are obviously one of the big concerns. Composite structures — we've already been on that for quite some time.

Receivers which are more sensitive, and we've certainly seen some problems with that. F-4 problems have cropped up in recent years — I'm referring primarily to P-static problems that didn't show up at all with the equipment that was previously used, so increased sensitivity of equipment certainly makes a difference.

The reliance upon avionics for flight-critical systems can most succinctly be said to be fly-by-wire systems. You must take very great care if you have an exclusively fly-by-wire system. The F-18 is not exclusively fly-by-wire, although it is such a system. We probably have less in the way of protection considering that there is some mechanical backup, enough to be able to survive with than we would have had if the thing was strictly fly-by-wire. We certainly went through the design in a great deal of detail, and tried to have reasonable confidence that there wouldn't be any problems even with the fly-by-wire system.

Okay. We've reached installation provisions. This is mainly on the equipment boxes you use, and how those boxes are grounded. Over the years we have taken great care to make sure that the boxes have adequate grounds, and there's a chart here showing one of the ways that we did it.

The chore of deciding what kinds of wires to use early in the game extends beyond simply deciding what type of circuit to use, because the wires are also categorized as to power, signal, chassis, and those with shields. That enables you to do more of a thorough job of segregating the ones that are likely to be susceptible in preventing power from interfering with the circuits that are likely to be susceptible to it. It's mainly the bonding of the equipment and the proper segregation of the wiring.

Here is an example of the bonding of a box which has to have quick access. In this case it has "bayonet" mounts. The pins actually stick out to engage (here is the mate to the bayonet that fits into the box), and then you have the beryllium copper spring fingers that are on the back side that work against the side of the box. This is what has evolved as the easiest method of achieving sufficient bonding of the boxes when they're to be quick access.

Now, I've shifted gears completely. There are two or three charts on the MIL-STD 1553. On the MUX bus for the F-18, we have implemented a rounded waveform that looks like a sinusoidal pulse. Subsequently the 1553 came out with a spec as a trapezoidal pulse, and we found, through a number of tests, that there were several problems that we had difficulty coping with when we used the trapezoidal pulse. Two boxes were made, each weighing 50 or 60 lb. They are essentially transmission lines in a box which enables you to simulate sections of line and stubs and so on, and you can plug in a waveform in one end and look at what the waveforms happen to be at various points.

This chart illustrates that we found a considerable problem with distortion in the waveforms as the wave propagates from point to point along the line. This is with the 100-nsec rise time of the trapezoidal pulse. We also found that this particular pulse causes some EMI problems because of the larger number of harmonics than that waveform had.

Here is a similar waveform-input filter. I think a lot of our people have talked about sinusoidal pulse for a waveform. In fact the next chart has something called sinusoidal pulse. It's not really, but it looks more like a sinusoidal-shaped pulse than it does a trapezoid because it's rounded. This is achieved by using a square wave which gets filtered and it rounds the pulse out. That is the pulse we used on the F-18. The people who work on this for McDonnell want to be able to use it for the multiplex busing. This is the corresponding waveform for the rounded pulse. If you recall the distortion in the trapezoidal waveform, you can see that this one is much freer from distortion as you go from one point to another along the line.

This was a comparison between the two types of wave forms — the trapezoidal and the sine waves, although it's really not a sine wave. It's a rounded pulse as opposed to trapezoidal.

I've already said that the trapezoidal wave, having more frequency components, gives us more trouble with the harmonics, and therefore the radiation control is also a bigger problem. This chart indicates that when you have a trapezoidal

wave, you must take great care with the shielding in confining those harmonics, so that they don't couple with other systems.

Now, finally — last change of pace — one thing that we have gone to, a little more than on an experimental basis, is fiber optics. In particular we have put a fiber optics link on the AV-8. These are some of the reasons we think it's worth doing. The EM immunity of the fiber optics links is obvious, so it becomes a question of whether it is practical to implement. I wish I had a chart that had some other information on the trade-off studies that we've done on fiber optics, insofar as cost, weight, performance, and durability.

There have been a number of tests to find out exactly what kinds of problems we would expect to run into if we used fiber optics links. You put the fiber optics into insulating cases, and the unit looks like a wire to the people who install them. The fibers pull and kink, and do the things the installers are used to seeing wire do. We want to know if fiber optics are going to break, and exactly what kind of performance you can expect out of them. That's one of the areas that we worked on before we got around to putting the fiber optics link in the AV-8.

You can see the link that we have on the AV-8, which goes from the auxiliary CNI panel to the CNI data converter in the aft avionics bay.

A lot of the avionics in the AV-8 are in the aft avionics bay because the front end is not large enough to hold everything.

Hector was the last one who asked a question about lightning protection on the wing. Since I like to talk about lightning, I'll say something on that before somebody asks a question.

I already told you what we did for the F-18 wing in terms of testing and what the design ended up being, which is essentially nothing in terms of provisions for lightning protection on the F-18.

The F-18 has a metallic substructure of aluminum spars and ribs, and a structural graphite composite skin, which was found not to be a problem structurally for lightning, nor was there found to be any internal arcing from it.

When the AV-8 wing was constructed in the box beam configuration that the structures people use for testing prior to building an actual wing, we borrowed it and used it to conduct a series of lightning tests. Our findings for the AV-8 were similar to those on the F-18. There wasn't really any problem with structural damage, although contrary to what was found on the F-18, there was a considerable problem with internal arcing.

There's a long, tortuous trail that leads from there to where we are today. Without trying to go through all the details: We checked a number of things to try to prevent the internal arcing, and some worked reasonably well. At least in terms of considerably reducing the amount of arcing. Nothing seems to completely prevent it. When I say arcing, you should realize I'm not talking about an inductive arc, a dielectric breakdown type of arc, and not the kind of arc that the fuels people use with their capacitive discharge probe to test for energies for fuel ignition. The arcing I'm talking about is when the current density at the transfer points, typically between the metal and the composite

part, becomes so hot that there is melting at the interface. When you have melting, you also get some vaporization and molten particles that are blown out. That's what I'm talking about.

There still is a question as to what conditions can cause fuel ignition or, for that matter, if ignition can be caused.

Boeing did a test series a few years ago that showed that you get this kind of arcing for all kinds of configurations. They also showed that under certain conditions you can get ignition. However, they generally did not test their specimens with live fuel, and so there wasn't really a quantitative evaluation of what kind of arcing causes fuel ignition. In those cases people always seemed to talk about minimum energy for fuel ignition.

Minimum energy for fuel ignition is not a good quantity to refer to for this kind of situation. What you really need to be talking about is the time-temperature profile of the molten particles versus the temperature and fuel mixture that you have, in order to find out when you're going to get ignition. It's in this area that some work needs to be done, because I've been unable to get quantitative data that will enable me to discern with reasonable accuracy under what situations these hot particles can ignite fuel.

On the AV-8 we implemented as much in the way of improved bonding as we could. We still found that there was some amount of internal arcing. We subsequently conducted live fuel tests with an actual wing configuration. We were unable to get fuel ignition under these conditions.

This, to me, is somewhat comforting but I still don't know quantitatively where we are. I don't know whether we were a few percent below where ignition would take place, or whether we had a large margin, or what.

We initially put foil on the AV-8 wing in the region where there would be a swept stroke across the wing, in the wet-wing area where you would be concerned with ignition. Subsequent to testing, at the direction of the Navy (and based on the fact that we were unable to get ignition with the actual wing with the actual fuel mixture) that protection is no longer present. All we have is the best bonding that we could achieve under the manufacturing conditions. This is in fact adequate, and gives no internal arcing for normal levels of strikes; but if you get up to 100-kA levels, you do get internal arcing.

Recent data (and Felix could tell you a lot more about this) indicates that the old ground-based statistics on lightning are off quite a bit, and that the 100-kA 99 percentile that's been used traditionally is probably unrealistically high. The recent data were taken across a large number of strikes and at high altitude.

Based on this recent data, our people generally believed the design that we have is completely safe; certainly the tests have indicated it is. If we're talking about levels of lightning which are a factor of maybe four or five typically in terms of the maximum severity (which would indicate that the maximum level lightning that you would be likely to achieve is on the order of 40 kA), then the structure certainly should be safe.

Of course, this estimate doesn't really include the region of the low-altitude strikes, which should have statistics much more comparable to the ground-based statistics that we've been using for a good number of years.

The AV-8 wing has had the foil on it in the past. We do not plan to put foil on the production model unless something changes. So that's my pitch on this aspect.

MR. EHRET: John Ehret from the FAA. What material was molten? Was it aluminum, gaskets, or the . . .

DR. SCUBY: There wasn't any internal arcing on the F-18 wing. There wasn't anything visible on film, and there wasn't anything that came off the cell. Subsequent to the results on the AV-8, however, I went back and dug up the old F-18 test article. I looked at the fasteners with a microscope, that went through the composite skin into the metal substructure, and found that there was a little bit of microscopic pitting on these fasteners, and similarly on the metallic substructure. Those pits were next to the composite skin on the fastener and on the aluminum substructure, indicating that the current had tried to transfer to the metallic substructure as soon as it got down to metal. These pits were very minute, and they had not shown up on film.

What you see in the graphite epoxy are fibers that are charred -- epoxy that's been evaporated, and on the fastener you see pits where there's been molten metal. The fastener is not making a good bond. You have a lot of contacts around the shank of the fastener.

The current has just too high a density to be carried without melting at those points. You get melting of the metal in the high current density points. It can be any kind of fastener, it doesn't really matter. They are only metal, and it doesn't matter whether they're stainless or titanium, or whatever. You get some amount of pitting, the titanium not quite as much as the stainless; you have melting of both.

MR. PHELPS: Dick Phelps, Pratt & Whitney Aircraft. Your slide showed a metallic overbraid on the cable-exposed area. Is that a ferrous material or is it copper?

DR. SCUBY: It's not ferrous. It's plated.

MR. PHELPS: Is that applied over cables that are already shielded?

DR. SCUBY: Yes. The only place it's applied over wires that are already shielded is in the exposed areas like the wheel well. I don't think there's even any in the cockpit, which is somewhat exposed, although the wire bundles are recessed down inside the cockpit.

In fact, what we did was to try to categorize the regions into a clean region and a dirty region, and the wheel well is obviously exposed. You try to have a conduit for the wires to run through in the wheel well. It's not practical to use a rigid conduit. So you end up using the overbraid, which gets bonded carefully at both ends where the run goes through the bulkhead to the clean areas.

As far as I recall, the overbraid is applied only in the areas that are directly exposed, although there was some early consideration to some other areas. But I seem to recall that they were concluded to be safe.

ELECTRICAL POWER DATA ACQUISITION UNIT

Hardware Has Been Developed for Recording Anomalies on Aircraft Electrical and Electronic Systems

Robert Norton, Ted Thomas, and I. Mehdi

The Boeing Company
Seattle, Washington

MR. BOGARD: Gentlemen, I'd like to introduce to you the next speaker. Mr. Robert Norton works for the Boeing Company in lightning data acquisition. He graduated from the California Institute of Technology, with a B.S. degree in physics in 1969. He received his Master's degree in physics from the University of Washington in 1970. He's worked in various parts of industry in the area of infrared and optic data acquisition and research. Robert Norton.

MR. NORTON: I'm going to briefly describe an instrument that was built at Boeing with independent research and development money. The program was started at Boeing about 5 yr ago with the awareness that there wasn't any in-flight-acquired lightning data. Consequently a program was started to develop instrumentation that could acquire in-flight lightning strike data, and record the temporal properties of the lightning waveform. The idea was to acquire the data around a desired trigger point, both pretrigger and post-trigger data.

The objective was to keep the instrumentation relatively inexpensive so that it could be put on a number of aircraft at one time. We are investigating that possibility with the Navy. It had to be highly reliable and fairly rugged, because some of the applications would require it to be flown into turbulence and thunderstorms. We wanted the instrument packages to be modular so we could make modifications of the instrumentation fairly easily during the process of acquiring data, so that the different parts of the system could be changed independently of each other. It also had to be self-contained and not require operator intervention. It would take its data based on the preset trigger levels, record it, and then set itself for a new strike. We wanted to get pretrigger data as well as post-trigger data.

This vugraph¹ shows a rough block diagram of the system. There are three main parts: the sensors, the front-end system or the transient digitizer, and the data logger. The sensors we've used are high-frequency, high-bulk-current sensors; a shorted-turn or loop-type sensor; and a shunt sensor. The front-end system acquires the data continuously from sensors, converts it using high-speed analog to digital, and then stores it in a solid-state memory.

Once the desired trigger level is reached, a time delay takes place during which additional data are accepted, and then the memories are locked and the data held. The trigger information is also passed to the data logger system, which then goes through a pulling sequence, and accepts the data from each of the front-end systems.

¹Vugraphs for this section not available for publication.

Theoretically we can have up to 256 sensor/front-end system combinations on a single data logger. But in reality you wouldn't want that many.

The connection between the data logger and the front end is a data bus, twisted-pair or coaxial cable, or fiber optics. It is flexible in terms of the way it can be connected. In a few minutes Ted Thomas will be telling you about the modification of the basic architecture for a different application.

The data logger itself is microprocessor-based, which allows flexibility in the changing of the front-end systems and the arrangement of the sensors without having to make hardboard changes for most cases.

The mass storage device can hold in excess of 1 megabit of data. The data logger after receiving the trigger signal, waits a certain amount of time for the lightning transients to calm down, and then begins a pulling sequence, accepting the data from each of the front-end systems.

Once the data are accepted, a header is added indicating the time and other information regarding the data that were acquired.

The system also has a display system on the front in a position for an operator to observe which parameters were recorded.

DR. MASSON: Do you know offhand what kind of microprocessor you are using?

MR. NORTON: It's an Intel 8085.

This illustrates the method of pre- and post-trigger data acquisition.

Again, the data are continuously accepted, converted from analog to digital, and stored in the memory. When the trigger occurs, a variable time delay allows the unit to accept some additional data and then goes into hold, ready to transfer the data to the logger system.

Here is the picture of the instruments being used. On the left you see the data logger and on the right the front-end system, with the displays and control mechanisms on the front panel for setting the clock and making other adjustments.

What you see here are the fiber optic terminals, but we have other units that use coaxial cable connections.

This gives you a better picture of the cassette unit. It gives you the idea of the dimensions of the unit as well. It's a four-track system, high density.

In March 1980 the equipment was first put in an F106-B, part of the storm hazards program coordinated by Felix Pitts, and Norm Craig, NASA Langley Research Center. This gives you an idea of the kind of sensors that are on the aircraft. The program was designed to acquire data regarding severe storms for the design and operation of aircraft. In addition to the electromagnetic data on lightning, there are sensors for optical data, there are sensors for air chemistry experiments, and there are sensors for collecting data for a composite experiment as well. You can see the composite tail, to which a shunt sensor was added, which was flying this summer.

The first 2 yr of the program were mainly for testing the instrumentation. There were problems, as you might expect, with the first installation.

However, in 1981 we did acquire data on a strike near NASA Langley. The strike occurred at 25,000 ft, with -20°C ambient air temperature. This is the recorded waveform. The peak current obtained was about 14,000 A — a slow rise to 5,000, and then a very rapid rise to 14,000.

Late in the 1982 season we added an additional three front-end units, and an additional data logger. This was funded by the Air Force, under Rudy Bevin in the AEHP program, which Bill Cooley will be talking about shortly.

This addition will give us the capability for acquiring multilevel and multi-strike data. In essence, we'll have six channels, each with a 60-MHz sample rate, and two data loggers.

Are there any questions before I turn it over to Ted Thomas, who will give you a discussion on the power system?

MR. KENDALL: How fast a rise time can you disseminate with this unit?

MR. NORTON: The sample rate we're using now is 16.6, around 17 nsec, that is, a sample taken every 17 nsec.

MR. KENDALL: Two nanoseconds couldn't possibly be recorded.

MR. NORTON: Not with the current system, no.

A QUESTIONER: Where are your sensor locations on the 106 that can differentiate a nose-to-tail strike from wingtip?

MR. NORTON: Yes, you can. With the nose and tail, there was a sensor on the tail, on the composite section, and also on the nose. And let me show you this is what the sensor on the nose connected to the boom looked like.

In addition there was a shunt sensor on the tail. You could tell, based on the acquisition which channel was hit.

MR. PETERS: Peters, FAA, Los Angeles. Could you calibrate those sensors so that the actual current could be measured?

MR. NORTON: Yes. The sensors were calibrated on the ground with a swept CW and pulse testing in March of this year. That was before I was involved in the program. But, yes, the system has been calibrated.

MR. EHRET: John Ehret, FAA. What was the maximum voltage that you got hit with?

MR. NORTON: Well, this is 14K current, and this year, in fact . . .

MR. EHRET: What was the voltage level?

MR. NORTON: Well, the measurements on these sensors is the current measurement.

MR. ISTWAN: Where is the processor reducing the data from this research aircraft?
The flights were just terminated at the end of September, so it was pretty preliminary information.

MR. NORTON: I might add that we've had a very successful season this year with 15 waveforms acquired. And Bill's saying, it's just being reduced.

A QUESTIONER: Will the data be available?

MR. NORTON: It will be published, I'm sure, yes.

A QUESTIONER: Do you limit your trigger point or how do you set your trigger point for your . . .

MR. NORTON: You set your trigger point to a fraction of full scale, and your full scale is set with attenuators. In this case we had 25 kA on one, and on the shunt, 17; and then we set the trigger level at a fraction of that. These values can be modified on the equipment. In other words, we set it, for example, for 0.4 of the peak.

A QUESTIONER: Will your sample rates, then, possibly skip over your peak?

MR. NORTON: No. The sampling rate won't. But if, of course, the peak is lower than your trigger level, you won't get the data. That's correct.

A QUESTIONER: I get the impression that your sensor will only indicate up to a maximum of 25 kA.

MR. NORTON: It depends on the sensor and the attenuation you set on your instrument. I believe the bulk current sensor is 25 kA maximum. But our strikes to date were about half of that -- the ones we got last year were running around seven. They're obviously cloud-to-cloud strike.

A QUESTIONER: Is there a program coming up for cloud-to-ground . . .?

MR. NORTON: Yes, we're looking into that for next year. We're hoping that we can fly lower and get some cloud-to-ground data, which will be higher current levels.

CAPTAIN VOGEL: Ray Vogel, U.S. Air Force. Do you see the limitation of your 17-nsec sampling rate severely limiting you for being able to observe the actual rise time of the lightning pulse?

MR. NORTON: Not at all. In fact, we've expanded our data. I didn't mention how many data points, but in the one curve I showed, there are 12,000 data points. And we can expand it. We get numerous data points in even a sharp rise like that.

CAPTAIN VOGEL: So what is your observed most rapid rise time for lightning?

MR. NORTON: Well, this rise was in excess of 8 kA/ μ sec. The other data, as I say, are being examined right now. But I don't have the current information on that. It will be available shortly.

CAPTAIN VOGEL: I wonder if your sensor is a loop. Is that correct, a loop?

MR. NORTON: This one is not. There were several types of sensors. There was a loop antenna essentially, shorter turn, inside the cockpit. That was in 1981. This year we've gone to the bulk current sensor, which I showed you, and a shunt sensor on the composite tail. But the system itself can be used with any kind of sensor you like, as long as you attenuate so that what goes to the analog to digital

MR. ISTWAN: If there is no vector consideration with respect to the sensing of the current . . . with the bulk sensor, you don't have to concern yourself with transverse versus longitudinal for a maximum?

MR. NORTON: I don't think I understand that question.

A QUESTIONER: It's around that wire that you showed in the picture. The current actually goes through the sensor, the current that it's measuring.

MR. ISTWAN: What I'm trying to find out is if the actual strike peak current could have a vector component that you're measuring, a component of the peak, and not necessarily the actual peak amplitude.

A QUESTIONER: The sensors are in the boom out in front of the airplane, so all the current must come through the wires. We would calibrate the setup during the ground testing; that's a clip-on type current probe.

A QUESTIONER: Is the sensor the round object you're looking at?

A QUESTIONER: Yes. The transformer used for RF current measurements is quite accurate up to 100 MHz and beyond.

MR. NORTON: We'd better move on to Ted Thomas. He will talk about a variation on this basic architecture used for monitoring transients on power systems. His equipment is on the table for you to look at later.

MR. THOMAS: Shortly after the work was started on the lightning logger, we decided it would also be useful to do the same sort of thing for electrical transients on the main power buses of an aircraft.

This is the type of thing we wanted to monitor. We wanted to look at a main bus, the generator output, and load voltage, all ac voltages, plus dc coming out of the transformer rectifier unit going to a dc load through the dc main bus.

You can see there are four channels of two different types. For the ac type, we'd like to look at transients, the positive and negative over-voltages.

In the case of the dc trigger unit, we'd like to see transient over-voltages or under-voltages. We originally started thinking about the high-speed spikes, which theory had shown were on these power buses, but it also looks attractive as a diagnostic and study tool for such things as power drop-outs and switching transients.

We call the device an electrical power data acquisition system, or EPDA. Much of the circuitry is derived directly from the lightning logger. But the goals are somewhat different. We're looking at relatively low frequencies, say, up to 1 MHz, so we can see, with some degree of detail, a 1- μ sec spike. We wanted to

monitor for long durations of greater than tenths of a second so we could see chains of events like power switching.

We wanted to have large recording capacity and also to record relatively fast. Those two goals are contradictory. We also wanted a single portable unit with four input channels. It should be easy to set up and use; the same requirement as the data logger. We also wanted to be able to set up, turn it on, and come back to see if anything was recorded. Like the lightning logger, we wanted to capture both post- and pretrigger data, and have a variable trigger point. This allows you to see what's happened before the event triggers on, and also what follows after.

These are some of the features we actually incorporated into the equipment. There are four channels. They're independent, or they can be dependent. Each channel has its own adjustable positive and negative trigger to measure over-voltage and under-voltage for dc's or positive and negative spikes for ac's.

You can operate the channels completely independently or you can chain them together so an event on any channel causes everything to be recorded. The recording is digital on two tape cassettes. We use a different type of cassette than they used on the lightning logger. Ours is a 1/8-in. single-track microcassette.

We have two different modes of operation. The normal mode would be automatic, in which case as soon as an event is detected, the data are recorded. The other mode is manual, which allows you to take a quick look at the data on an external oscilloscope and decide whether you want to record them or reject them.

There is an internal time-of-day clock which is recorded on tape. The variable attenuators and sampling interval settings for each channel are also recorded on tape along with the data.

Once you've recorded the data, the cartridge is taken to an off-line computer for plotting, just as on the lightning logger. We're planning to use a strip-chart rather than using an XY plotter as they used. The strip-chart recorder is very much like the standard four-channel oscillogram, 8 in. wide by however many feet long you want.

This is the front panel and starting on the left, the square block is an alphanumeric readout from which the internal computer prompts you for manual setup operations. Using four pushbuttons below, you can set up the automatic or manual mode and also the time-of-day clock, or run some self-diagnostic test.

The thumb wheel switch labeled "Delay Time" sets the ratio between the pretrigger and post-trigger data. It has 16 steps, ranging from 0, which means all pre-trigger data saved, to 15, which means 15/16 of the data being post trigger. A setting of 8 puts the event directly in the middle of the recorded data space.

Each of the four channels across the bottom are four-coaxial connectors, which go out to external attenuator probes connected to the power buses. Directly above each is an LED indicator, which lights when you've captured a transient on that channel. The light stays lit when you do capture a transient, whether in automatic or manual mode, as long as the channel is holding the transient. As soon as the data have either been recorded or rejected, the light goes out

and the channel returns to monitoring operation ready to capture the next transient.

There are eight incremental sampling intervals you can set by thumb wheel ranging from 200 nsec or 5 MHz to 25.6 μ sec, or 39 kHz.

Like the lightning logger, we have a variable attenuator, one for each channel. It's a 10-dB step attenuator, with 11 steps from 0 to 10 dB.

This allows us to have about a 3:1 adjustment in the field, so that the trigger levels are actually an internal adjustment setup before you install it.

On the other side are two microcassette tape units. They store a total of 96,000 bytes of data, each byte being one data sample. We have 16,000 bytes of dedicated memory for each channel. These 96,000 bytes contain about 10 complete channels worth of data. If you get two four-channel events, you essentially fill the tape with data.

We do have the option of storing less than the full 16,000 per channel of data, which gives you more events on the tape.

Like the lightning logger, the tape recorder switches over automatically when it reaches the end of the first tape, so that no data are lost at the tape cross-over. The computer also prompts you when the end of the second tape is reached.

Here is a backwards quick view of the reproduction method. We have a special tape reader that plugs either directly into the computer or through a data modem into an off-line minicomputer. This shows an XY plotter. Actually we have a brush-type strip-chart recorder.

The power buses connect through external resistive voltage divider attenuators. The equipment has a fairly small voltage range without the attenuators. Typically, you might use a current transformer output. And then a 10:1 probe is useful for 28-V dc power. A 100:1 probe is normal for 120-V ac. This allows for capturing transients up to about 750 in each direction.

Then if you're looking for really high voltage transients, you can use a 200:1 probe, which allows you to get up to about 1500-V transients.

This is my last vugraph, which shows the equipment specifications. There are four input channels, each using an 8-bit analog-to-digital converter. It's either the same one or a different version from the one used in the lightning logger. You have 16,000 samples per channel dedicated memory. We can store durations up to 0.4 sec in the slowest sampling rate, and at the fastest sampling rate we still get over 3 msec worth of data. This means you can capture one complete 400-Hz cycle even at the fastest rate. The recording medium is dual microcassettes; 96,000 bits between the two tapes. That's 10 complete channels.

The recording duration is one of the problems. If you record all the data that are there, it takes 120 sec per channel; if you have all four channels, it takes 8 min before the system is completely recovered. We're going to work to speed that up. It's theoretically possible to double the tape density and halve the recording time. Also, by recording only the first portion of the data, you can cut rather drastically, as well as getting more events on the tape.

The equipment size is 17 by 17 by 7 in. It is a very economical unit. We've packaged it as a ruggedized laboratory unit rather than an airborne unit. However, we intend to fly it, and we certainly hope it's going to hold together. It weighs about 35 lb and runs on either ac or dc power, and at about any frequency - 60, 50, 400 Hz. It's also possible to carry along a 24-V battery pack. It uses 80 W. We have a 2.4 A-hr battery pack which would carry it for about 30 min without any charging.

We've been working on this as a back burner project for 2 yr or more, and we're just finishing our first four-channel unit. We hope to have it running on our electrical power simulator within the next week, and hope to get it on an airplane within the next month. We should have two completed and ready to go by the end of the year. We're anxious to get as many test data as we can. We've had some interest in using it as a diagnostic instrument for recording, particularly switching transients on the new commercial airplanes. If anyone would be interested in arranging a loan or otherwise seeing it, we'll be very happy to talk to you about it.

Are there any questions?

MR. KENDALL: How do you protect against false triggers? What kind of tests do you use to make sure that the unit does have good data and not false data?

MR. THOMAS: That's actually what I'm doing now. I'm testing it by running it on an actual aircraft generator system. We have a small one in our lab. I'm testing it by setting the unit close to the highest current section and switching power in the worst ways I can think of.

The next step would be to take it onto our full 767 simulator and try some of the types of switching transients that we'll actually be seeing on the airplane. We have been encountering some false triggering problems. We're sort of beating them down one at a time now.

MR. KENDALL: Are the BNC connectors the floating type on that panel?

MR. THOMAS: Yes, they're floating on the panel. They are grounded, I think, to a single-point ground internally.

ADVANCED DEVELOPMENT PROGRAM FOR FUTURE AIRCRAFT

Discussion of a Multiagency, Multiyear Program to Develop, Test, and Document
Protection Against Atmospheric Electricity Hazards

William W. Cooley

The Boeing Company
Seattle, Washington

MR. BOGARD: I'd like to briefly introduce Dr. Cooley. He is an engineering manager with the Boeing Military Airplane Company in the electrical-mechanical technology staff located in Seattle. He is the program manager of the AEHP program that he will be discussing shortly. He received his Ph.D. in electromagnetics from the University of Washington in 1966.

He has over 25 yr of experience in electrical engineering, including 10 yr teaching at the University of Washington and at Seattle University. He's worked in numerous EMP programs, including Minuteman in-place ground facilities and DNA-DCA communications. He led the development of the test and analysis methods used for the above EMP assessments. He has recently participated in systems engineering and lightning protection design validations for the Boeing 767-757 flight management systems.

He's a senior member of the IEEE and past chairman of Seattle professional groups on antenna propagation, microwave theory, and EMC technologies. Dr. Cooley.

DR. COOLEY: Thank you. What I prepared for you today is an overview briefing of the AEMP program initiated by the Flight Dynamics Lab, and cosponsored by the FAA, NASA, Army, Navy, Air Force, and DNA, to work the lightning protection for future aircraft against atmospheric electricity hazards.

The AEMP program was started in order to define the aircraft vulnerability problem for indirect effects and the fixes that might be made, realizing the present cost background and the increase in potential vulnerability from ever-increasing use of composites and computers on the new aircraft.

To provide a brief background and start everyone on the same basis, the Air Force experience over the 10 yr 1967 through 1977 has cost something like \$21 million in manpower and equipment. This was while reporting a strike rate of 6 in 100,000 hr in peacetime conditions.

Our own commercial experience is a little more severe in strikes than that, in that we expect about once a year an airliner will be struck with lightning. That's something like once in 3000 yr. The costs are not considered significant for the commercial aircraft. There are a variety of reasons for that. The military aircraft operating in peacetime can divert around weather a little more readily than can commercial operators.

Threats to aircraft involve very complex electromagnetic effects. The arcs, streamers, and corona, the location where the lightning attaches, or whether it's weak or strong lightning complicates the threat definition. We will be

talking about some of these threats for both direct physical damage and indirect-induced transients.

The basic thing that happens for indirect effects, though, is that both voltage and current finally get to the equipment as induced transients, and either upset or damage critical components.

Now, there are other phenomena such as arcing and sparking, but this program is directed toward protecting the electronics from the potential damage from electrical transients. There are other people working with structures and what physical damage protection ought to be used. The aircraft systems that we're looking at are the engine, fuel, explosives, stores, crew safety, flight systems, avionics, and the electrical systems.

That's the concern from the technology side. When you talk to the Weapons System Program Office (SPO) they will tell you they've had too much already; figure 17-1 shows what we hear from our KC-135 SPO.

The requirements for EMI and the "weight" of the requirements in the figure 17-1 picture are about as shown; EMI certainly is tolerable. Lightning protection requirements on an airplane like this are also tolerable. The EMP requirements can go out of sight. The SPO wants to know when the EM requirements are all going to be put together, and to stop bringing them problems and start bringing them specifications, design criteria, and qualification test standards.

That is where this program got started. Remember the thrust is on the advanced aircraft, ATF fighter, ACM missile, advanced-bomber/transport, and JVX helicopter, all of which have less conducting structural materials and more computers. The AEHP program objective is to develop and demonstrate protection measures, design criteria, and specifications for the advanced aircraft in order to assure reliable operation of electronic equipment in natural lightning environments.

This is a two-phased program. Phase one is for 21 mo to do the assessment protection trade-offs and detail, definition of the second phase. Phase two is for 33 mo to demonstrate lightning protection in a simulated environment on a full-scale live test bed aircraft. The phase two objective is to validate the phase one protection approach and complete design criteria, design guidelines, and qualification test procedures. It's an ambitious program with the combined phases expected to run 5 yr.

We see, and I don't want to risk overemphasizing, the central task as being to produce protection criteria and guidelines for the designers. The installation designer and electronic equipment designer have a lot of questions today. How do you find installation requirements for shielding the wiring for equipment? Where does a designer get help without going to Maxwell's equations or laboratory testing? Where do they put the shielding in the structure and how should the ends be treated? What kind of enclosures and ventilation opening do you use in equipment bays? What are the EMC guidelines for the design of poorly conducting or nonmetallic aircraft? What kind of simple analysis, tools, and techniques are available to the designers that will help them do their job? The same thing applies for the avionics designers. What kind of qualification test do they have to do to qualify equipment? What kind of guidelines can we give them, in terms of packaging or bench testing, that they must meet?

We have a schedule to put answers to these things in context. The 21-month phase one period up front is to do the technology development and detail planning for the phase two validation. One of the reasons I put this schedule together is to point out that along the way we plan to draw in industry and interested parties through regular review and workshops. These workshops will be open to a wide variety of engineers of the aircraft/electronic design community.

Support for this program comes from the Wright Aeronautical Labs. The Air Force Weapons laboratory, in their support of EMP protection is also doing some basic measurements on lightning environments, and they have developed some of the newer data on the critical rates of rise for the lightning threat.

The Army Aeronautical Systems Division is providing program support by furnishing a YUH-60 helicopter test bed. The Navy is supplying an F-14 fighter and supporting technology from their earlier efforts. DNA is interested in the relationship between EMP and lightning and is also participating. The FAA and NASA are also participating, and there's a National Interagency Coordinating Group (NICG) to draw together some of the work and to coordinate the efforts of these agencies and their individual programs.

What we're looking at is a definition of the lightning threat that's appropriate for aircraft electronic-electrical equipment. If any of you are really into this, there are several ongoing experiments to define natural atmospheric electricity. There are 10-yr histories of data from Switzerland and Italy, work going on in South Africa, and also in the United States, particularly at Tampa Bay.

As we read the tea leaves from these experimental efforts (and I really mean that, because almost every lightning pulse differs from the next lightning pulse), we see that the threat for the electronics equipment must be concerned with multiple events, as well as single pulses, because upset of the digital equipment is a very serious concern.

If we look at only one lightning pulse, we're not going to get there. We see the duration of an event or flash as 50 to 500 μ sec, some 10 to 100 msec in between, and there may be as many as 24 pulses occurring within 2 sec.

The individual pulses or strikes look like table 17-1. We're looking at the definition of two kinds of lightning. At the bottom of the chart are the moderate and the severe. Moderate lightning is the kind expected anytime lightning strikes the airplane; severe is the kind expected once in the lifetime of the aircraft — a cloud-to-ground event and with the aircraft near the ground — that would be threatening to any flight-critical equipment.

Moderate lightning is more of a threat that would affect the reliability and the mean time between failures (MTBF) of systems on board — more of a maintenance problem. These two threat levels, 10,000 A for the moderate and 200,000 A for the severe, are really pretty close to what people have measured.

The parameter that is of most concern is the peak rate of rise, because of the $L(di/dt)$ type of mutual inductance coupling, and the E-field effects $C(de/dt)$ that go with that rate of rise — 5×10^{10} and 2×10^{11} A/sec.

TABLE 17-1.- DEFINITION OF SINGLE STROKE THREAT (DAMAGE EFFECTS)

Waveform	$I(t) = I_0(e^{-\alpha t} - e^{-\beta t})$					
	<u>I_0</u>	<u>α</u>	<u>β</u>	<u>t_{pk}</u>	<u>$t_{1/2}$</u>	
Moderate:	20.6 kA	$14.3 \times 10^3 \text{ sec}^{-1}$	$2.5 \times 10^6 \text{ sec}^{-1}$	2.1 μsec	50 μsec	
Severe:	206 kA	$14.3 \times 10^3 \text{ sec}^{-1}$	$1.0 \times 10^6 \text{ sec}^{-1}$	4.3 μsec	50 μsec	
Spectrum	$I(f) = I_0[1/(\alpha + j2\pi f) - 1/(\beta + j2\pi f)]$					
	<u>Dc limit</u>	<u>Upper turning frequency</u>		<u>Lower turning frequency</u>		
Moderate:	1.4 A/Hz	400 kHz		2.3 kHz		
Severe:	14 A/Hz	160 kHz		2.3 kHz		
Lightning parameters						
	<u>Peak current</u>	<u>Peak rate of rise</u>		<u>Action integral</u>		
Moderate:	20 kA	$5 \times 10^{10} \text{ A/sec}$		$1.5 \times 10^4 \text{ A}^2\text{-sec}$		
Severe:	200 kA	$2 \times 10^{11} \text{ A/sec}$		$1.5 \times 10^6 \text{ A}^2\text{-sec}$		

The action integral isn't so terribly important for the transients from severe stroke, but the action integral is important if we try to use terminal protection devices such as varactor diodes, or resistors to limit transient voltages. That parameter is of concern when devices have to absorb the energy of the strike. I don't want to continue discussion about lightning, just enough to put into context what we're doing on the AEHP program.

A comparison is shown in figure 17-2 of our moderate and severe threats, with some recent measurement by Weedman and Krider at Tampa Bay that shows submicro-second rise times. These data are shown to get some idea of how our moderate threat definition is in line with that kind of a measurement. The comparison is for a nearby lightning, 50 m away. If the lightning is closer than 50 m, it's going to attach to the aircraft. This is about as nearby as you can get without having the lightning directly attach. I didn't want to discuss attached lightning and the other threat processes because we're getting into too much detail. We're presently reviewing recent measurement data and proposing a lightning threat for this program. These results will be coordinated with the rest of industry.

The other major activity I want to talk about is how we are doing the vulnerability assessment, and describe the tests planned for the ALCM and F-16 mockup. Both of these test beds will be modified to have wiring and structural elements like those advanced aircraft. We're suggesting the simulation techniques considered for the data needed from the tests and the test bed modification, and planning and conducting the tests. From the data of those tests we'll determine the vulnerability of other electronic equipment.

There are other tasks that will provide the data on electronic equipment susceptibility, and there is also an analysis effort to predict expected induced

transient values. Then we'll conduct testing to find out how good the prediction tools were. We want to gain confidence in our analysis techniques when we predict for future aircraft without testing.

The vulnerability assessment analysis techniques and tests will lead to the modification design for the phase two test beds. These tests will provide data for wiring and installations representative of advanced aircraft that will help in the design of future aircraft systems.

It's a little difficult to determine the design to lay down for future aircraft by testing today's equipment. We think by developing analysis tools and test methods we will be able to project to new design.

The ALCM test will be at Sandia Labs in New Mexico, where they have the capability of "full threat lightning simulation." Sandia can generate the severe threat criteria. They have two 20,000-gal oil tanks filled with capacitors. In fact, they have a little trouble generating that 50- μ sec half-time; it normally goes much longer. By providing an electromagnetic return circuit, we can simulate the effects of the lightning on the ALCM in flight.

By a variety of configurations, we can get corona on the vehicle, or high currents, or high E-field. This will be a threat-type stress test.

ALCM is an operational vehicle, and there will be electronic equipment operating. Fiber optics will carry all signals in and out of the missile. A hydraulic driven generator will provide on-board power. This will break all electrical connection to the lightning currents.

The other test bed we have for phase one is a graphite/epoxy test sample of the advanced F-16. We intend to take out what metal that exists in this forward fuselage section, so we'll have a basic structure that's as advanced as aircraft structure today.

The rest of the airplane will be constructed of wood and metal frame. This will allow us to maintain the proper length relationship between wire bundles and equipment throughout the aircraft structure.

We're not going to learn much from the tail section of this model, although the tail structure does provide a way to simulate a lightning strike from wingtip to tail. You've got to have a tail in order to get the right EM environment in the forward fuselage where we're doing the testing. The mockup will also aid the evaluation of test techniques for full aircraft.

Initially our testing will be exploratory, with point-to-point wiring, testing the topology of the grounding scheme. This would also include the aft bays and cockpit and tail interconnection with the grounding accomplished similar to our recommended design practices. The final testing will be accomplished with operational equipment. The thing we learned from EMP is that there isn't any one test. I think that's certainly true for lightning, too. There are so many factors involved that to do a single test, and call that lightning, is inconclusive.

Table 17-2 shows the recommended simulation test techniques for lightning; the choice depends on the data needs. If you are trying to get design data, then you may want to mock up part of the airplane or part of the wiring and do some

TABLE 17-2.- RECOMMENDED SIMULATION TEST TECHNIQUES

Three methods are suitable for:			
• Design data • Assessment data • Qualification/surveillance tests			
Required features — direct strike	Low level		High level
	Coupling measurement + bench test	Scaled pulse test	Full threat test
High voltage — E-field phase	Linear only	Limited by pulser	OK
High current — H-field phase return strokes	Yes	Yes	OK
Continuing current	Yes	Yes	OK
Fast rise-times (30 to 100 nsec)	Yes	Yes	Limited by pulser
Electromagnetic test cell			
Inflight conditions	Yes	Yes	Yes
Currents and fields	Yes	Yes	Yes
Lightning channel attachment	Yes	Limited by pulser	Limited by pulser
Functional responses			
Upset	Yes	No	Yes
Damage	Yes	No	Yes
Adapt to new threat parameters			
EM coupling	Yes	Limited by pulser	Limited by pulser
Functional responses	Yes	Limited to observed	Limited if threat higher level

tests. That would be quite acceptable for design data. If you want to assess a particular design, and determine whether the aircraft is going to survive the lightning threat, you'll want to do full threat testing or threat relatable simulator testing. But at the same time you may want to determine what's wrong, why it either failed or passed, or why it met a particular hardness criterion. You than may want to do some other kind of low level testing to determine what that big strike really did show.

There are then other kinds of testing, such as qualification and maintenance testing. As we get the aircraft systems designed for protection against lightning, we will have to follow up on the protection throughout its life cycle. There is no point in putting shielded cable in if the maintenance operation leaves all the shields undone as part of changing an engine, for example. You have to see that the installed means for protection remain installed. What happens in the maintenance depot can be very important in the overall protection effectiveness.

The basic differences in the kind of tests are either low or high level. We have found swept, continuous wave (CW), low-level current injection very useful to find what levels of lightning pulses would be there. You can start from the

measured point-to-point transfer function and calculate back from the lightning spectrum to determine the equivalent pulse that would have been there; then by going to bench testing, using the traditional EMI fixtures, and exposing the test specimen to pulsed current injection similar to that used in MIL-STD 461 testing.

The other type of low-level tests you might want to do, since high-current lightning sources are expensive, is to scale up from a smaller pulse. There are some limitations to this, particularly in how well this scaling procedure adapts to new pulse parameters. There's a lot of research going on in this field, and every few months new lightning environment data are made available — the Langley F-106 data, for example. We're still learning new things about what the lightning threat environment really is.

The same environment limitations also apply to high-level testing as well. If you design a full-threat test, it will do all the right things. But if the threat environment changes, as it becomes better defined, you are going to have to rebuild some of the test equipment.

The analysis tools used in this program will help us predict the result of these changing threats. The predictive tools must handle various nonconductors, semiconductors, and conductors for assorted vehicle configuration and applicable threats attached nearby on the vehicle. Static electricity is also of great concern where there's a lot of nonconductive material used. The various analysis tools must be able to compute current and field strength in the cockpit structure, equipment bays, etc.

AEM protection must apply over a broad frequency range. As an example, when graphite/epoxy is used there's a significant amount of current inside the panels at particularly low frequencies. Yet on the other hand, the lightning pulse is like a 12-kHz low-frequency waveform with a rise that has harmonics of hundreds of megahertz.

We have some predictive analysis tools that have come out of EMP programs, particularly the PRESTO code shown in figure 17-5. This is a program that Boeing built for a defense nuclear agency to calculate nuclear weapon effects. Nothing nuclear about it. It's got a user friendly executive program to control the data from geometric descriptions and cable configurations into frequency-domain analysis, time-domain analysis, and nonlinear analysis. Component thresholds and safety margin reporting schemes and a variety of display and plotting configurations are also available in the program. We intend to take this program and add the applicable lightning code modules to it. This code will be available to any government agency sponsored user through DNA.

The steps involved in prediction shown in figure 17-6 require you to handle the lightning environment and how it hooks onto the airplane, the currents that are involved, the charges on the airplane, what comes through the cockpit and bays, penetrations from outside the airplane — the windows, hatches, exposed cabling, metals, hydraulic lines, air conditioning, etc. — everything that brings current into the interior. This includes the wiring, through induced voltages and currents, common differential modes distributed throughout the internal spaghetti factory, and finally how it gets into the electronic equipment — or going from the internal E's, H's, and I's to the internal electronic equipment.

We've been doing some of this kind of analysis for lightning. I guess Boeing has thought about this problem as much as, or maybe more than, anybody else in this area, but others are certainly able to do it as well. Figure 17-7 is an example from our YC-14. We did a lightning analysis to see how the exposed wiring in the wing would get induced voltages and currents into it due to lightning attached to the wing, and then that was relatively easy. The voltage sources are calculated from mutual inductance coupling to the currents on the outside of the airplane. How that induced voltage gets through to the wire bundles and interface units and finally down to the ac/dc buses is more difficult. We had also located installed sensitive equipment in a variety of places.

This YC-14 model becomes a big electric circuit model. Everybody knows how to do ac circuit/dc circuit analysis and has computer codes. But this PRESTO program lets you put all this together, connecting together the individual analysis through the executive code.

The vulnerability analysis aspect of the program shown in figure 17-8 is used to set requirements for future aircraft design. We've developed a generic fighter-missile-bomber-helicopter model. We know something about their mission profiles and configurations and what equipment is required for flight and mission completion. Through this analysis we can determine what kind of protection is required for their functional hardening without the penalty of overprotection.

With these kinds of computer prediction tools, we can carry out the assessment, and through the testing we'll get the feeling about the uncertainty of those tools for the impact advanced composite structure.

Another major task is the protection and what do we do to harden the system. The objective is to get effective concepts, know what weight-cost penalties there are, and balance the protection for lightning, EMI, and EMP. There is a needed balance, and with any aircraft, there's always some kind of compromise. We want to protect the aircraft against loss; we don't want to degrade the protection against EMI or EMP. It may not be able to arrive at enough protection for lightning that would also include EMP in every case, but at least we want to consider it and arrive at a balance.

In some cases we may be able to add enough protection for lightning and EMP. If we can add a little more and also do EMP, then we'll do that. But it's a balance of these effects. And the specifications will consider that AEM-EMP balance.

The protection philosophy shown in table 17-3 that is going to come into play will also include systems level protection. We can't protect just boxes or just cables. We have to develop some kind of topology for the shielding and grounding, the way currents enter the system, and design to prevent any currents from getting into the electronics.

One way to do this is to add just enough metal to the back of the composites so that all the currents stay on the outside like they do now on metal aircraft. That would be one way, the Faraday shield.

You don't need very many mils of aluminum foil to accomplish this. It may turn out that this is a cost-effective protection method — just take aluminum wrap and build it into the layers of the composite. Composites already need some thickness or metal to prevent a structural burn-through of the direct strike.

TABLE 17-3.- PROTECTION PHILOSOPHY

-
- DEVELOP SHIELDING/GROUNDING TOPOLOGY TO PREVENT HIGH CURRENTS FROM ENTERING ELECTRONICS
 - TRADE STRUCTURES, ELECTRONIC INTERFACE AND SUBSYSTEM HARDENING FOR BEST SYSTEMS LEVEL MIX
 - SELECTIVELY INTEGRATE LIGHTNING, EMI/EMC, NEMP PROTECTION METHODS
 - EMPHASIZE CRITICAL SYSTEMS AFFECTING SAFETY AND MISSION
 - FLIGHT CONTROL
 - ENGINE CONTROL
 - STORES MANAGEMENT
 - ELECTRICAL POWER SYSTEMS
 - USE GROUND SIMULATION TESTS AND ANALYSIS FOR HARDNESS DESIGN EVALUATION
 - EMPLOY BEST EXISTING LIGHTNING CHARACTERIZATION
 - BOUND KEY PARAMETERS TO DEFINE SAFETY MARGINS
-

It may turn out that by adding a minimum of additional aluminum we would protect the lightning transients as well. We have to look into this in more depth because of the joints and doors, and the practice of putting airplanes together in pieces. We recognize all these materials and process concerns.

Another way might be to roll the electronics into a conduit-enclosure topology that's separate from the airplane rather than use the airplane outer hull; just use enclosures, shielded cable, and conduit to tie all the electrical equipment together and connect to the airplane in only one place.

There can't be any currents in this inner enclosure, because it doesn't hook to the composite structure except at one place. The only reason you want that one place is so the crew doesn't get shocked when they lean over against the side wall. The crew would have to be inside the internal metal enclosure. Conceptually you could do that, and there are some really fantastic insulators. Capton, for example, takes 7000 V/mil breakdown. Then with very little material on the inside of the structure you could insulate everything from the damage of lightning and EMP.

There are certainly other trade-offs: You can either work the structures, as I've been talking about, or you can work right down into the box level and demand that the electronic vendors make their boxes withstand 2000 V or more. This could be done by fiber optics, by high-impedance circuits, by ballast, by terminal protective devices, or by RC filters, where the R's take some of the energy. There are a variety of ways to do that. Again, by looking at the fighter-missile-bomber-helicopter computer analysis program in a generic sense, we'll be looking at the systems that really count. There will also be some testing on these system level protection schemes as part of the F-15 mockup.

To bring this to a close, there is one additional thing I would like to mention in the way of design criteria. When we see you next year at one of these

workshops, we'll have a draft of what we think the right design approach is at the system-subsystem level, and we'll circulate that for comment.

The real goal, the goal of the design criteria, is to be able to take an airplane configuration; find that specifications are needed; apply them to the wiring and equipment installation; design to values; and apply them to the avionics equipment qualification test levels, such as a 500-V pulse test on the equipment; install them; and away you go. That's the goal.

That is a pretty sporty course, and it's not the way we're doing it today. The designers, analyzers, and testers are all meshed together trying to figure out how big this elephant is and where all the problems are in each new aircraft. The details in the design today are not really adequate to do any EM analysis early enough to avoid costly changes.

But, in spite of all this, even if we achieve our goal, somebody has to verify that the design team hasn't overlooked something. There will always have to be a team of people required for the tests and analysis shown in figure 17-9: To take the lightning environment, calculate the coupling, find out what the equipment will take — what happens when the equipment is disrupted, and put together a design verification. Namely, in the aircraft as-built, is the coupling less than what the equipment will stand? And if not, can we accept what happens? Or, do we have to harden? And if it is hardened, then what? Go back through this loop and finally verify that the design is adequate.

The same process will have to be repeated when the equipment is changed. Somebody will come along later and change something; these changes will have to be designed, then taken through the verification tests and analysis. At the present, this kind of activity is going on at the same time things are getting designed, and we have a much more complicated procedure than we need.

I want to say a final word about the qualification tests for AEM protection that we would expect to see in terms of the testing at the subsystem equipment level with mockups and qualification acceptance testing. We'd expect to see vehicle tests on either the prototypes or first article. The question still remains as to whether a full threat is needed. This is the question that Skouby touched on as well, whether we have to go to the 200 kA, 2×10^{11} , one-shot-and-go demonstration test or not. But we need something that's threat-relatable, and we only need it for flight and mission critical equipment.

Again, there's some continuing protection verification needed — what those tests are is open. They'll surely be low level, and perhaps they could be built-in. You could build in signal generators and verify that the shields are all hooked up, for example. That's some example of the kinds of questions that we're going to answer in the 3 or 4 yr.

Yes?

A QUESTIONER: One of your earlier slides showed an F-111 and a C-130 that had been involved in lightning-strike-caused crashes. Neither of these airplanes has very sophisticated electronic controls or flight controls.

MR. THOMAS: The F-111 had problems with the stability augmentation.

A QUESTIONER: What was the cause of the crash? Was that determined?

MR. THOMAS: There are Air Force reports on that.

A QUESTIONER: Was there mechanical damage to the airplane or was it avionics?

MR. THOMAS: No, it was electronics. I don't remember exactly which equipment was involved, but it had something to do with the yaw dampers and that they were computer-controlled. The airplane was in formation; it seemed to be struck, and a couple of minutes later it crashed because of loss of lateral stability.

The C-130 is pretty well known; it had something to do with the fuel tank or fuel gauging. Both of these aircraft incidents are pretty widely known. I don't think I am inventing anything here. That was out of an Air Force study, by the way.

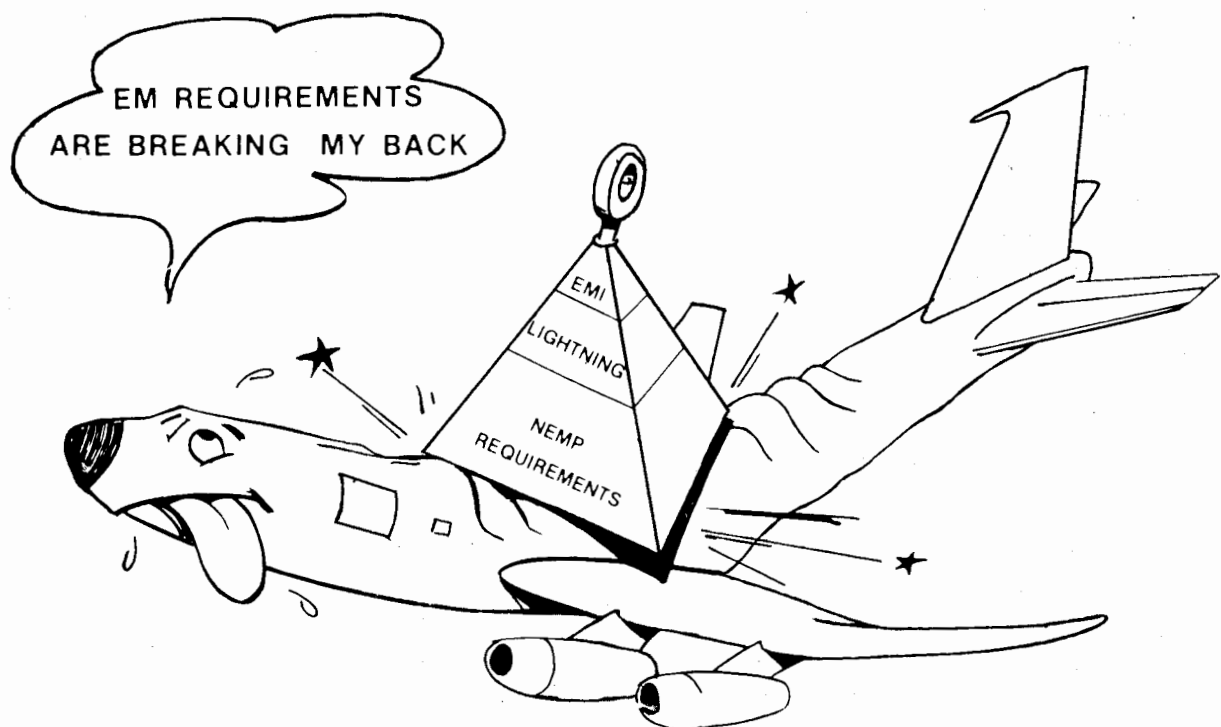


Figure 17-1.- Weapon System Program Office view.

Waveform	$I(t) = I_0 (e^{-at} - e^{-\beta t})$				
	<u>I_0</u>	<u>a</u>	<u>β</u>	<u>t_{pk}</u>	<u>$t_{1/2}$</u>
Moderate:	20.6 kA	$14.3 \times 10^3 \text{ sec}^{-1}$	$2.5 \times 10^6 \text{ sec}^{-1}$	$2.1 \mu\text{s}$	$50 \mu\text{s}$
Severe:	206 kA	$14.3 \times 10^3 \text{ sec}^{-1}$	$1.0 \times 10^6 \text{ sec}^{-1}$	$4.3 \mu\text{s}$	$50 \mu\text{s}$
Spectrum	$I(f) = I_0(1/[a + j2\pi f] - 1/[\beta + j2\pi f])$				
	<u>DC Limit</u>	<u>Upper Turning Frequency</u>	<u>Lower Turning Frequency</u>		
Moderate:	1.4 amps/Hz	400 kHz	2.3 kHz		
Severe:	14 amps/Hz	160 kHz	2.3 kHz		
Lightning Parameters					
	<u>Peak Current</u>	<u>Peak Rate-of-Rise</u>	<u>Action Integral</u>		
Moderate:	20 kA	$5 \times 10^{10} \text{ amps/sec}$	$1.5 \times 10^4 \text{ amp}^2\text{-sec}$		
Severe:	200 kA	$2 \times 10^{11} \text{ amps/sec}$	$1.5 \times 10^6 \text{ amp}^2\text{-sec}$		

Figure 17-2.- Definition of single stroke threat (damage effects).

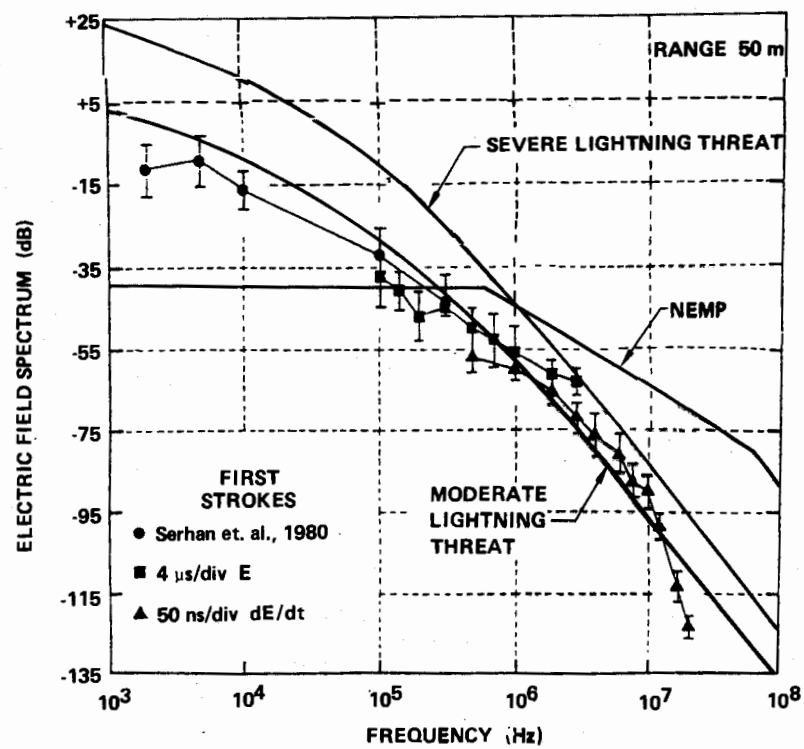


Figure 17-3.- Comparison of electric field data with initial threat definitions.

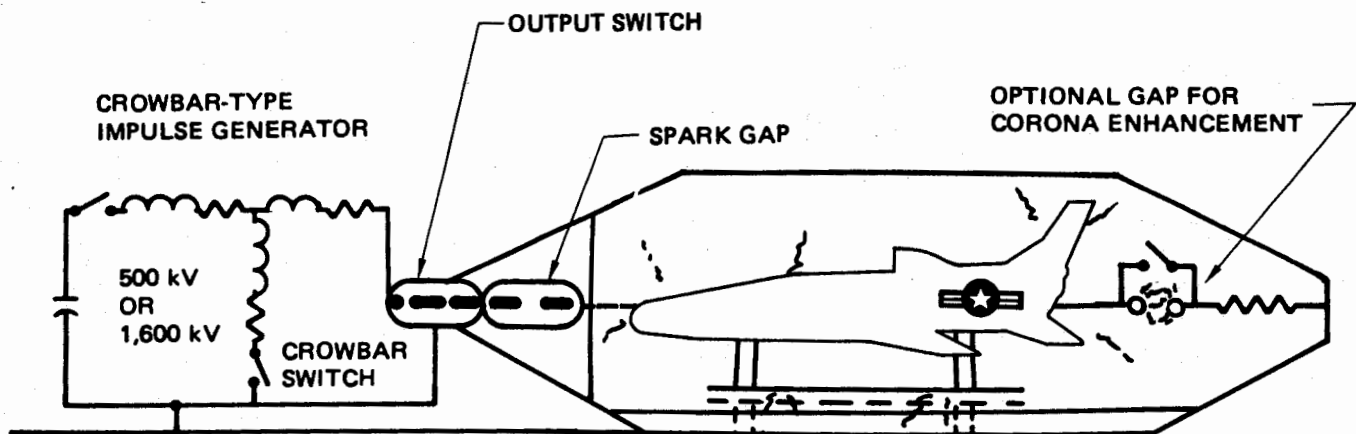


Figure 17-4.- ALCM test setup.

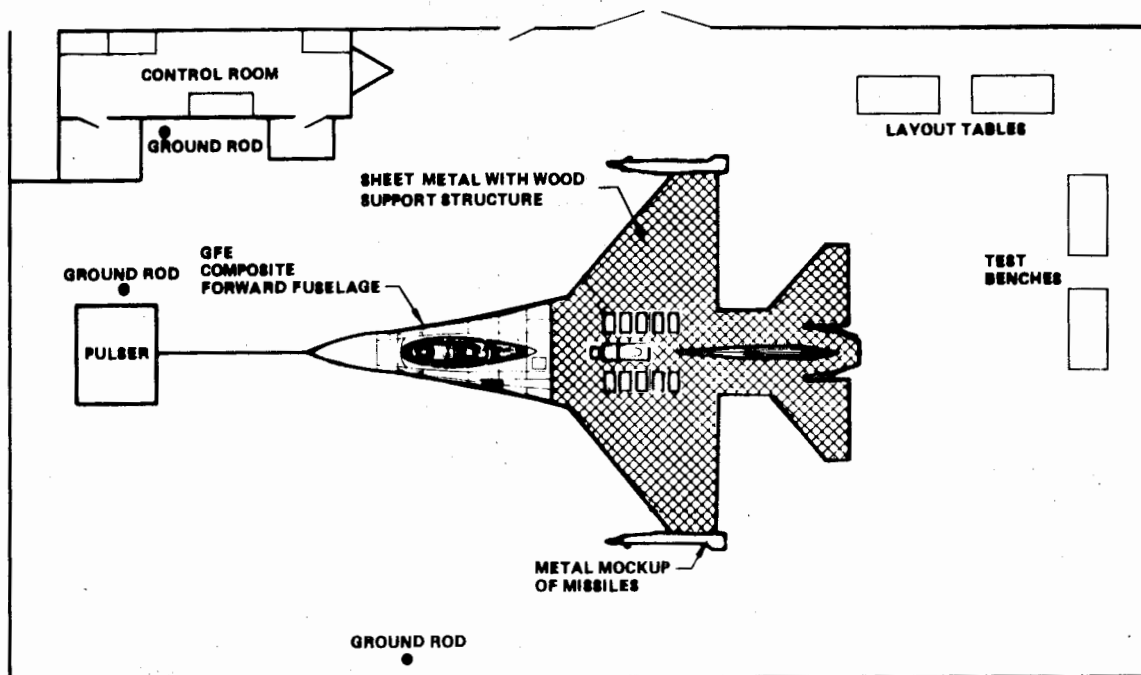


Figure 17-5.- F-16 mockup test setup.

Three methods are suitable for:

- Design data
- Assessment data
- Qualification/surveillance tests

Required Features – Direct Strike	Low-Level		High Level
	Coupling Measurement + Bench Test	Scaled Pulse Test	Full Threat Test
High voltage - E-Field phase	Linear only	Limited by pulser	OK
High current – H-field phase return strokes	Yes	Yes	OK
Continuing current	Yes	Yes	OK
Fast rise-times (30 to 100 nsec)	Yes	Yes	Limited by pulser
Electromagnetic test cell			
Inflight conditions	Yes	Yes	Yes
Currents and fields	Yes	Yes	Yes
Lightning channel attachment	Yes	Limited by pulser	Limited by pulser
Functional responses			
Upset	Yes	No	Yes
Damage	Yes	No	Yes
Adapt to new threat parameters			
EM coupling	Yes	Limited by pulser	Limited by pulser
Functional responses	Yes	Limited to observed	Limited if threat higher level

Figure 17-6.- Recommended simulation test techniques.

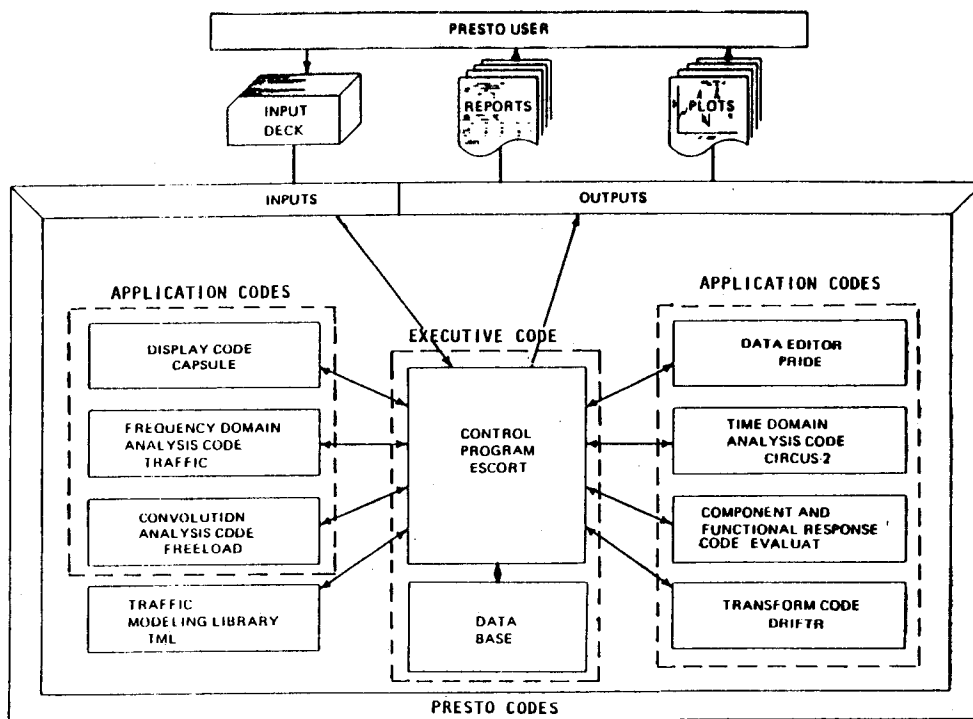


Figure 17-7.- Interrelation of PRESTO codes.

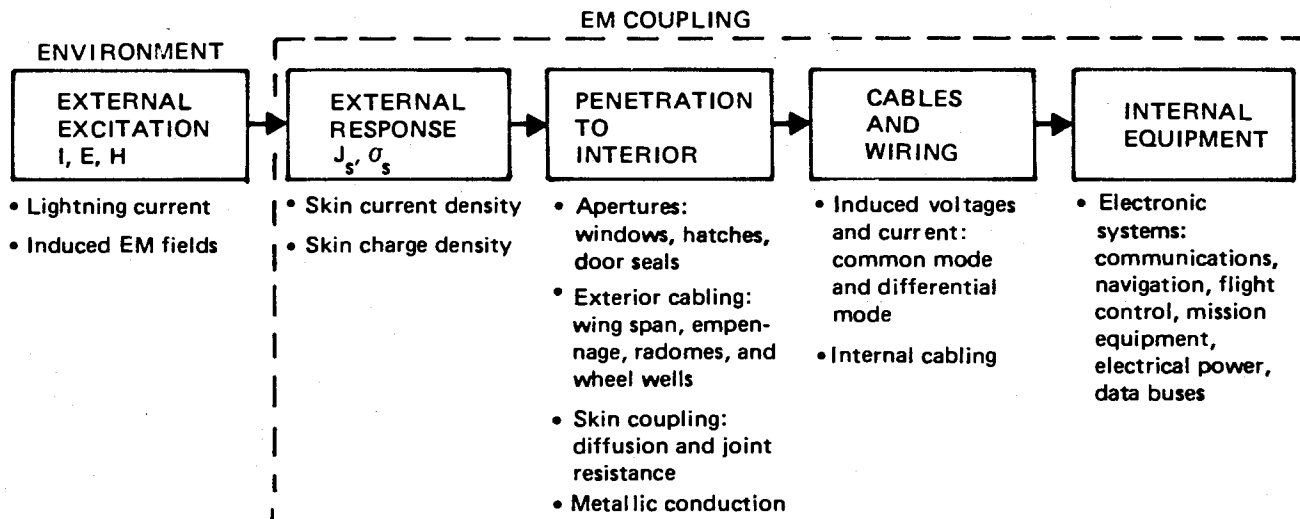


Figure 17-8.- EM response prediction steps.

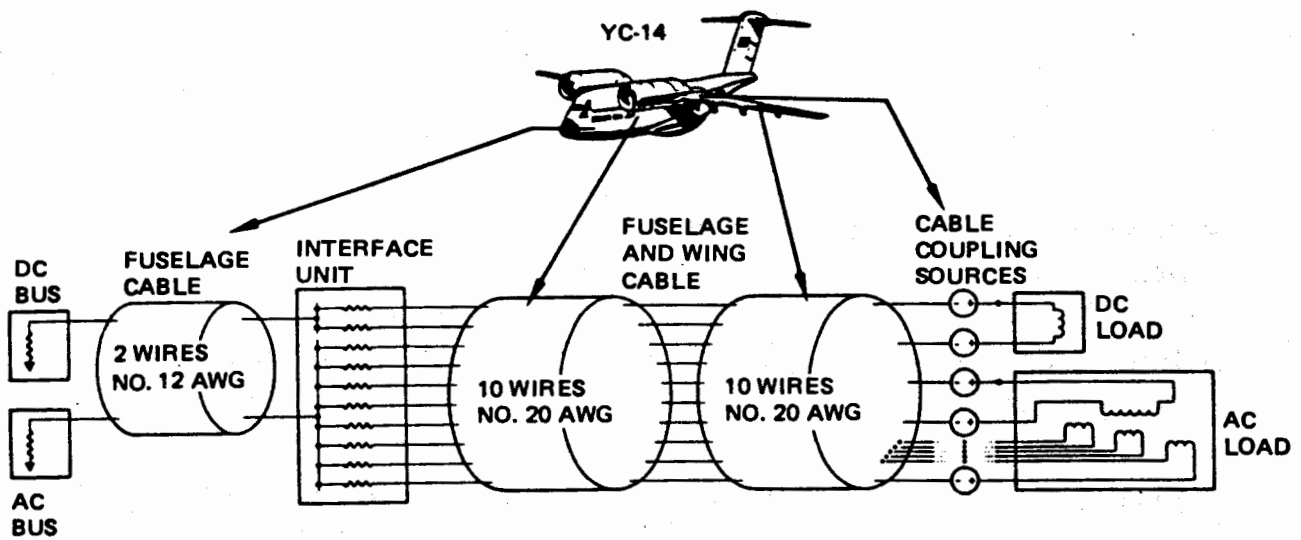


Figure 17-9.- EM analysis model.

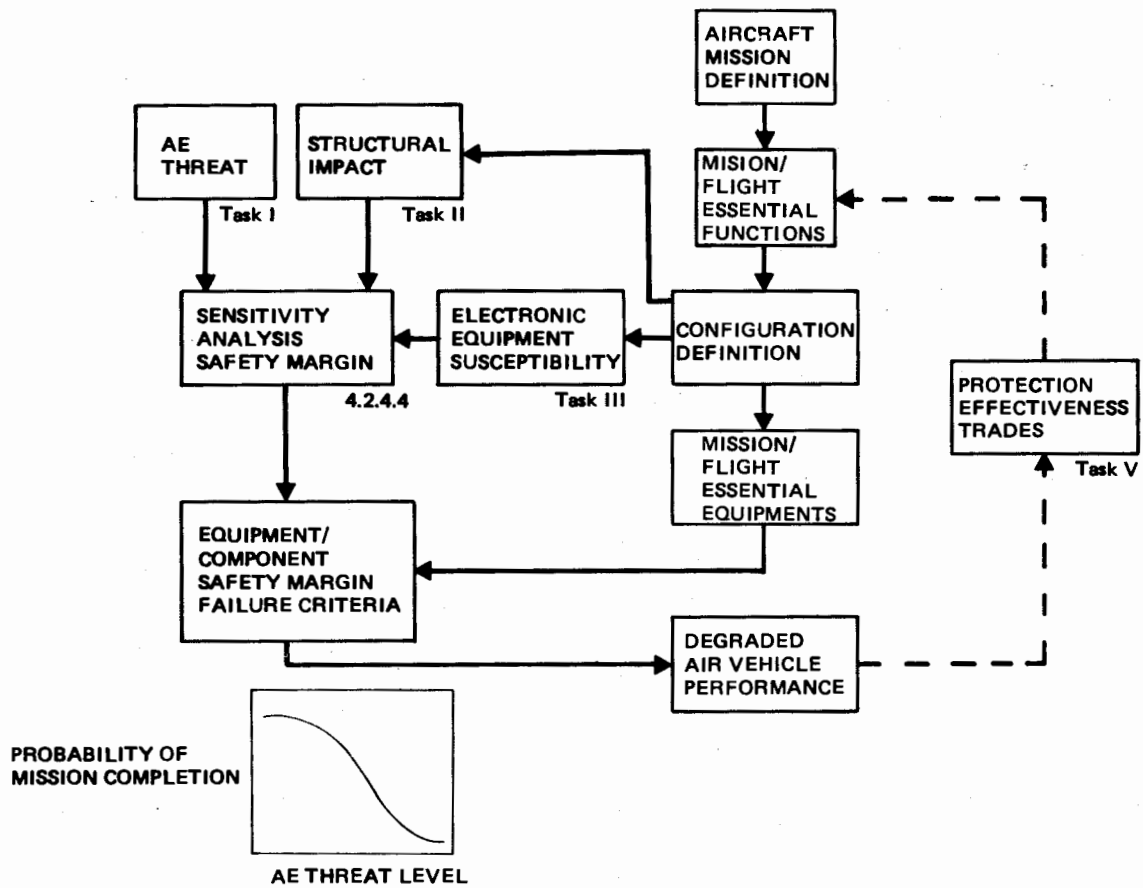


Figure 17-10.- Vulnerability analysis.

- **Develop shielding/grounding topology to prevent high currents from entering electronics**
- **Trade structures, electronic interface and subsystem hardening for best systems level mix**
- **Selectively integrate lightning,, EMI/EMC, NEMP protection methods**
- **Emphasise critical systems affecting safety and mission**
 - **Flight control**
 - **Engine control**
 - **Stores management**
 - **Electrical power systems**
- **Use ground simulation tests and analysis for hardness design evaluation**
 - **Employ best existing lightning characterization**
 - **Bound key parameters to define safety margins**

Figure 17-11.- Protection philosophy.

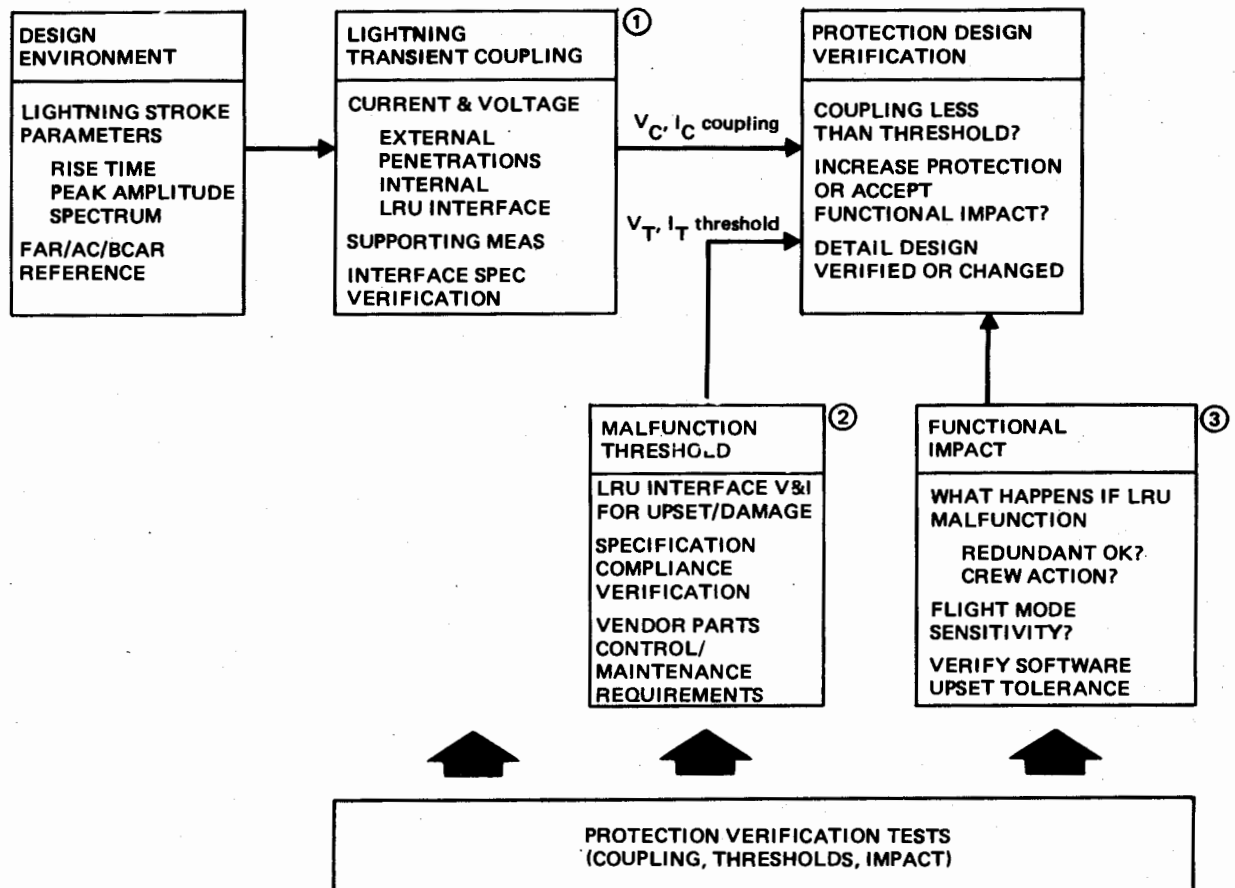


Figure 17-12

PLAN TO DEFINE ELECTROMAGNETIC COUPLING EFFECTS ON AIRBORNE DIGITAL AVIONICS

William Larsen

Federal Aviation Administration, Ames Research Center
Moffett Field, California

MR. LARSEN: Earlier, on Tuesday, Nick Rasch identified the Advanced Integrated Flight System (AIFS) Program. What I will talk about this afternoon is a subset of the AIFS Program. We have put together a plan in the area of Aircraft-Generated Electromagnetic Interference and its effect on Future Avionics Systems. You have heard quite a bit on this and related subjects over the past several days. We all have an interest in this area, some concerns, and there will be more to come in the months and years ahead.

There are people here and others that want to add information in terms of design specifications and test criteria for both the box and systems level as well as validation and revalidation criteria. In this context, Keith Kalanquin from Boeing and others have suggested that the RTCA Committee reconvene to update D0160A, the environmental test specifications for avionics equipment.

One of the things we have considered here is that the commercial transports as we know them have turned to digital avionics to replace the older analog and electromechanical equipment for flight critical displays and controls. This technology offers a great deal, but there still remains a number of unanswered questions, both in design/architecture and testing.

We have heard of some plans and of ongoing work in these areas during the progress of the workshop, and there will be more as the programs unfold over the months and years. We're seeing that the digital device is a current device, rather than a voltage device, and its characteristics are entirely different from the hardware we have worked with before. These digital devices are much more susceptible to higher-frequency interference than analog devices of the past. In fact, the digital device is some 10 times more susceptible to upset than analog devices, although when they are used in digital circuitry certain error correcting techniques can harden their operation at the system level.

The trend is toward more and more integration where additional precautions will have to be taken, particularly for flight-critical control and display systems. Much of the basic research to develop the technology for these flight-critical systems is now under way, and the results have been made available here the past several days.

The objective of the program I'm about to introduce to you today is to gain some degree of understanding of the aircraft-generated EMI threat. A better definition of survivability, particularly for flight-critical avionics, and a better determination of the test criteria and methods that will ensure adequate protection. One thing I want to ensure in passing is that we require some degree of systems testing, preferably at the aircraft (as installed) level, in the environment that the black box is to operate in.

As a final product of the program, I would expect a set of tentative qualification criteria and testing procedures. The need for this has been alluded to in several of the other presentations as well. EMC requirements for protection

<u>Name</u>	<u>Company</u>	<u>Mailing Address</u>
Kenneth D. Tillman	Pratt & Whitney Aircraft	P.O. Box 2691, M.L. B-173 West Palm Beach, FL 33402
C. H. Tran	Hitco	3016 Auburn Way N. Auburn, WA 98002
Jim Treacy	FAA	ANM-103N 9010 E. Marginal Way, S. Seattle, WA 98108
Gene Vandermohen	FAA	ANM-1305 9010 E. Marginal Way, S. Seattle, WA 98108
Ken Van Nortwick	Boeing Company	P.O. Box 3707, M/S 6A-29 Seattle, WA 98108
C. Larry Vaughan	FAA	Flight Stds. Div. ASO250 P.O. Box 20636 Atlanta, GA 30320
Pete Venuti	Boeing Vertol Company	P.O. Box 16858 Philadelphia, PA 19142
Ray Vogel	USAF	ASD/ENACE Aeronautical Syst. Div. Wright-Patterson AFB, OH 45433
Hugh E. Waterman	FAA	ANM-1301 4344 Donald Douglas Drive Long Beach, CA 90808
David A. Whittle	Civil Aviation Authority	Barbazon House Redhill Surrey, England
R. R. Willoughby	Boeing Company	P.O. Box 3707, M/S 06-28 Seattle, WA 98124
Jack Wright	FAA	AAL-FSDO-63, Suite 216 6601 S. Airpark Place Anchorage, AK 99502
H. Youssef	Lockheed-California	P.O. Box 551 (B63-3 PA01)(D78-21) Burbank, CA 91520
Murray Zigler	Sikorsky Aircraft	Avionic Design N. Main Street Stratford, CT 06602

against lightning as well as internally generated EMI for flight critical and flight essential systems are needed. There is also a need for an understanding about composites. We've had several speakers provide excellent presentations of programs about what is happening in this field. As these programs develop, additional information will be available.

In dealing with the EMC of tomorrow's systems, we need to harden and do our testing across a broader frequency band. This has been discussed extensively today. In the past with the analog systems, lower frequencies were important. With the high speed of tomorrow's digital systems, test frequencies may be important in the 100-MHz range or higher. Earlier we heard that some Boeing people are setting up to measure aircraft radiated and conducted emissions. Also there needs to be greater knowledge of the transfer function between the local EMI environment and the digital system's response to a disturbance. A previous study by the Air Force some time ago on a KC-135 and Convair 340 showed that aircraft configuration and internal structure (racks, bays, cable, and equipment layout) dramatically alter the EMI signature.

As for threat determination: This program calls for measurement of a typical ambient and ESD in order to establish some shielding/hardening requirements. These requirements will reflect the criticality of the function/system they refer to.

Now let me talk about the laboratory available at Ames and some of the proposed testing. We have a dual-dual configured digital flight control system that was acquired for developing the methodology of validation testing. So far we have done work in the area of software verification and reliability and failure mode analysis assessment. Under this program we'll be doing EMI testing. This information will be published in the FAA Handbook, Volume I -- Validation of Digital Systems in Avionics and Flight Control Applications DOT/FAA-CT-82/115.

A QUESTIONER: Bill, what is the time frame on that? When was "now"?

MR. LARSEN: Now? Now is very much the same situation that you have. You put together a program and go out for funds. When you acquire those funds, you do what you have to do within the available monies. We started early this spring to put together a program plan, and we hope to start testing in April or May of '83 and then come out with the tentative guidelines and standards during the fall of '83.

DR. YOUSSEF: That will be '84? Standard -- after the test -- the test will be '83, right?

MR. LARSEN: Early '83 and '84, yes. The results of the test will be available in late '83 and a draft standard or advisory circular in 1984.

Here is a picture of the facility we have. On your right you see a flight-control system and then on the left side you see a PDP 11/60. We're able to support an aircraft model in the 11/60, and then have the full flight-control system on the right side.

This is a more detailed view. Down at the bottom we have the actual flight control computer, and the other computer over here, with the glare shield panel and some of the instrumentation above.

During the testing we will have to first find out where our system is the softest and protect that so we can then do our measurements on the actual airborne equipment. This unit was purchased about 3 yr ago, and it was delivered about 2 yr after the original purchase.

During the initial testing, we would document the system in terms of emissions and then go back and look at it in terms of susceptibility. The harmonics issued from the various clocks in the computer. That's probably where most of the emissions will come from, but we'll go by the system with a fine-tooth comb to see where we stand in both the area of emissions and susceptibility.

Here is a continuation of some of the tests that we intend doing.

That's what I have. Stan Schneider is next.

TABLE 18-1.- BACKGROUND

-
- ONE OF THE MOST PROFOUND RECENT ADVANCES IN COMMERCIAL JET TRANSPORTATION HAS BEEN THE ADVENT OF DIGITAL AVIONICS. ALMOST EVERY FUNCTION OF THE FLIGHT OPERATIONS IS NOW INVOLVED OR WILL BE INVOLVED WITH DIGITAL MONITORING OR CONTROL TECHNIQUES.
 - HOWEVER, DIGITAL DEVICES ARE CURRENT DEVICES RATHER THAN VOLTAGE DEVICES AND AS A RESULT ARE SOME 10 TIMES MORE SUSCEPTIBLE TO UPSET THAN THE PREVIOUS ANALOG DEVICES.
-

TABLE 18-2.- OBJECTIVE

TO REVIEW BOTH EMISSIONS AND SUSCEPTIBILITY OF DIGITAL EQUIPMENT IN ORDER TO UNDERSTAND:

- EMC REQUIREMENTS FOR PROTECTION AGAINST LIGHTNING AND INTERNALLY GENERATED EMI FOR CRITICAL SYSTEMS.
 - REQUIRED PROTECTION WHEN COMPOSITE FUSELAGE MATERIALS ARE USED INSTEAD OF METAL MATERIALS.
 - REQUIRED/SPECIAL TEST METHODS TO ENSURE DIGITAL DESIGNS ARE PROPERLY TESTED TO THE NECESSARY DEGREE OF TRANSIENT HARDNESS BASED ON SYSTEM CRITICALITY.
-

TABLE 18-3.- NEED

-
- THROUGH UNDERSTANDING OF ALL THE DATA ASSOCIATED WITH DIGITAL AVIONICS AND AIRCRAFT THREAT ENVIRONMENTS
 - WORST CASE THREAT DETERMINATION
 - DEFINITION OF SURVIVABILITY SPECIFICATION
 - ESTABLISH SURVIVABILITY SPECIFICATION LIMITS
 - BOX AND SYSTEM TEST PROTOCOL
 - AIRWORTHINESS STANDARDS
 - QUALIFICATION TESTING
 - IMPLEMENTATION GUIDELINES
-

TABLE 18-4.- LABORATORY TESTING (FY 1983)

REPRESENTATIVE DIGITAL FLIGHT CONTROL SYSTEM

I. EMISSIONS

- ELECTRIC-FIELD RADIATED EMISSIONS PROFILE
- POWER LEAD EMISSIONS PROFILE (NARROW AND BROADBAND) STABILIZED LINE IMPEDANCE

II. SUSCEPTIBILITY

- CONDUCTED SUSCEPTIBILITY/POWER LINE SPIKES
- MAGNETIC INDUCTION SUSCEPTIBILITY-I/O CABLES
- SYSTEM RADIATED SUSCEPTIBILITY
 - MAGNETIC INDUCTION
 - ELECTRIC FIELD

I. EMISSIONS

A. ELECTRIC-FIELD RADIATED EMISSION PROFILE (1 MHz-1 GHz)

1. SUBSYSTEM CLOCK HARMONICS
2. TOTAL SYSTEM
 - a. LOOK AT WHOLE SYSTEM
 - b. SMALL LOOP PROBE/HIGHEST EMISSIONS SOURCE

B. POWER LEAD EMISSIONS PROFILE

1. CONDUCTED EMISSIONS ON POWER LEADS (NARROW AND BROADBAND)
2. SNIFFER PROBE/LOCATION OF EMISSIONS

II. SUSCEPTIBILITY

A. CONDUCTED SUSCEPTIBILITY/SPIKED ON POWER LINES

1. POWER LINE CONDUCTED SUSCEPTIBILITY
2. IEEE 472 TEST
3. ESD POWER LINE INDUCED TEST
4. NORMAL MODE TEST

B. I/O CABLES/MAGNETIC INDUCTION SUSCEPTIBILITY

1. SIGNAL LINE/MAGNETIC INDUCTION TESTS
2. ESD SAE 1499 TESTS

C. SYSTEM RADIATED SUSCEPTIBILITY

1. ELECTRIC-FIELD RADIATED SUSCEPTIBILITY/STD CASE TEST
 2. ELECTRIC-FIELD RADIATED SUSCEPTIBILITY/CASE TEST W/ESD GENERATOR
 3. ESD BROADBAND RADIATED TEST
 4. ESD DIRECT DISCHARGE
 5. ELECTRIC-FIELD RADIATED TEST/SHIELDED ENCLOSURE
 6. MODIFIED ELECTRIC-FIELD RADIATED TEST/TUNED LOOP SWEEP TEST
-

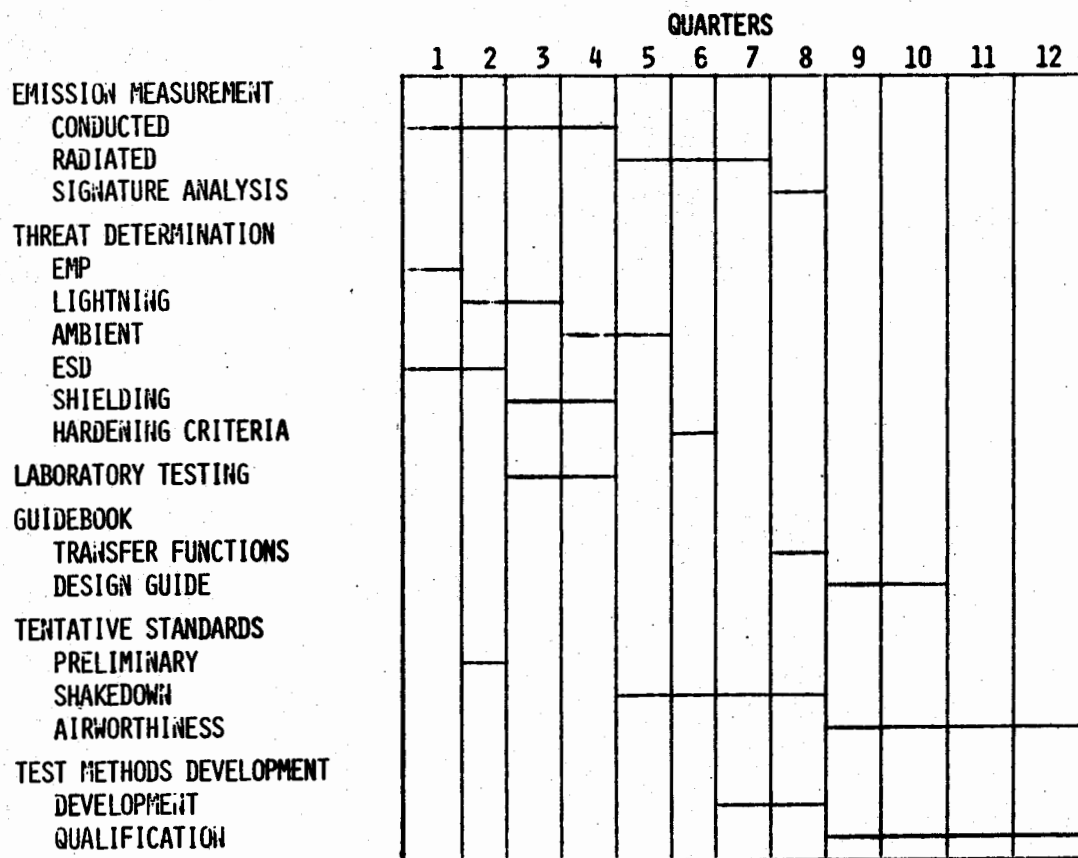


FIGURE 1
PROGRAM PLAN

Figure 18-1.- Program plan.



Figure 18-2.- Digital flight control verification laboratory.

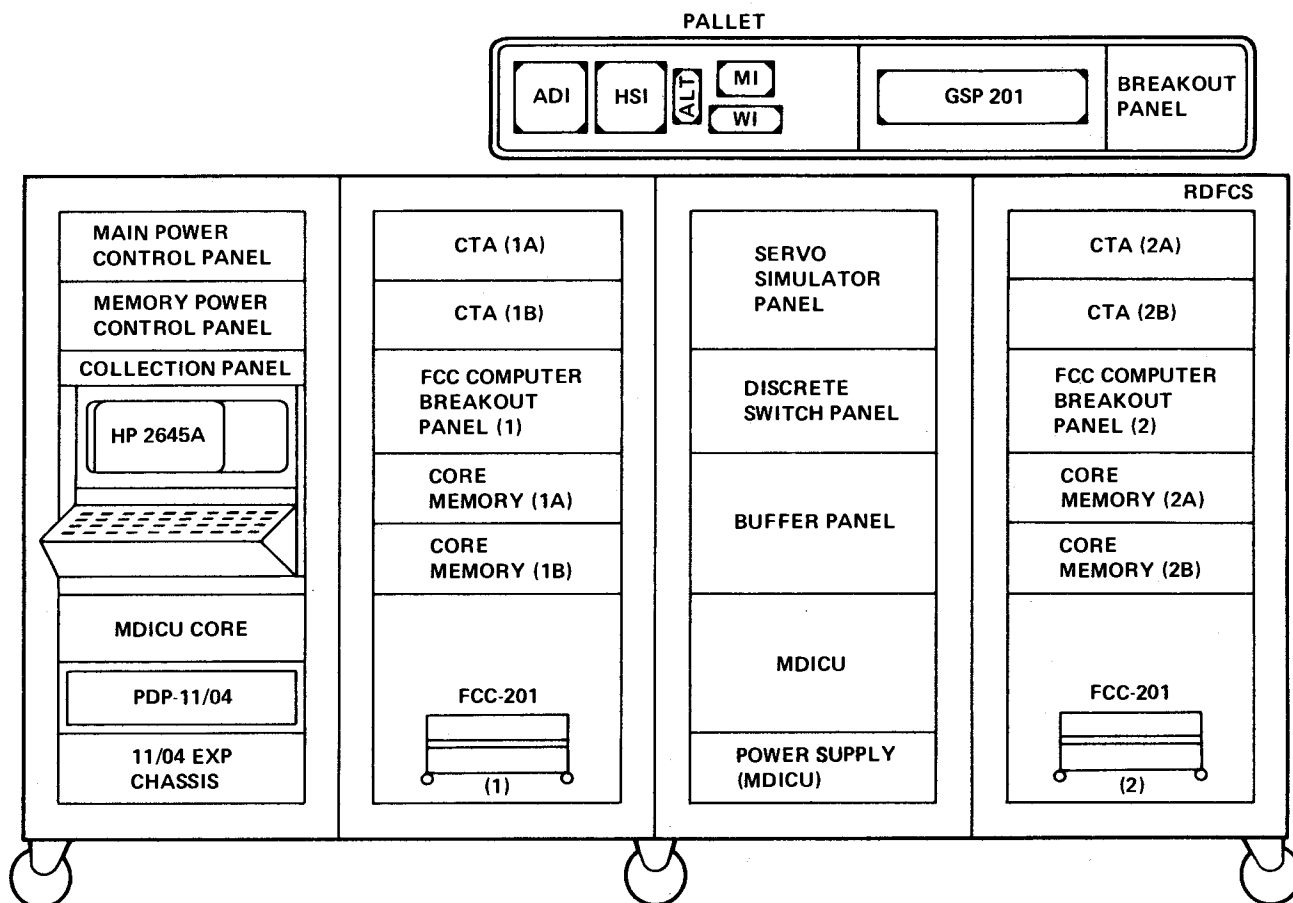


Figure 18-3.- Pallet components.

WORKSHOP SUMMATION

S. D. Schneider

The Boeing Company
Seattle, Washington

MR. SCHNEIDER: Thank you. I asked Nick Rasch and Bill Larsen if I could have a few minutes to wrap up.

First of all, I can speak for Boeing in thanking you gentlemen for allowing us to participate. As you recall from the first day, this was definitely an FAA-sponsored workshop. We provided the physical plant and have the public relations people, Howard Quig, John Gerike, and Kerry Kelly, to thank, plus Jim Bogard from our organization.

Also, if you're interested in lightning data, we have received some from our lightning data logger. You might contact Felix Pitts, our program manager on the NASA Langley Research Center F-106, for data. He releases whatever data have been recorded.

I've talked to a few people about work on ESD and lightning for ground-based computers, and they pretty well echo what Chris has said.

However, I question if ESD is a concern for flight decks or avionic equipment on aircraft. I suspect, and I emphasize suspect, that the ground-based computed people are trying to get things faster and cheaper and probably don't have the expertise that the airframe and black box people have in designing equipment against such events.

When there is a need for ESD protection (it's usually some special box), there's normally some special handling procedure involved. Sometimes it's just putting a little static discharge placard on it to warn people, "Beware of touching the pins if you're hot." In a flight deck it's hard for me to envision a person walking in there highly charged. It's difficult for them to get into their seat and carry a charge with them. They might touch something on the way. And once they're airborne I can't really envision a significant charge source. So I just raise the question, Chris, whether that really applies to aircraft, at least to commercial jet transports.

Keith Kalanquin, would you like to add something?

SUPPLEMENTARY REMARKS

Keith M. Kalanquin

The Boeing Company
Seattle, Washington

MR. KALANQUIN: Yes, Stan, I have a couple of comments I'd like to make.

One of the first things I would like to say is, I hope you didn't get confused in my discussion about single-point shield grounds. I do agree that we talk about digital circuitry and digital logic, and that those interfaces do require a dual-shielded ground, where the shields are grounded on each end.

As you go into the faster rise times required for the bit rates of the future systems, then those shield grounds become much more important. The need for them to be short becomes very obvious.

There's another thing I'd like to mention. We wrote the D6-16050-2 document just prior to the start of the 767 program. Over the past few years, while I was working on the 767 program, I have had an opportunity to observe where the document has, in certain areas, failed us.

I shouldn't say "failed" because it hasn't, as far as I'm concerned. What bothers me, and I think it should be of concern to you, is that if you go into digital technology and get into the development of your circuit design, the loop areas of your circuit cards become very important. EMC characteristics of the system can be directly related to this layout.

The problem that I see with EMC development and testing, and particularly on measuring generated interference is that a number of avionics manufacturers cannot afford to maintain their own EMC facilities. Consequently, they go to an outside testing agency for this testing. This then becomes very expensive.

So often what you see happen is the equipment manufacturers will wait until the last minute during qualification tests to really do some detailed testing of their equipment.

By that time in the program, if you've got a problem, you've really got a problem. Both you as the buyer and the equipment manufacturer as the seller, are right up against the wall in meeting the deadline. What I'm toying with is developing (particularly in future programs as we get into the digital world where we've got the faster rise times, and the faster data rates when it really becomes important) some means of encouraging the equipment manufacturer to do testing early in the program. To know the EMC characteristics of the circuit board layout, to make sure there's no common impedance or inductances in the ground circuit, or that the transient responses will not couple over to other circuits. Good EMC design can only be achieved by EMC testing prior to design and packaging freeze dates.

If we get into exotic test setups, that require the equipment manufacturers to go out and buy expensive equipment that will be used only 10% of the time and then will sit on the shelf for 90% of the time, we have automatically forced the

manufacturers to use an outside testing agency. The economics of the situation force them to do this. We've got to encourage the manufacturers into early testing.

MR. SCHNEIDER: Thank you, Keith. And once again, Nick Rasch, Bill Larsen, thank you very much for letting Boeing participate. I'll turn it over to the man of the hour again, Chris Kendall.

REVIEW OF THE WORKSHOP AND EMI PROTECTION

Concepts for Advanced Technology Aircraft

Chris Kendall

Chris Kendall Consultants
Mariposa, California

MR. KENDALL: Again, as we try to summarize, if there are any questions on your minds, I'd like to give you an opportunity to ask them, since we're at the final hour.

Okay. We covered a lot of ground. Recognizing that various organizations have presented some interesting data with a lot of correlatable information, I think we are seeing one underlying theme concerning digital systems. We see today's data rates going higher and higher. Right now we're looking at a 1-megabit data stream perhaps through 1553. I see the 429 bus, and others in use today, being somewhat lower.

We are now looking toward a new generation in the 10 to 20 megabit range, and perhaps in the future as high as 100 megabits. We must recognize that making this transition through these various steps of data speeds undoubtedly will require proper sampling and proper maintenance, digitally speaking, for the air vehicle. We are going to be getting into some very serious digital avionics systems.

The concerns are what the differences, if any, will be and how we are going to make this transition.

Lightning is another area of concern on which we've seen a lot of information. We're finding that even the threat of lightning is an area in which our understanding is growing . . . the true waveforms and true threats to the vehicle, including what the lightning might do to the digital systems.

We've covered lots of information. We've had the opportunity to see what happened on some major aircraft, including the F-18. We've heard some projections as to where the cabling might have to go if we go into these higher-speed data rates, with a definite hope of going to fiber optics as an ultimate solution.

But in the interim, there's the possibility of going to better shielding. Someone mentioned double-shielded, braided cables as a necessity to contain radiation of these digitized signals. The possibility of going to some advanced type of cable shielding is something that will have to be explored.

There was mention this morning about the need to terminate these cables and about the different techniques to maintain this hardening, depending upon the level of hardening required (EMP, lightning, or what have you).

The possibility of going to EMI hardened connector back shells, etc., was mentioned where there is definite or very severe hardening needed against the EMI threat. We see a need to look at the digital transfer techniques, especially in light of composites, and perhaps also a need to look toward better hardening of these data transfer concepts. I would like to underline one thing in all this

that perhaps hasn't really been 100%. As we go to these new digitized systems, we undoubtedly will be marrying the analog and digital technologies. We still live in an analog world.

Therefore, we cannot expect to take this hardening only to the digital lines coming into a given piece of equipment. If a piece of equipment performs both analog and digital functions, and we use both analog and digital inputs, then the amount of hardening to the analog leads cannot be ignored. The analog cable also receives the threat, whatever the cause, and unless these leads are protected, we're going to have some concerns.

The same thing applies in reverse for radiation. We have heard concerns and some examples of digital radiation interfering, because of its harmonic content, with certain receivers which have become increasingly sensitive over the years. We have to be concerned not only about the digital cables themselves, but also the analog leads as radiators of the high-frequency energies coupled onto them from the internal PC board layout techniques and wire runs within various avionic boxes. Once this coupling occurs, it seeks any antenna to escape. The analog cables, the digital cables, and even the power line cables are going to be important to us to rethink.

Recently we've had a case in which an EMI filter was located 10 in. inside a digitized system. The power lines were shielded by a braided cable from the EMI filter to the exiting connector, and the shield was grounded at both ends in an RF manner. Yet the power lines caused excessive radiation emissions in the 100 MHz band. The braided cable could not contain the high amount of RF energy coupling through the filter. This is not an unusual situation, we see it often.

In this case, a solution was to add two small-value capacitors between each ac input pin and chassis potential to eliminate the threat right at the connector. We recognize that this threat is going to get worse, in that it can potentially get worse. I'm sure that's why we needed to look at the EMC problem now, and that's why we're all interested in reviewing the EMI problems. We want to ensure that these potential problems are reviewed now, and that our concerns are projected toward the days to come, when our data rates and oscillator frequencies increase.

Our main concerns are real — the need for testing and for sampling faster and faster rise times is obvious. Some of the instrumentation that was discussed this morning has shown that need. We've gone from fairly slow sampling rates, but we must now go to faster sampling rates to better understand the rise time, amplitude, and waveform parameters of the environment on board an airplane. Once we can better categorize these facts and the energy behind them, I think we can better address the problem.

Some concern has been voiced, of course, about things like static discharge; things we don't really know exist; things we have to explore. We have opportunities to see other disciplines going through this. They didn't realize problems existed. When you shared in the commercial sector, there were no measurements.

Now, we probably need to launch into a program, such as Bill outlined, to explore particular threats. Do they really exist? Or are they theory? Documentation is important. Once this has been done, we can review the standards, and the programs

for better investigation, as Bill mentioned, and ultimately come up with some guidelines in the design aspects.

Through education, we hope subcontractors who are in a financial bind, as Keith mentioned, can meet the need and are willing to do the necessary testing even though they don't have their own facilities and often not even their own engineering capabilities, at least not at a high level.

I don't think anyone building a piece of avionics today wants to do it incorrectly. They do the best they can, working to what they believe are the proper design techniques. Unless we're aware of the shortcomings of certain techniques, I think the manufacturer will not be able to implement all of the things that could be useful in controlling this aspect of design.

Through guidelines and education, I believe we can better understand these threats and how to combat them. Therefore, we'll end up with systems that are much more durable and reliable as we go into these new advanced digitized avionics designs.

That's about all I had to say. Anyone have a comment?

A SPEAKER: I'm curious about the fiber optics. How much relief from EMI do we get, or are fiber optics just as susceptible in a different area?

MR. KENDALL: That's a good question. I'm not an expert; perhaps someone who is can comment. One thing I have experienced in dealing with fiber optice — they're going to put me out of business. Maybe that's good. They're not a conductor; the cable simply does not conduct. So it does not have the opportunity to act like an antenna.

There are some concerns about the hybrids used today that receive the energy, amplify it, and turn it into usable data.

We have had a number of areas of concern about the silver epoxy used to take the substrate and ground it to the case. The epoxy had enough impedance so that we were able to inject ground noise into that input and cause the output to be scrambled. So we know that there are some critical areas.

They are hybrids. There's a lot of care in the design. We're dealing with extremely high-gain amplifiers that are fairly broad. Therefore, there are concerns. But, that is an easier concern to fix than fixing an entire 100- or 200-ft cable. In some respects it has some real advantages. There may be concerns about optical conditions under certain radiations. I don't know.

Anyone else care to comment on that?

MR. ZIGLER: The wide-band aspect of the fiber optics makes it very valuable. Of course, we really want to go to a lot of megabits, and that's the way to go. The EMI, your big reduction, is because of your long cables and the little problems you have in the conversions. We have always had that kind of problem in the box; but we've eliminated the cables, which I'd say are 99% of the problem, at least in the aircraft.

MR. KENDALL: Thank you.

MR. ZIGLER: The only problem I think we have is a possible effect from nuclear-type radiation, but I think if we have that kind of a problem, we have others also.

MR. KENDALL: Any other comments on that area?

MR. SCHNEIDER: Stan Schneider, Boeing. We still have the power line problem.

A SPEAKER: Yes, power lines can be filtered a lot easier than . . .

MR. SCHNEIDER: True.

MR. KENDALL: Good point.

Any other questions? Yes?

A SPEAKER: I was just going to point out, with the fiber optics comes a problem with the lower reliability of the emitters — the light emitters themselves — which translate the data to pulses. We may be trading one thing for another if we're not careful.

The pulse itself gets degraded by the fiber. And under pressure, visible pressure on the fiber, you can change the wave shape. So there is a problem.

We should be very careful that we are not trading one set of problems, that we're aware of, to another set we're not so aware of.

MR. KENDALL: Very good.

MR. ZIGLER: I should add, reliability is one of the big things holding fiber optics back. They are having connector problems. I think it will be a few years before we see them.

MR. KENDALL: Yes.

Well, I think we all appreciate your kindness as a listener and also as a contributor, and I certainly have enjoyed doing what I could. We would appreciate any comments you have, in writing or otherwise. I'm sure they can be valuable as we try to pursue these areas.

EMI WORKSHOP ATTENDEES

<u>Name</u>	<u>Company</u>	<u>Mailing Address</u>
Michel Allouche	Airbus Industrie	B.P. No. 33 Certification Dept. 31700 Blagnac, France
D. T. Auckland	Syracuse Research Corp.	Merrill Lane Syracuse, NY 13210
Glenn Bailey	Beech Aircraft Corporation	9709 E. Central, M/S E-20 Wichita, KS 67201
J. A. Beteille	Aerospatiale France	Abet/sy 31060 Toulouse, Cedex, France 03
James Bogard	Boeing Company	P.O. Box 3707, M/S 47-31 Seattle, WA 98124
Peter Botocki	Airbus Industrie	B.P. No. 3 Saint Martin Du Touch 31026 Toulouse, Cedex, France
William E. Broadway	Gulfstream American	FAA DER, P.O. Box 2206 Dept. 895, M/S D-04 Savannah, GA 31402
N. B. Christenson	Federal Aviation Administration (FAA)	AWS-150, Airplane Branch P.O. Box 1689 Fort Worth, TX 76101
Joseph T. Cincotta	FAA	AWP, ACDO 33 831 Mitten Road Burlingame, CA 94010
Robert Close	Sperry Flight Systems	6847 S. 180th Street Seattle, WA 98188
A. T. Coleman	Gates Learjet Corp.	Tucson Int'l. Airport Dept. 2-761, P.O. Box 11186 Tucson, AZ 85734
William W. Cooley	Boeing Military Airplane Company	P.O. Box 3707, M/S 41-47 Seattle, WA 98124
D. M. Corrington	General Electric Company	Mail Drop J40, Neumann Way Cincinnati, OH 45215
Lynne D. Covalt	FAA	DOT/FAA NMFSDO-61 9010 E. Marginal Way S. Seattle, WA 98108

<u>Name</u>	<u>Company</u>	<u>Mailing Address</u>
Tom Cronley	Lockheed Georgia Company	Dept. 7293, Z410 86 S. Cobb Drive Marietta, GA 30063
Duncan Cropper	Chandler Evans, Inc.	Charter Oak Blvd. West Hartford, CT 06101
Peter Cuneo	FAA	181 S. Franklin Ave., Room 202 Valley Stream, NY 11581
R. Davies	Lucas Aerospace	York Road, Hall Green Birmingham, B288LN England
Frank Day	FAA	NMFSDO-61, FAA Building Boeing Field Seattle, WA 98108
Carlisle Dolland	Airesearch Mfg. Co.	2525 W. 190 St. Torrance, CA 90503
D. O. Edwards	Alaska Airlines	P.O. Box 68900 Seattle, WA 98168
John S. Ehret	FAA	P.O. Box 92007, ANM 174W Worldway Postal Center Los Angeles, CA 90009
Jim Erickson	FAA	DOT/FAA, ASW-216 P.O. Box 1689 Forth Worth, TX 76101
Jim Findlay	Douglas Aircraft	CI-E26, 36-41 3855 Lakewood Blvd. Long Beach, CA 90546
Hal E. Foland	FAA	Federal Office Building 601 E. 12th Street Kansas City, MO 64106
John S. Foster	Boeing Commercial Airplane Company (BCAC)	Dept. 7450, M/S 6A-29 2037 Seattle, WA 98124
Ted Frantz	BCAC	P.O. Box 3707, M/S 78-30 Seattle, WA 98124
Sam K. Frick	FAA	4344 Donald Douglas Drive Los Angeles Area Office Long Beach, CA 90808
Walt Glockner	FAA	Great Lakes Region 2300 E. Devon Des Plaines, IL 60018

<u>Name</u>	<u>Company</u>	<u>Mailing Address</u>
John R. Gozinsky	BCAC	P.O. Box 3707, M/S 47-31 Seattle, WA 98124
E. J. Haldas	FAA	P.O. Box 92007, AWP-250 Worldway Postal Center Los Angeles, CA 90009
Leonard O. Hendry	Beech Aircraft Corporation	9709 E. Central, M/S 90-E14 Wichita, KS 67201
William J. Hillman	Lockheed	D7340, Bldg. 90 P.O. Box 551 Burbank, CA 91520
David J. Horne	Lucas Aerospace	155 Rt. 46 West Fairfield, NJ 07621
R. J. Huhn	FAA	Foreign Aircraft, ANM-150S 9010 E. Marginal Way S. Seattle, WA 98108
Capt. Dale W. Istwan	Airline Pilots Assn.	11534 Corlyn Drive St. Louis, MO 63138
T. E. Jackson	Transworld Airlines	Kansas City Int'l Airport P.O. Box 20126 Kansas City, MO 64195
Kris Jankowski	Chandler Evans Co.	Charter Oak Blvd. D940 West Hartford, CT 06101
Z. A. Jennings	General Electric Company	1000 Western Ave. Mail Drop, WL 364 Lynn, MA 01910
R. Earl Jobe	Jobe Enterprises, Inc.	DERNM121 19653 Military Road, S. Seattle, WA 98188
Paul K. Jodon	Avco Lycoming	550 South Main Street Stratford, CT 06497
C. W. Kaiser	FAA	ACE 130A, Box 20636 Atlanta, GA 30320
Keith M. Kalanquin	BCAC	P.O. Box 3707, M/S 02-15 Seattle, WA 98124
Chris Kendall	Chris Kendall Consultants	5705 Pilot Peak Road Mariposa, CA 95338

<u>Name</u>	<u>Company</u>	<u>Mailing Address</u>
Fred Keuhl	Ozark Airlines	OMO Engineering Box 10007 Lambert Airport St. Louis, MO 63145
Frank King	General Electric Company	Mail Drop E-184, Neumann Way Cincinnati, OH 45215
Stephen R. LaCroix	Garrett Turbine Engine Co.	111 S. 34th Street Phoenix, AZ 85010
P. M. Lance	Lucas Aerospace	Digital Systems York Road, Hall Green Birmingham B288LN England
Wayne Langston	FAA	Airplane Branch, AWS-150 P.O. Box 1689 Fort Worth, TX 76101
Bill Larsen	FAA	P.O. Box 25 Moffett Field, CA 94035
Darrell Lowe	General Electric Company	112 Andover Park E. Aircraft Engine Business Group Seattle, WA 98188
James E. Lytle	FAA	SW-GADO-8, FAA Building Lake Front Airport New Orleans, LA 70126
Charles A. Mackal	FAA	ANM-130S, FAA Building Boeing Field Seattle, WA 98108
Larry D. Malir	FAA	Aircraft Certification 601 East 12th Street Kansas City, MO 64106
Gerald J. Markey	FAA	Freq. Eng'r. Branch AAF-730AAF-730/AES-510 800 Independence Avenue Washington, DC 20591
G. Martinec	Boeing Company	1555 Union Avenue, N.E. #10 Renton, WA 98002
Gerald M. Masson	Johns Hopkins University	EE & CS Dept., Barton Hall Baltimore, MD 21218
I. Mehdi	Boeing Company	P.O. Box 3707, M/S 47-31 Seattle, WA 98124

<u>Name</u>	<u>Company</u>	<u>Mailing Address</u>
Kenneth W. Meyer	FAA	NW Mtn Region, Systems Cert. 3501 N.W. 67th Street Seattle, WA 98117
Donald P. Michal	FAA	ACE-115C 2300 E. Devon Des Plaines, IL 60018
Stu Miller	FAA	P.O. Box 92007, ANW1405 Worldway Postal Center Los Angeles, CA 90009
Milton Moorhead	BCAC	P.O. Box 3707, M/S 73-32 Seattle, WA 98124
E. N. Mosman	FAA	Systems and Equipment Section Room 2008, Terminal Building Mid Continent Airport Wichita, KS 67238
Kevin Mullin	FAA	ANM-104S 9010 E. Marginal Way S. Seattle, WA 98108
Lauren Nelson	Eastern Airlines	International Airport Miami, FL 33157
Gary Noble	Boeing Company	3303 Casino Road, So. M/S 07-09 Everett, WA 98203
Robert Norton	Boeing Company	P.O. Box 3707, M/S 47-31 Seattle, WA 98124
K. A. Ostrander	3M	Ryan Stormscope 6530 Singletree Drive Columbus, OH 43229
Edward L. Park	FAA	DOT/FAA AWE 253 New England Region 12 New England Ex Park Burlington, MA 01803
Robert Patterson	Collins Air Transport Division, Rockwell Int'l	550 S.W. 7th Street Renton, WA 98055
Max Peacock	FAA	DOT/FAA, ANW-103 9010 E. Marginal Way Seattle, WA 98108
Herb Peters	FAA	P.O. Box 92007, ANM-173 W Worldway Postal Center Los Angeles, CA 90009

<u>Name</u>	<u>Company</u>	<u>Mailing Address</u>
Richard F. Phelps	Pratt & Whitney Aircraft	400 Main Street, M/S 121-05 E. Hartford, CT 06108
Felix Pitts	NASA Langley Research Center	M/S 477 Hampton, VA 23665
Nickolus Rasch	FAA	Technical Center Atlantic City Airport, NJ 08405
A. Rasmussen	FAA	FAA Building, Boeing Field Seattle, WA 98108
S. D. Schneider	Boeing Company	P.O. Box 3707, M/S 47-31 Seattle, WA 98124
J. Selboe	Norwegian CAA	Aeronautical Inspection Dept. P.O. 18 1330 Oslo Airport, Norway
Cliff Scouby	McDonnell Aircraft Company	Dept. 313, Building 33 P.O. Box 516 St. Louis, MO 63166
John Small	BCAC	P.O. Box 3707, M/S 47-19 Seattle, WA 98124
H. M. Smith	Douglas Aircraft	3855 Lakewood Blvd., MC 36-43 Long Beach, CA 90846
C. D. Stackhouse	FAA	FSDO-65 6501 E. Apache Tulsa, OK 74115
John Stangohr	Beech Aircraft Corporation	M/S 90E-14 9709 E. Central Wichita, KS 67201
C. C. Sturm	FAA	AWS-121 800 Independence Avenue, S.W. Washington, DC 20591
Tim Teckman	BCAC	P.O. Box 3707, M/S 73-32 Seattle, WA 98124
Ted Thomas	Boeing Company	P.O. Box 3707, M/S 47-31 Seattle, WA 98124
Ron Thomas	Sperry Avionics	Box 29000 Phoenix, AZ 85038
R. W. Thompson	FAA	Western Aircraft Certification P.O. Box 92007, ANM-173W Worldway Postal Center Los Angeles, CA 90009