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Final Report

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16. Abstract

The Federal Aviation Administration developed a Risk Assessment Tool (RAT) for the Electrical Wiring Interconnection System (EWIS). This report documents further developments of that RAT. The developments include the results of a paired comparison workshop in which expert judgment was elicited on the effects of wire environment on wire failure rate. This data was used to develop a multivariate function that when it is scaled using historical failure data from the emergency path lighting system, the function estimates the failure probabilities of wires for most of the environmental and physical conditions found on aircraft. A damage potential analysis was expanded to include a model of damage to structure that depends on the power, energy, and heat dissipation of an electrical arc. An agreement between the developed model and damage data was acceptable. However, potential improvements to the model have been identified. Methodologies and software tools have been developed to improve the accuracy and efficiency of importing the required aircraft EWIS data into the tool's model database. Using these tools, 7783 wires, 1774 bundle sections, and 579 connectors were modeled and imported into the database. Finally, a prototype report was generated to improve consistency between the reports generated by the EWIS RAT and Aircraft Certification Office expectations. These improvements have been integrated into the EWIS RAT.

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LIST OF ACRONYMS

2D	Two-dimensional
3D	Three-dimensional
ACO	Aircraft Certification Officer
AFHA	Aircraft Functional Hazard Assessment
AWG	American Wire Gauge
CAD	Computer-aided design
CATIA	Computer-Aided Three-Dimensional Interactive Application
CFR	Code of Federal Regulations
EPL	Emergency Pathway Lighting
EWIS	Electrical Wiring Interconnection Systems
FAA	Federal Aviation Administration
FMES	Failure Modes and Effects Summary
ID	Identification number
LRU	Line replacement unit
NEL	Negative Exponential Life
OEM	Original equipment manufacturer
PDF	Probability Density Function
PHM	Proportional Hazards Model
PSSA	Preliminary System Safety Assessments
RAT	Risk Assessment Tool
SDR	Service Difficulty Report
SFHA	System Functional Hazard Assessment
STC	Supplemental Type Certificate
VAC	Voltage alternating current
VDC	Voltage direct current

EXECUTIVE SUMMARY

There has been a greater understanding of the importance of the Electrical Wiring Interconnection System (EWIS) in aircraft safety in recent years. However, discussion continues about how the EWIS should be analyzed in an aircraft safety assessment. The Federal Aviation Administration (FAA) has initiated many programs to improve the understanding of safety issues related to the EWIS. This report documents efforts to further develop the EWIS Risk Assessment Tool (RAT).

Fourteen wiring experts from various backgrounds (military, commercial, and regulatory) that had experience with EWIS failures attended a paired comparison workshop. The Bradley-Terry Model, using the Negative Exponential Life method of analysis, was applied using the experts' answers to a paired comparison survey of wire failures in aircraft environments. From this, wire failure functions for both opens and shorts were generated based on the wire properties, routing, and environmental conditions. These failure functions were scaled using historical failure data from one environment found on aircraft. However, the appropriateness of the scaling is questionable and further research may be required to validate the findings. This information was integrated into the EWIS Failure and General Information database of the EWIS RAT.

An analysis of laboratory and field experience data was performed to provide better estimates and explanations of arcing damage. Models were created based on the amount of arc energy available and the dissipation of that energy in the target. Predicted results of the models showed good agreement with laboratory tests. However, further refinements could be made that would improve the accuracy of the models. This improved arcing damage information was integrated into the EWIS RAT program's damage potential analysis.

Developments have been made in the EWIS RAT to simplify the collection and entry of data. This was done in coordination with an aircraft manufacturer to gather the necessary information from different groups within the organization. EWIS data from a recently certified aircraft was imported into EWIS RAT. Although much of the data was available, some of the data required a methodical integration between multiple database sets for the necessary EWIS RAT data to be generated. Some of the data had to be manually generated since certain aspects necessary for EWIS safety reports were not generated by the original equipment manufacturer (OEM). Integration of the EWIS RAT or any EWIS risk assessment methodology would require changes to current OEM design processes. Using the aircraft information made available by the OEM, EWIS safety reports were generated to meet criteria outlined as part of Title 14 Code of Federal Regulations Part 25.1709.

The EWIS RAT was developed to be as general as possible, giving consideration to varying nomenclatures and different aircraft configurations. The EWIS RAT can be useful in the certification process for an EWIS evaluation.

1. INTRODUCTION.

1.1 BACKGROUND.

The Electrical Wiring Interconnection System (EWIS) Risk Assessment Tool (RAT) software (hereinafter referred to as the tool) was developed to aide users in the formulation of risk assessment of the aircraft EWIS. While the tool is still in its beta version, it appears that it may be helpful in the performance, understanding, and standardization of the EWIS risk analysis for a Type Certification (TC) or Supplemental Type Certificate (STC).

The software is composed of two databases that feed the analysis/report generator module. The EWIS Model database collects and organizes information relevant to an aircraft's EWIS design. The EWIS Model database contains aircraft design-specific data that are stored at three distinct levels: the wire level (wire type, wire gauge, system, voltage, circuit protection, failure effect, etc.), the bundle level (constituent wires, curvature, length, adjacent bundles, etc.), and the zonal level (vibration, temperature, exposure to fluid, etc.). In addition to EWIS data, the EWIS Model database also contains aircraft and system safety data that can be used to drive EWIS separation analysis for the EWIS. The EWIS Failure and General Information Database contains information that is non-aircraft-specific on the following: EWIS failure data, damage potential data, Air Transport Association system codes, environmental and operational levels, and other aircraft model-independent information. The information in these databases, which is easily updated as more data becomes available, is used to analyze the EWIS. The results of the analysis are presented in a series of reports that are designed to be useful in the certification and safety analysis process. The flow of information through the tool is shown in figure 1.

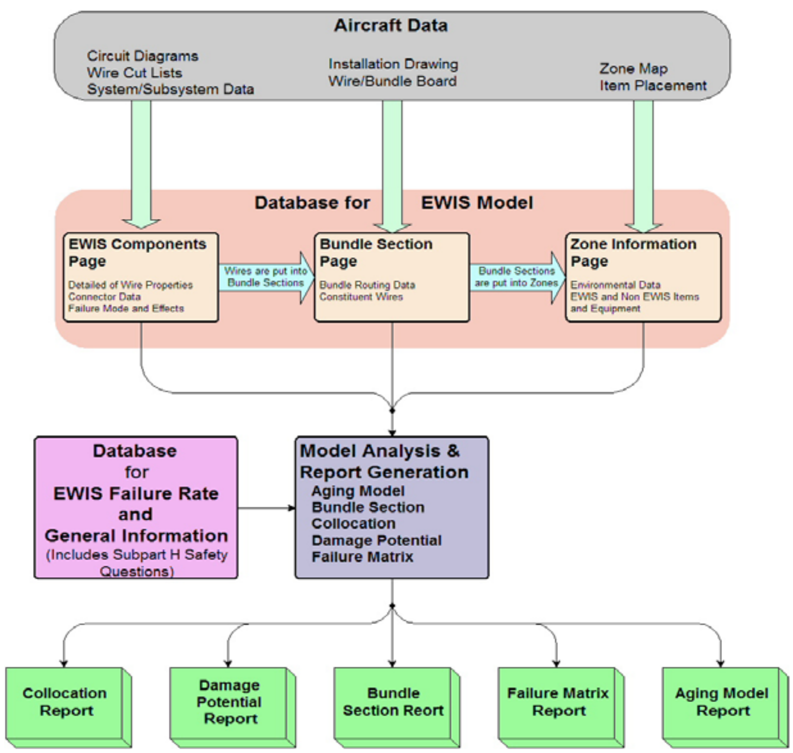

Figure 1. Flow Diagram of EWIS RAT

The tool is composed of two databases that feed the analysis/report generator module. Significant aircraft design data are collected and organized in the EWIS Model Database, and non-aircraft-specific data are kept in the EWIS Failure Rate and General Information Database. Information in these databases is used in the analysis of the EWIS. The results of the analysis are presented in a series of reports that are designed to be useful in the certification and safety analysis process.

The calculation and report generation modules query the EWIS database, and/or calculate failure probabilities, etc., then arrange the results into one or several reports, depending on the desired analysis.

The following is a description of each report model.

- The Collocation Reports evaluate the collocation of systems, subsystems, failure effects etc., and can also be generated at the bundle or zonal level. In general, they should be used during development of the EWIS, and the Bundle Section Report should be used as certification documentation. However, when performing the Common Mode Analysis, the failure effect collocation report can be used to show independence of defined basic EWIS events.

- The Damage Potential Report calculates the amount of damage that can result from an arcing or an arc-tracking event in the bundle. Key bundle variables include the number and gauge of power wires, circuit protection, voltage, and wire insulation type. Damage includes potential damage to the bundle itself, adjacent bundles, adjacent equipment, structures, and flammable material. The potential damage should be considered in the Particular Risk and Zonal Analysis, and depending on the analysis, could require actions such as separation, segregation, or other mitigation techniques.

- The Bundle Section Report is the integration of the Damage Potential and Collocation Reports, and specific EWIS separation and safety issues. In this module, each bundle section is analyzed. Therefore, a risk analysis is performed on the entire EWIS. This report documents the physical failure analysis and the common mode analysis of the functional failures.

- The Failure Matrix Report lists all basic events (corresponding to those events from the individual system fault trees) and generates the probability that those basic events will occur due to an EWIS failure. These basic events can be placed into the system fault trees to obtain more accurate failure rates of the system. These include the EWIS effects on the functional failure of the system for an aircraft. With the addition of the EWIS failures, the system fault tree will delineate how the fault occurred and the probability that an EWIS failure can result in aircraft-level hazards.

- The Aging Model Report demonstrates how different environments can change the rate of EWIS failures, and therefore, the probability of basic events. If these probabilities are used in the system fault trees, then the reduction of system reliability due to an EWIS failure can be calculated as a function of aircraft age. At this time, the only aging model in the database is a hydrolytic deterioration model that is applicable only for aromatic polyimide insulation.

1.2 PRESENT WORK.

As the aviation community reviewed the tool, several concerns were raised repeatedly. These focused on four main areas: (1) What is the validity of the data? (2) Who will enter the EWIS data into the database? (3) What are the practical issues of entering all of the required data into the EWIS Model database? And, (4) What is the use of the tool and how is the tool to be used?

The goal of this project was to resolve these issues and develop a tool that would be useful to the aviation community. The following areas were researched to address these issues.

1.2.1 Validity of Data.

Research was conducted in the areas of data validity, the acceptance of the data in the aviation community, and more specifically, its acceptance by aviation regulators. These issues include both the EWIS component failure rate data and the damage potential data. In general, the EWIS component failure rate refers to both wire and connector failure rates. However, in this project, only the wire failure rate was used.

1.2.1.1 The EWIS Component Failure Rate Data.

The EWIS Component Failure Rate Data is the backbone of the failure matrix reports. The software must be able to access the failure rates for the different EWIS component failure modes under different environmental and operational conditions. In general, historical data is considered a good source for failure rate data. In the present version of the tool, the Service Difficulty Report (SDR) database was used along with a modified paired comparison methodology to develop the EWIS component failure rate numbers. As more issues continue to be reported and recorded into the databases, they can be imported to the tool. In addition, data is sparse for many different environmental and operational conditions found on an airplane. Considering both of these limitations, it is difficult to derive a multivariable function for the failure rate of EWIS components that could withstand rigorous examination; consequently, the validity of the data in the tool was subject to question.

To address these issues, a formal application of the Bradley-Terry Model for the paired comparison using expert opinion was used to develop failure equations for wire opens and wire shorts. The failure equations are functions of wire properties, bundle routing, and zonal environments. This method used the judgment of the experts, in place of in-service data, as data that is analyzed using formal methods to develop quantitatively functions of failure rates and wire environment. This method has been used by several industries where historical data is sparse, including a host of applications in the nuclear, chemical, and transportation industries, in the National Aeronautics and Space Administration, and in the application of originally designed marketing surveys.

During a pair comparison workshop, a group of 14 experts on aerospace wiring issues from military, operator, manufacturer, or regulatory backgrounds were asked a series of questions regarding the severity of different types of wiring environments. Each question involved different environments and the expert was asked to judge in which of the two environments a wire would be more likely to fail first. The data was first analyzed with regard to the consistency of the experts' answers as individuals, then as a group. The data was then analyzed using Negative Exponential Life (NEL) formulation of the paired comparison technique to derive relative failures of a set of sample environments. The NEL method was developed specifically to take elicited data from the paired comparison process and to develop quantitative relationships between the variables. A regression analysis was performed on the relative failure rates to obtain the parameters of a wire failure rate function. These relative failure rate parameters were scaled using actual historical failure rate data; the best available data was collected from one of the sample environments. The resulting failure rate function was then incorporated into the EWIS RAT program and the parameters stored in the EWIS Failure and General Information Databases.

1.2.1.2 Damage Potential Data.

The Damage Potential Analysis determines the amount of damage that can occur due to an electrical discharge or arcing event. This data can be used in Common Cause Analyses, such as Particular Risk and Zonal Analysis. Two efforts were made to improve the validity and acceptability of the software's current Damage Potential Analysis.

The first objective was to develop a model that calculates the potential damage done to EWIS and non-EWIS components and material based on the energy available in the electrical arc. Parameters of the model include source voltage, wire gauge, insulation type, circuit protection, series impedance, etc. The model was developed for damage to metallic targets, i.e., what the wire arcing damaged. Damage was measured in terms of the amount of the target that melted or evaporated. Comparison with laboratory data suggested that the dissipation of heat due to thermal conduction in the target reduces the amount of damage done to the target. A correction was made to the damage formula by introducing a heat dissipation/thermal conduction factor.

It was also found that the resultant damage to the wires involved in the arc should be considered. Not only does this reduce the energy available to damage the target, but if enough of the wire is destroyed, the arc will extinguish as the arcing distance becomes greater. In the model developed for this effort, the difference in heat dissipation due to target geometry was not considered. Initial work modeled the heat dissipation using a finite element method. The comparison of model results to laboratory test results was positive. Therefore, this technique shows promise as a method of taking geometry into consideration.

The model parameters were fit based on laboratory arcing data and were incorporated into the EWIS RAT program. Parameters affecting the calculation of the damage are stored in the EWIS Failure database and can be updated as more data becomes available.

To develop the damage potential analysis, the Beta-version damage scale of the tool was translated into levels that would more specifically describe the potential damage to the user. The damage potential was divided into four categories that were incorporated into the EWIS RAT analysis:

- Level of damage to aircraft structure and hardware (including hydraulic and oxygen lines, etc).
- Level of damage to other wires in the bundle.
- Required separation and segregation to prevent inter- and intrabundle damage.
- Possibility of igniting other items.

1.2.2 Simplifying Data Collection and Entry Into the EWIS Database.

Another area of development was to simplify finding and entering the required data into the EWIS database. In working with Cessna Aircraft Company, it was found that data exists in different places within the organization (in the wire cut sheets, harness manufacturing directions, installation drawing, etc). However, often, this data is not in a standard format that will allow easy integration of data sets from different groups within the organization. Methods were needed to bring these different data sets together in a way that they could be imported to the database.

To perform this task, original aircraft design data available from a recently type-certified aircraft was used. The major sources for the data came from a wire list data extraction from the circuit diagrams in the form of board postscript files. Additional data was obtained from Computer-Aided Three-Dimensional (3D) Interactive Application (CATIA) models of the EWIS. In some cases, additional software code had to be written to extract the desired data. A program was written to interpret the line and text information in the form board postscript file. This was done to define each bundle section and to correctly identify the branch points or the reference designators of the termination points. An additional program routed the wires from the wire list into the bundles sections using the reference designators as command points that connect the form boards and wire list data. The use of the 3D CATIA models was limited to connector locations because they were not as complete as the form board data in terms of labeling all the reference designators, etc. The complexity of interpreting the 3D CATIA models was much greater than the two-dimensional (2D) form board data and was too large a task to be completed in scope of this project. However, after a review of the content of the 3D files, it appears that many of the same techniques used in 2D could be applied in 3D.

Using the 2D form board data, the intrabundle collocation analysis could be performed; however, the interbundle and bundle to non-EWIS collocation analysis was limited to bundle sections adjacent to connectors.

The wire failure effect data was required but unavailable. While the original equipment manufacturer (OEM) had wire failure basic events in the system fault trees, the individual wire failures and modes that caused the basic events were not listed. Because the data was required in many of the analyses, it was created manually for one of the system fault trees top events. Using these methods, 7783 wire, 1774 bundle section, and 579 connector data were imported into the program.

1.2.3 Improving Correspondence With EWIS Safety Reports Generated and Aircraft Certification Officer Expectations.

After the OEM EWIS data was entered into the program, a series of safety analyses were completed. These reports were assembled into a prototype of an EWIS safety report, which can be useful to satisfy the requirements of Title 14 Code of Federal Regulations (CFR) 25.1709. As discussed previously, the reports were limited because the EWIS failure effect data was largely unavailable and because the data was, for the most part, based on the 2D form board data instead of the 3D CATIA models. It was planned that an Aircraft Certification Officer (ACO) would review the prototype reports. However, due to time constraints, the reports were not reviewed.

2. RESEARCH TASK RESULTS.

2.1 PAIRED COMPARISON ANALYSIS OF WIRE FAILURE IN DIFFERENT ENVIRONMENTS.

Accurate EWIS component failure rate data is the backbone of the failure matrix report. This data is needed when the EWIS failure effects are represented in the system fault trees and system safety analyses. This failure rate depends on the component's environment and properties. The EWIS RAT software must be able to assess the failure rates for the different EWIS component failure modes under different environmental and operational conditions.

To improve the data in the Beta version tool, the goal was to develop a multivariant function that calculated wire failures dependent on wire properties, routing considerations, and environmental conditions. (Wire properties, routing considerations, and environmental conditions will hereafter be referred to as the wire environment.) Therefore, using expert opinion, a formal pair comparison experiment was applied to the problem of wire failure. This methodology was employed because the wire failure data for the different environmental and operational conditions found on aircraft was sparse; therefore, a failure function could not be created based on only historical data.

2.1.1 Wire Failure Model.

The goal of this effort was to develop a theoretically sound model for wire failure. In this model, wire failure specifically refers to two modes of failure: fail to ground (including wire-to-wire and wire-to-structure failure) and fail to open (e.g., broken conductors).

2.1.1.1 Time to Failure Distribution.

The development of a time to failure Probability Density Function (PDF) for wire failure based on environmental factors was considered. The PDF for T_g (time to wire failure to ground) and T_o (time to wire failure to open) is assumed to be the exponential distribution given by

$$f(t_i|\lambda_i) = \lambda_i e^{-\lambda_i t_i} \quad (1)$$

where $i = g$ or $i = o$ (dependent upon failure mode modeled) and the parameter $\lambda_i > 0$ is referred to as the failure rate for failure mode i. To completely specify the distribution, this parameter must be estimated, usually from past data. The exponential distribution has been applied successfully for years in reliability and risk analysis to model the failure behavior of electronic components [1 and 2]. Assuming that the individual failure modes behave independently, the time to wire failure, regardless of failure mode, $T = \min\{T_g, T_o\}$ has an exponential PDF with failure rate $\lambda_g + \lambda_o$. Thus, each failure mode may be considered separately in the analysis.

2.1.1.2 Incorporation of Physical and Environmental Factors.

Through review of industry documents and discussion with industry experts, a list of physical and environmental factors and their critical values were compiled, as shown in table 1. This table lists the physical and environmental variables and the break points of those variables. The variables are divided into Wire Properties, Bundle Properties, and Zonal Properties. While most of the variable break points are self-explanatory, definitions for the break points of the variables Vibration and Ops/pressurization can be found in RTCA DO-160D [3].

Table 1. Environmental Factors Contributing to Wire Failure

Category	Variables	Levels			
		1	2	3	4
Wire properties	Wire gauge	4/0-8 AWG	10-16 AWG	18-22 AWG	24-28 AWG
	Conductor type	Aluminum	Copper	High-strength copper alloy	
	Insulation type	Polyimide	Hybrid (PI/FP composite)	ETFE and other FPs	
	Splices	No	Environmental	Nonenvironmental	
Bundle properties	Bundle size	Large (>1.25 in.)	Medium (0.5-1.25 in.)	Small (0.2-0.5 in.)	Very small (<0.2 in.)
	Bundle protection	Some level of protection	Not protected (open)	Protected metal conduit	
	Curvature of wire	Low (diameter >10x)	High (diameter ≤10x)		
	Bundle orientation	Horizontal/ vertical wire	Longitudinal wire		

Table 1. Environmental Factors Contributing to Wire Failure (Continued)

Category	Variables	Levels			
		1	2	3	4
Zonal properties	Operations/main traffic	Low	Moderate	High	
	Operation temperature/ Pressure	Benign (pressure and temperature control)	D1 (pressure but no temperature control)	D2 (no pressure or temperature control)	D3 (power plant high temperature and pressure not controlled)
	Vibration	Low	Moderate	High	Extreme
	Exposure corrosive fluid	Yes	No		
	Exposure conducting fluid	Yes	No		

PI = Polyimide
FP = Fluorescent penetrant
ETFE = Ethylene tetrafluoroethylene

Incorporating physical and environmental factors into a time to failure PDF is a common practice in reliability and biometry. A common model for incorporating these variables is the Proportional Hazards Model (PHM).

Usual estimation of the parameters requires an extensive amount of failure data in many environments. As this data was unavailable, the use of expert judgment was employed. Expert judgment, or subjective data, has been used successfully in risk analysis for years and there are several techniques in practice for collecting, combining, and using expert judgment. One of these methodologies is the NEL model, which is based on a popular expert judgment elicitation method known as paired comparison [4]. The approach consists of four steps:

1. Obtain a single failure environment for which there exists significant exposure time and failure data. From this environment, obtain a failure rate estimate. The emergency pathway lighting for two aircraft models were selected.

2. Select an additional number of failure environments for a paired comparison. These environments are listed in appendix D. The result of the paired comparison will be a set of failure rate estimates obtained to within proportionality constant.

3. Given the failure rate estimates obtained using the previous two steps, obtain the parameters estimates of $\beta_0, \beta_1, \ldots, \beta_{15}$ based on a regression analysis of the failure rate estimates obtained in step 2 and coded values for the physical environmental variables.

4. Compare the failure rate estimate for the failure environment selected in step 1 to the failure rate estimate using the paired comparison and regression results in steps 2 and 3 to estimate the constant of proportionality for all failure rate estimates.

Once the estimates for the parameters are obtained, the complete failure rate and corresponding PDF may be specified for any environment.

2.1.1.3 The Experts' Judgment Experiment.

Fourteen wiring experts attended a one-day workshop to participate in an expert opinion elicitation. Table 2 lists the experts.

Table 2. List of Selected Experts

Name	Position	Company/Organization
Richard Anderson	Director, Maintenance	Air Transport Association
Jerome Collins	N/A	N/A
Luci Crittenden	Flight Operations Engineer	National Aeronautics and Space Administration-Langley
Keith Fairley	Managing Director	Cable Connect Solutions
Bryce Fenton	Design and Regulatory Specialist	Cessna
Tony Heather	Senior Airworthiness Surveyor	Civil Aviation Authority
Bjorne Jakobsson	Avionic Systems Engineer	Airtran Airways
George Slenski	Principle Engineer	United States Air Force
Larry Stevick	Senior Specialist Engineer	N/A
Dane Swenson	Avionics Wiring Analyst	Delta
Mark Thomas	N/A	N/A
Kirk Thornburg	Vice President Maintenance Engineering	Airtran Airways
Glenn White	Program Analyst	Federal Aviation Administration

Initially, the experts were given an overview of how the wiring environments and the variable break points were determined and how a paired comparison was conducted. The experts were asked to compare the 15 sample environments. These environments were selected in consultation with nonparticipating experts. The selection was based on realism, minimal change in environment comparisons, encompassing a wide variety set of wiring environments.

The experts were asked to fill out 105 survey questions for both the open and shorting failure analysis. Each question compared two environments, and the experts were asked to indicate the environment (E) that would produce a failure sooner. The questions were presented in the form shown in figure 2 where, for ease of comparison, the environments were categorized according to wire, bundle, and zonal properties and the changes from environment 1 (E_1) to environment 2 (E_2) were shaded.

WIRE ENVIRONMENT 1		COMPARISON 11	WIRE ENVIRONMENT 2	
WIRE PROPERTIES			**WIRE PROPERTIES**	
Wire Gauge	18-22 awg		Wire Gauge	
Conductor Type	Copper		Conductor Type	
Insulation Type	Hybrid (PI/FP Composite)		Insulation Type	
Splices	None		Splices	
BUNDLE PROPERTIES			**BUNDLE PROPERTIES**	
Bundle Size	Moderate (0.5-1.25 in)		Bundle Size	
Bundle Protection	Not Protected (Open)		Bundle Protection	Some Level of Prot.
Curvature of Bundle	Low (> 10x)		Curvature of Bundle	
Bundle Orientation (Shock)	Horizontal/Vertical Wire		Bundle Orientation (Shock)	
ZONAL PROPERTIES			**ZONAL PROPERTIES**	
Ops/Main Traffic	High		Ops/Main Traffic	
Ops Temp/Alt	Benign (P&T Controlled)		Ops Temp/Alt	
Vibration	Moderate		Vibration	High
Exposure to Corrosive Fluid	No		Exposure to Corrosive Fluid	
Exposure to Conductive Fluid	Yes		Exposure to Conductive Fluid	

Figure 2. Paired Comparison Question Format

2.1.1.4 Individual Experts.

The first analysis conducted was to determine if the experts' responses specified a true preference structure or were randomly assigned. This was determined by analyzing the number of circular triads in each expert's comparisons. A circular triad occurs when the expert suggests, for example, that E_1 is more severe than E_2, E_2 is more severe than E_3, and E_3 is more severe than E_1, thus violating the transitivity property. When experts compare a large number of events, however, it is not surprising that a few circular triads may result. Therefore, a threshold was set as to the number of circular triads that would be considered acceptable.

David [5] and Kendall [6] developed tools to determine if an expert answers randomly or shows a logical consistency in his answers. Beginning with the assumption that that an expert answers randomly (the null hypothesis), the analysis tries to reject this hypothesis. If the hypothesis is rejected (i.e., there is a logical structure to the answers), the expert's opinions are kept. If the statistic fails to reject the hypothesis, the expert's opinions are considered in further analysis. For the specific case considered here, it was determined that the null hypothesis could not be rejected at the 5% level of significance.

Table 3 summarizes the performance of the 14 experts. The experts were numbered 1-15, with expert 4 missing. This is because there were 15 elicitation books created and only 14 experts attended the meeting. Books were randomly assigned and thus book 4 was unassigned. Table 3 shows that experts 1, 6, 7, 8, and 10 are dropped from the open failures analysis and experts 1, 6, and 10 are dropped from the shorting failures analysis. In addition, as experts 1, 6, and 10 were dropped from both analyses, their data will not be considered from any of the surveys.

Table 3. Summary of Experts' Circular Triads

Expert No.	Open Failures		Shorting Failures	
	Number of Circular Triads	Null Hypothesis	Number of Circular Triads	Null Hypothesis
1	106	Fail to Reject	122	Fail to Reject
2	59	Reject	97	Reject
3	37	Reject	26	Reject
5	49	Reject	43	Reject
6	121	Fail to Reject	102	Fail to Reject
7	114	Fail to Reject	75	Reject
8	100	Fail to Reject	57	Reject
9	58	Reject	41	Reject
10	113	Fail to Reject	102	Fail to Reject
11	35	Reject	32	Reject
12	14	Reject	27	Reject
13	35	Reject	79	Reject
14	55	Reject	45	Reject
15	46	Reject	37	Reject

The experts can be partitioned into three groups: those that are effective in both open and shorting failure analysis, those that are effective in one analysis but not the other, and those that are effective in neither, as shown in figures 3 and 4. It is clear that for the open failure analysis, there is a clear separation of experts with a solid preference and those without a preference. For the shorting failure analysis, the division is less clear. Note that the order the experts are listed in table 2 does not correspond to the Expert No. column in table 3.

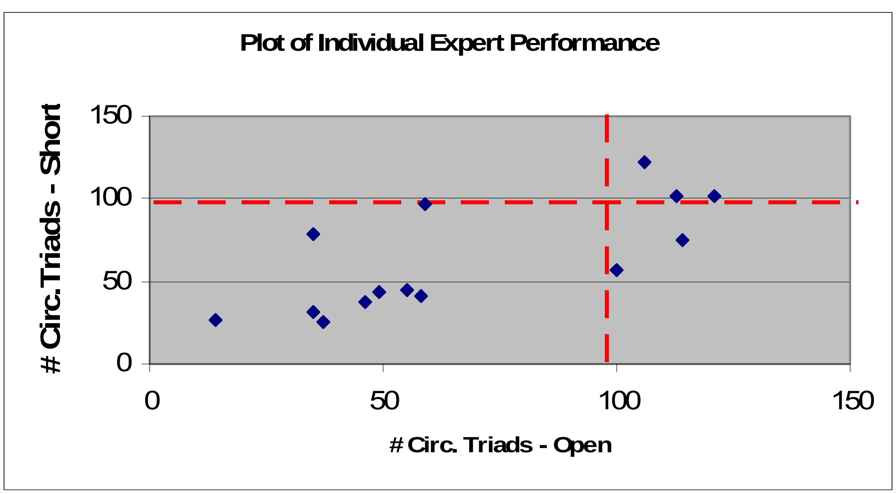

Figure 3. Comparison of Individual Expert Performance

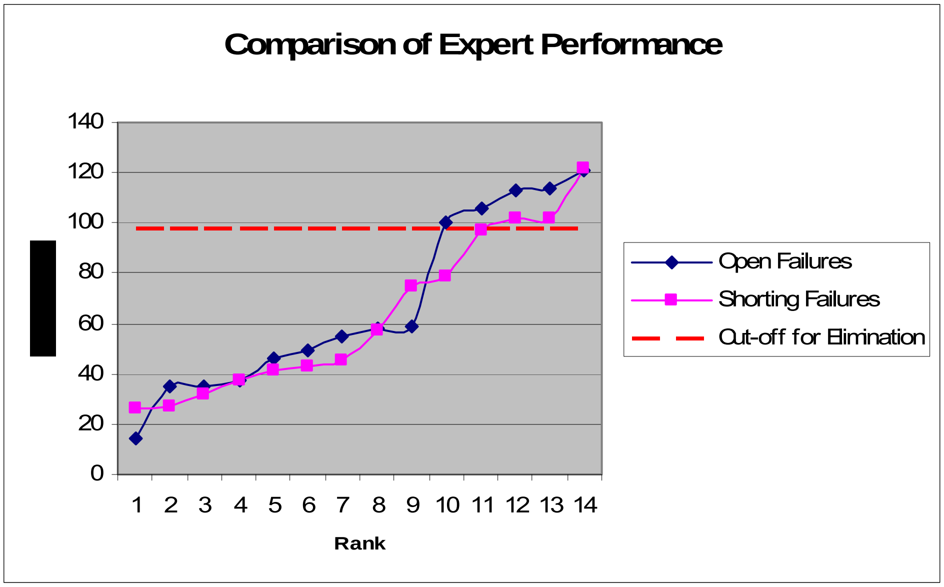

Figure 4. Comparison of Overall Expert Performance

2.1.1.5 Experts as a Group.

Methods to statistically test the agreement of experts as a group were also developed [6]. From the open failure analysis, after dropping experts 1, 6, 7, 8, and 10, the hypothesis may be rejected that the agreement was due to chance at the <0.001 level of significance (i.e., there is one chance in one thousand that the agreement between experts is due to chance). For shorting failure analysis, after dropping experts 1, 6, and 10, the hypothesis may also be rejected that the agreement was due to chance, at the <0.001 level of significance.

2.1.1.6 Obtaining the Failure Rate Estimates.

Ford presents a solution procedure for obtaining the combined failure rate estimates from the paired comparison data [7]. The PC-based computer program was employed for this procedure to obtain the estimates (to within a scale constant) of the candidate wiring environment failure rates combined with their joint 90% bounds, which are provided in table 4. Note that even within the candidate environments, there is a two order of magnitude separation in the failure rate estimates.

Table 4. Bradley-Terry (NEL) Estimates and Joint 90% Confidence Bounds for the 15 Candidate Wiring Environments

Environment	Open Failures			Shorting Failures		
	Lower	Bradley-Terry Estimate	Upper	Lower	Bradley-Terry Estimate	Upper
1	0.016	0.039	0.068	0.020	0.045	0.067
2	0.060	0.121	0.260	0.047	0.085	0.160
3	0.007	0.026	0.047	0.007	0.019	0.039
4	0.017	0.042	0.073	0.031	0.070	0.130
5	0.068	0.119	0.190	0.077	0.150	0.220
6	0.150	0.265	0.420	0.057	0.102	0.170
7	0.004	0.014	0.029	0.006	0.017	0.032
8	0.021	0.050	0.089	0.012	0.028	0.044
9	0.018	0.042	0.063	0.030	0.059	0.110
10	0.019	0.048	0.080	0.019	0.044	0.075
11	0.004	0.020	0.040	0.003	0.012	0.022
12	0.005	0.018	0.041	0.007	0.024	0.038
13	0.110	0.158	0.260	0.160	0.252	0.430
14	0.001	0.008	0.018	0.004	0.012	0.019
15	0.010	0.030	0.055	0.047	0.081	0.120

Bradley developed a statistic to test the appropriateness (goodness of fit) of the Bradley-Terry (or NEL) model [8]. Using this statistic, the NEL model could not be rejected based on the data at the 5% level of significance.

2.1.1.7 Obtaining a Regression Fit.

To determine the numerical values (or coded values) for the covariates X_i, which are needed for the regression analysis, the experts were also asked to fill out the survey questions shown in figure 5. In this survey, for each failure type and each variable, the expert was given a base variable level, assigned a value of 1, and asked to access the ratio at which the environment would become more or less severe as a single variable value was moved to its other possible values. Only the expert scores provided by the experts that passed the consistency test were used in this analysis.

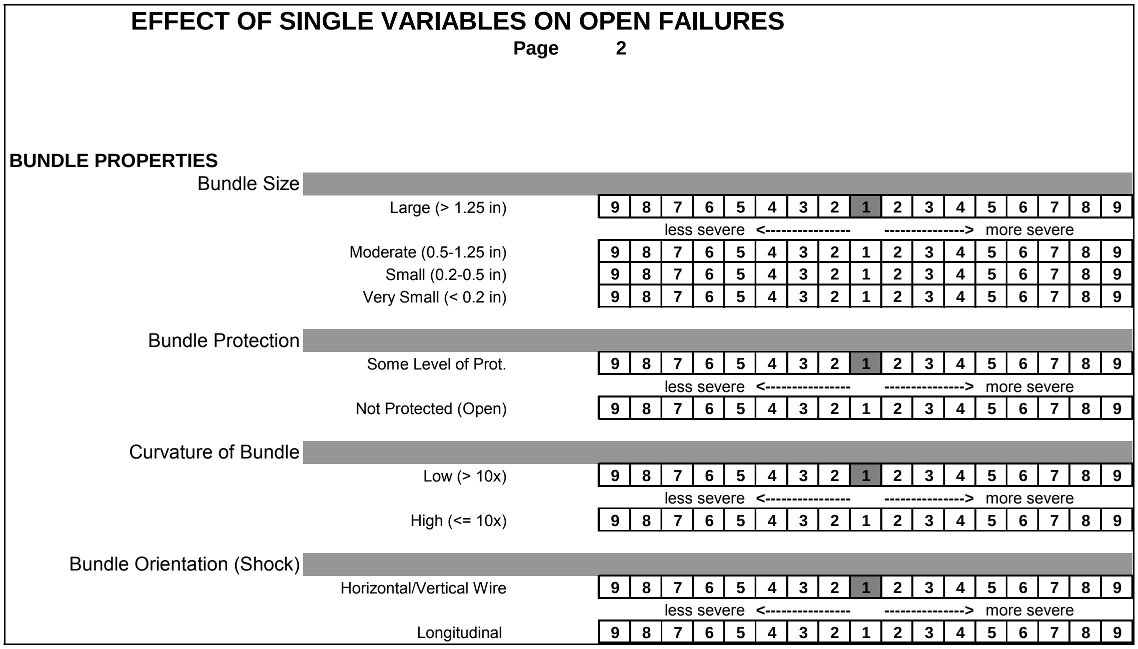

Figure 5. Example Survey for Determining the Values for X_i

Given the candidate environment failure rate estimates and the coded values for the environmental variables, a backwards selection method was used to determine the most appropriate model relating the expert responses to the coded environmental variable values for both open and shorting failures. Variables were dropped whose P-value for the t-statistic was significantly above 0.20 during the backward elimination process. While this is fairly lenient, emphasis was placed on including as many variables as possible and within reason. The unusually high multiple-R square value (coefficient of determination minus goodness of fit) is to be expected due to the small number of degrees of freedom. The coded values of the environmental variables are shown in table 5.

Table 5. Coded Values for Environmental Variables

Variable	Level	Geometric Mean	
		Open	Shorting
Wire Gauge	18-22 AWG	1.00	1.00
	4/0-8 AWG	0.22	1.13
	10-16 AWG	0.36	1.05
	24-26 AWG	3.18	1.73
Conductor Type	Copper	1.00	1.00
	Aluminum	3.13	1.39
	High Strength Copper Alloy	0.36	0.82

Table 5. Coded Values for Environmental Variables (Continued)

Variable	Level	Geom. Mean	
		Open	Shorting
Insulation Type	Polyimide	1.00	1.00
	Hybrid (PI/FP composite)	0.45	0.36
	ETFE and other FPs	0.37	0.32
Splices	None	1.00	1.00
	Environmental	0.95	0.83
	Non-environmental	5.40	2.41
Bundle Size	Large (>1.25 in.)	1.00	1.00
	Moderate (0.5-1.25 in.)	0.80	0.83
	Small (0.2-0.5 in.)	1.54	1.18
	Very small (<0.2 in.)	2.76	1.55
Bundle Protection	Some level of protection	1.00	1.00
	Not protected (open)	4.40	3.00
	Protected metal conduit	0.26	0.68
Curvature of Bundle	Low (>10 times)	1.00	1.00
	High (≥10 times)	2.34	3.24
Bundle Orientation	Horizontal/vertical wire	1.00	1.00
	Longitudinal	1.03	0.75
Operations and Maintenance Traffic	Low	1.00	1.00
	Moderate	2.79	2.32
	High	6.94	5.10
Operations Temperature and Altitude	Benign (P&T controlled)	1.00	1.00
	D1-P controlled but not T	2.03	1.39
	D2-P&T not controlled	3.17	2.37
	D3-high T, P not controlled	5.31	4.28
Vibration	Low	1.00	1.00
	Moderate	1.88	1.92
	High	4.82	3.88
	Extreme	6.79	4.93
Exposure to Corrosive Fluid	No	1.00	1.00
	Yes	4.12	5.07
Exposure to Conductive Fluid	No	1.00	1.00
	Yes	4.32	5.03

2.1.1.8 Rescaling the Failure Rate.

The analysis of the expert opinion elicited during the paired comparison workshop produced a wire failure function that gives relative failure rates for different aircraft environments. To obtain absolute failure rates, these functions needed to be scaled using wire failure rate data for one or more of the test environments. It was decided to use the SDRs to capture wire failures in the Emergency Path Lighting (EPL) System. Because the EPL is checked daily and must be repaired if inoperable, it appears that the SDRs capture a high percentage of the total wire failures in that system. Also, the environment for the EPL is fairly uniform and corresponds to test environment 10 in the paired comparison workshop. The failure rate for the EPL system was calculated using the SDR Database, the Federal Aviation Administration (FAA) Utilization Database, and an estimation of the total amount of wire in the system.

The FAA Utilization Database organizes the flight hour data into monthly intervals by aircraft model (and serial number) and airline. Therefore, the failure rate for two different aircraft models was calculated for the period 1999 to 2005 (1999-2001 in some cases) for several different airlines. The two model aircraft chosen were large transport airplanes with over 1000 of each manufactured. Five different airlines were included.

The lengths for some of these wire segments were obtained from one of the airlines and the other lengths were estimated from the dimensions of the cabin.

2.1.1.8.1 Calculation of Emergency Path Lighting Wire Failure Rate.

The failure rate was calculated for open and short failures by taking the number of failures of each type and dividing by the exposure, which, in this case, was the number of flight hours multiplied by the wire length in the EPL system. Table 6 shows that the open failure rate for the EPL is $1.1*10^{-8}$ opens per flight hour*foot of wire, and the shorting rate is $4.3*10^{-9}$ shorts per flight hour*foot of wire.

Table 6. Open and Shorts Failure Rates

Model	Airline	Total Wire Faults EPL	Faults Open	Faults Short	Exposure (hr*ft)	Open Fail Rate Opens/(hr*ft)	Shorts Fail Rate Shorts/(hr*ft)
A	1	24	20.4	3.6	2,395,867,568	8.5E-09	1.5E-09
A	2	11	4.1	6.9	1,072,760,435	3.8E-09	6.4E-09
A	3	4	3.0	1.0	1,269,781,137	2.4E-09	7.9E-10
B	1	18	6.9	11.1	1,946,962,446	3.5E-09	5.7E-09
B	2	14	7.6	6.4	1,592,952,814	4.8E-09	4.0E-09
B	4	101	80.6	20.5	2,704,349,215	3.0E-08	7.6E-09
B	5	24	19.9	4.1	1,549,750,703	1.3E-08	2.6E-09
Total		196	142.5	53.5	12,532,424,316	1.1E-08	4.3E-09

The “Unspecified” failures were divided between shorts and opens using the ratio of specified shorts to opens.

2.1.1.8.2 Scaling of the Wire Failure Function.

The wire failure rates from table 6 were used to scale the wire failure functions developed from the analysis of the data from the paired comparison workshop resulting in the following failure functions for opens and shorts.

- Failure Rate Open Failures =
  exp{0.0-(-3.1354)+0.4535*Wire Gauge Code + 2.0738*Insulation Type Code
  –0.4380*Conductor Type Code + 0.5639*Splices Code
  +0.5013*Curvature of Bundle Code - 8.1221*Bundle Orientation Code
  +0.2014*Ops/Main Traffic Code +0.2050*Ops Temp/Altitude
  +0.2239*Vibration Code + 0.4742*Exp Corrosive Fluid Code}
  * $2.53035*10^{-7}$ failures per flight hour per foot of wire

- Failure Rate Shorting Failures =
  exp{-13.0056-(-3.0756) + 0.9203*Wire Gauge Code + 1.7154*Insulation Type Code
  +1.1536*Splices Code + 0.2512*Bundle Protection Code
  +0.3723*Curvature of Bundle Code + 0.4368*Ops/Main Traffic Code
  +0.5998*Ops Temp/Altitude + 0.6605*Vibration Code
  +0.3456*Exp Corrosive Fluid Code + 0.2873*Exp Conductive Fluid Code}
  * $9.31508*10^{-8}$ failures per flight hour per foot of wire.

There are several issues that are of concern regarding the validity of the scaled failure functions. From analysis of the SDR data, the EPL appears to be a very harsh environment for wire. In fact, there were more wire faults reported in the EPL (196) than in all the other systems combined (92). While this may be due in part to under-reporting of wire faults in the other systems, clearly the EPL wire is located in one of most severe environments for wire. However, when the failure functions are examined, environment 10 is actually one of the more benign environments in terms of failure rates, with more than half of the other environments having higher rates of failure. The most probable reason for this is during the paired comparison workshop, the participants were not explicitly informed that the EPL wire was located in environment 10. If this is the case, then it would not be proper to scale the failure function by using this data.

2.1.1.8.3 Alternative Wire Failure Function.

An alternative method for scaling the wire failure function would be to use the overall wire failure rate of all systems. Using this method, the wire failure function would be scaled so that the environment with the median failure rate would have a failure rate equal to the overall failure rate. Table 7 shows the overall failure rate using wire failures from the EPL and all other systems. The exposure is the flight hours multiplied by the entire length of wire on the airplane.

Table 7. Overall Failure Rate Calculated Using Wire Failures From EPL and all Other Systems

Model	Airline	All Wire Faults	Exposure (hr*ft)	Wire Failure Rate Faults/(hr*ft)
A	1	40	688,501,641,168	5.8E-11
A	2	14	247,307,195,520	5.7E-11
A	3	6	350,488,045,776	1.7E-11
B	1	54	489,519,470,880	1.1E-10
B	2	16	400,238,561,818	4.0E-11
B	4	124	677,886,079,200	1.8E-10
B	5	34	379,503,131,568	9.0E-11
Total		288	3,233,444,125,930	8.9E-11

If this failure rate is used to scale the failure function, they become:

- Failure Rate Open Failures =
  exp{0.0-(-3.1354)+0.4535*Wire Gauge Code + 2.0738*Insulation Type Code
  – 0.4380*Conductor Type Code + 0.5639*Splices Code
  +0.5013*Curvature of Bundle Code - 8.1221*Bundle Orientation Code
  +0.2014*Ops/Main Traffic Code +0.2050*Ops Temp/Altitude
  +0.2239*Vibration Code + 0.4742*Exp Corrosive Fluid Code}
  * $3.33920*10^{-10}$ failures per flight hour per foot of wire

- Failure Rate Shorting Failures =
  exp{-13.0056-(-3.0756) + 0.9203*Wire Gauge Code + 1.7154*Insulation Type Code
  +1.1536*Splices Code + 0.2512*Bundle Protection Code
  +0.3723*Curvature of Bundle Code + 0.4368*Ops/Main Traffic Code
  +0.5998*Ops Temp/Altitude + 0.6605*Vibration Code
  +0.3456*Exp Corrosive Fluid Code + 0.2873*Exp Conductive Fluid Code}
  * $1.34751*10^{-10}$ failures per flight hour per foot of wire.

Note that the wire failure rate in table 7 was divided into open and shorting failure rates using the ratio of open and shorting failures found in table 6.

2.1.2 Failure Function and Integration Into the EWIS RAT.

The failure functions based on the EPL data were integrated as part of the EWIS Failure and General Information Database and replaced the failure function. If after further research and discussion, an alternative failure function is found to be more appropriate, the database can be updated reflected this. Additionally, all the environmental characteristics for the zones and bundles were modified to properly correlate with the failure function variables.

For calculation of the failure rates, the failure functions required several data points for each wire considered; in some cases, the data for this was not readily available. For this, the median level of severity for that particular environment variable was selected.

Checks were performed on the inputted data; the results from sample models were evaluated for accuracy. These comparisons were done for a number of sample data sets in the EWIS RAT, and the reported failure rates were compared with manual calculations for accuracy.

2.1.3 Validation Plan.

The validation of the failure rate equations is a challenging task. Expert opinion was used instead of historical data because it is generally believed that wire failures are underreported. In the past, wiring issues were not emphasized and wire failures were often reported as a failure of the device to which the wire was connected. Often, the effect of the wire failure is not significant enough to generate a service difficulty or maintenance report, and the wire is simply fixed.

One source of wire failure data that may be used to check the validity of the wire failure equations is the recent data from the U.S. Navy. In recent years, the U.S. Navy has placed emphasis on capturing wire failure data. Several different zones would be selected and characterized in terms of the 14 variables used in the paired comparison. Using the U.S. Navy databases, the wire failure rates for these zones could be calculated and compared to those generated by the failure rate equations. If there was good agreement for those selected environments, then it is likely that the failure rates calculated for the other environments would also be correct. While military transport aircraft are not identical to commercial aircraft in design or mission, there are enough similarities that the comparison would be valid.

2.2 MODELING OF ARCING DAMAGE AND INTEGRATION INTO THE EWIS RAT DAMAGE POTENTIAL ANALYSIS.

The purpose of this task was to improve the validity of the damage potential analysis in the EWIS RAT database and to present the data in a way that is more useful to the user. The EWIS RAT damage potential analysis calculates the damage that can be done by an electrical arcing event. Arcing damage can be done to metal structure and devices, installed lines (such as hydraulic, pneumatic, or fuel lines), and to the wire bundle or adjacent bundles. It is also possible for an arcing event to ignite adjacent non-EWIS such as thermal blankets, built-up lint, etc. This damage depends on the source voltage, circuit protection, series impedance, insulation material, etc. Damage can be mitigated by arc fault protection, bundle protection (e.g., Teflon tape), and other techniques.

The arc damage models developed in this project calculated the damage that can be expected to the arcing target (metal structure, devices, installed lines, etc.). Damage to the wire in the bundle, to adjacent EWIS and non-EWIS, and to the ignition of adjacent material was not modeled.

The approach used to model arcing damage is based on the quantity of energy dissipated during the arc. The results of the damage model are presented in terms of the amount of the material melted. These results were compared to damage measured in arcing tests conducted in the laboratory. Using realistic aircraft power, loads, etc., allows empirical refinement of the model that leads to improved agreement with the experimental data.

A model developed from the effort was incorporated into the EWIS RAT. Using the model, an estimate of the maximum damage that could be expected from electrical discharge can be made for each bundle section.

2.2.1 Definition of Damage Potential Scales.

To make the damage potential more useful as a tool to assess the potential damage of an arcing event, it was decided that the analysis should be reported in four categories of concern:

- Level of damage to aircraft structure and hardware (including hydraulic, oxygen lines, etc.)
- Level of damage to other wires in the bundle
- Required separation and segregation to prevent inter- and intrabundle damage
- Possibility of igniting nearby EWIS and non-EWIS material

Further, it was decided that the results should be reported using language that would provide the user with a visualization to better understand the extent of the damage as opposed to arbitrary scales. A list of categories includes:

- Level of damage to aircraft structure and hardware (including hydraulic, oxygen lines, etc.)
    - Little or No Damage: Unlikely to rupture standard hydraulic, fuel, or oxygen lines
    - Possible damage up to a maximum of 150 mm^3: Possible to rupture standard hydraulic, fuel, or oxygen lines (the size of a pencil eraser)
    - Possible damage up to a maximum of 735 mm^3: Possible to rupture standard hydraulic, fuel, or oxygen lines (the size of a quarter)
    - Possible damage larger 150 mm^3: Possible to rupture standard hydraulic, fuel, or oxygen lines (larger than the size of a quarter)
- Level of damage to other wires in the bundle
    - No damage leading to failure of other wires in the bundle possible
    - Possible damage to adjacent wires
    - Likely damage to many wires or all wires in the bundle

- Required separation and segregation to prevent inter and intrabundle damage

    - Separation (inter)

        - No separation required
        - Separation of at least 1 inch
        - Separation of at least 2 inches
        - Separation of more than 2 inches

    - Segregation (intra)

        - No segregation required
        - At least one layer of Teflon tape or tubing
        - At least two layers of Teflon tape or tubing
        - Segregation cannot insure damage prevented in this bundle section.

- Possibility of igniting EWIS and non-EWIS items (insulation blankets, lint, or other flammables)

    - Bundle section is unlikely to ignite standard insulation blankets, lint, or other flammables.

    - Bundle section may ignite standard insulation blankets, lint, or other flammables.

A damage model needs to be created for each of the categories. The models use parameters that define the power available in an arcing event.

<u>2.2.2 Damage Potential Parameters</u>.

There are seven aspects of a numerical model for the damage potential that had to be considered and addressed for an accurate assessment to be made.

- Source voltage and impedance
- The cumulative resistance to the point of the arcing event
- Arc duration (circuit protection trip curves)
- Arcing wire gauge
- Arcing wire insulation
- The number of power wires in the bundle
- The material to which the arcing occurs

The values for these parameters for a particular bundle section can be found or calculated from the EWIS RAT model database when a damage potential calculation is performed using one of the models developed in this bundle section.

2.2.2.1 Source Voltage and Impedance.

The source and impedance of any power wire could be assessed because each power wire was associated with a circuit protection device, and through that, a power bus and power source.

2.2.2.2 Cumulative Resistance.

For the analysis of the potential by wires within the bundle, the cumulative resistance of the circuit to the point of arcing is an important factor. A module was built into the EWIS RAT for the analysis of the cumulative resistance for any wire at any point in the aircraft's EWIS. Variations in the type of conductor, plating, and gauge are considered as they can affect the resistance of the wire.

2.2.2.3 The Trip Time for Circuit Protection.

Determining the duration of the arcing event is an integral part of developing a realistic and reliable mechanism for damage potential. This required the integration of the trip curves of the various protection devices.

While it was possible to fit a parameterized curve to the circuit breaker, fuse, and current limiter trip curves, there were test cases where Lectromec found that for an arcing event close to the power bus (i.e., when there was low cumulative resistance), the theoretical curve would indicate that the circuit protection would trip in less than 2 ms. Although circuit breakers are fast acting, there are physical constraints and lags that limit the speed at which a circuit protection device can respond; as such, a lower limit was placed on the time to trip. A minimum response time of 10 ms was placed on all thermal circuit breakers and 1 ms was placed on all fuses and current limiters.

To accommodate as many circuit protection schemes as possible, Lectromec personnel evaluated the common characteristics of the circuit protection types found on aircraft. It was found that most of the trip curves that were provided with protections followed a common shape. A parameterized function was developed that could be based on the inputs from the user for a particular protection; these values would be gathered from the trip curves for the devices.

2.2.2.3.1 Arc Fault Circuit Breakers.

Arc fault circuit breakers were handled differently than the traditional circuit protection devices. The EWIS RAT provides the user option to enter the minimum time to trip in the case of an arcing event. While the current specification indicates that an arc fault circuit breaker should activate after eight half cycles in which there are signs of arcing, the option is available to address the duration between recognizing the electrical arc fault and the time necessary to open the circuit.

2.2.2.3.2 An Upper Limit on Duration of Arcing.

In cases where there was insufficient electrical current for the circuit breaker to trip in a timely fashion, there was a problem with the simple damage potential model. This model suggested that if the circuit protection did not open, a continuous stream of metal would be melted or evaporated; this would suggest that given sufficient time, a low-current arcing event would result in unrealistically large levels of damage. It was determined from experimental results and numerical simulations that arcing events lasting more than 10 seconds tend not to show damage to the structure. The heat dissipation of the structure transfers most of the energy needed to cause damage. Furthermore, the destruction of the wire sample itself is a limiting factor.

2.2.2.4 The Number of Wires in the Arcing Event.

As part of the damage potential associated with a given bundle section, the insulation specification type of the wires are considered. In the case of a wire that is prone to arcing, an increasing number of wires are considered part of the arcing event (table 8). Further, these are the number of wires that are considered for the damage to structure and to the wire harness itself.

Table 8. Number of Wires Included in Arc Damage Calculation

Arc-Prone Insulation		Not Arc-Prone Insulation	
Wires in Bundle	Wires Considered in Arc	Wires in Bundle	Wires Considered in Arc
1	1	1	1
2-6	2	>1	2
7-18	3		
19-36	4		
>36	5		

2.2.2.5 The Material to Which the Arcing Occurs.

Because of the different material properties of equipment in an aircraft, the EWIS RAT was developed to allow the user to enter and select different materials to be analyzed in the damage potential report. This provides a more realistic picture of what damage could potentially be expected by the OEM in the case of an arcing event.

2.2.2.6 Arc Damage Models.

The purpose of this task was to develop a model that can be used to assess the damage caused by an arcing event. This model can then be used in the damage potential calculation of the risk assessment tool. The model should be conservative in that it models the worst realistic electrical arcing scenario. In other words, it may tend to overestimate the damage that would occur during an arc rather than underestimate it. However, the model should not overestimate damage so much that it conflicts with a common sense limit of the damage that could occur given a particular set of parameters.

This development began with a very simple model that assumes all arc energy causes destruction of the target. This model overestimates the damage by a large amount, as shown in figure 6, which compares theoretical and experimental damage. However, when the model was expanded to include heat dissipation, partition of arc energy, and destruction of the source wire, the agreement became much better. Appendix F traces the development through the different models with the integration of the third model into the EWIS RAT. This model is presented in the next section.

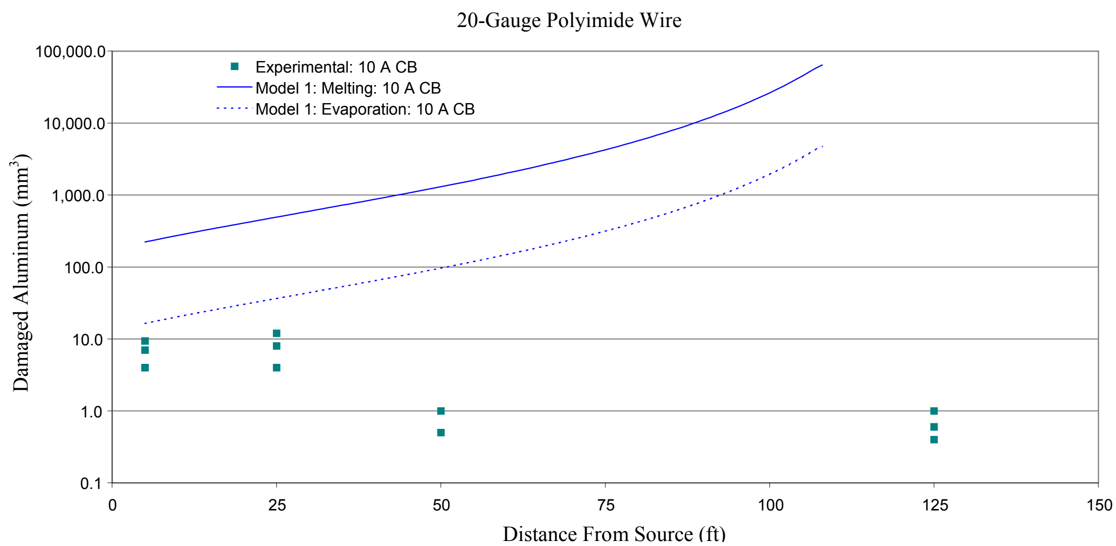

Figure 6. Comparison of Theoretical to Experimental Damages

When the third model was examined, it was evident that further development of the modeling would improve the accuracy of the results by considering details of the target geometry and thermal properties. Using a finite volume method, the geometry can be modeled and the heat dissipation calculated based on physical properties (thermal conductivities, specific heat-melting temperature, etc.) of the target material. Preliminary algorithms were created and used to show the correlation with laboratory data, which is shown in figure 6. Further development of this approach is needed before it can be integrated into the EWIS RAT.

2.2.2.7 Arc Damage Model Integrated Into EWIS RAT.

The arc damage model is based on the calculation of the amount of energy that is needed to melt a given mass of the structure (M) or target. This is given by the expression

$$M = \frac{E'}{\left((T_m - T_a)C + H_{fus}\right)} \tag{2}$$

where

E = Energy in the melt region
T_m = Melting temperature
T_a = Ambient temperature
C = Heat capacity
H_{fus} = Heat of fusion

The melting temperature, specific heat, and heat of fusion are properties of the target. In this expression, E′, represents the energy in the melt region, which is a function of the arc power. It depends on four other factors:

- The power dissipated in the arc
- The fraction of arc power incident on the target
- Thermal conduction of heat away from the hot spot of the target
- The duration of the arc, which depends on the tripping of the circuit protection and destruction of the source

Taking these factors into consideration, the energy in the melt region can be calculated using the expression

$$E' = \left(\frac{\gamma P_{arc}}{\alpha}\right)\left(1 - e^{-\alpha\tau}\right) \tag{3}$$

where

P_{arc} = The power in the arc
γ = The fraction of arc energy that is incident on the target
α = Proportionality constant for the conduction of energy away from the melt region
τ = The duration of the arc

In this expression, the arc power is calculated using the assumption that it will be the maximum allowed, given the source voltage (V_0) and resistance in series (R_{series}) with the arc (i.e., resistance of the wire). The maximum power occurs when V_{arc} equals 1/2 V_0, and so the power in the arc is

$$P_{arc} = \tfrac{1}{4} * V_0^2 / R_{series} \tag{4}$$

In this case, the current in the arc (I_{arc}) is $\tfrac{1}{2} * V_0/R_{series}$.

In equation 3, γ is the fraction of the arc energy that is incident on the target. Therefore, it must have a value between 0 and 1. Both α and γ are chosen to obtain the best empirical fit to the data.

The duration of the arc (τ) is lesser of two values: the time that the circuit protection will trip given the arcing current (I_{arc}) or the time required to damage the source wire such that the arc distance becomes too long and the arc extinguishes. The former is based upon the trip curve of the circuit protection and uses the maximum trip time of the 25°C band. The latter is found by calculating the energy (E_w) required to evaporate a given length of the source wire (3 mm, for example), using an expression similar to equation 3 and solving for τ.

Figure 7 shows a comparison of the calculated damage using this model to damage found experimentally. The tests were done on 20 American Wire Gauge (AWG) wire insulated with polyimide that arced to an aluminum blade. The model uses a γ value of 0.5 (50% of the arc energy damages the target) and an α value of 3. The solid line assumes that the aluminum must melt before it is damaged while the dashed line assumes the aluminum evaporates before it is damaged. Posttest examinations of the target suggest that damage is a combination of both melting and evaporation.

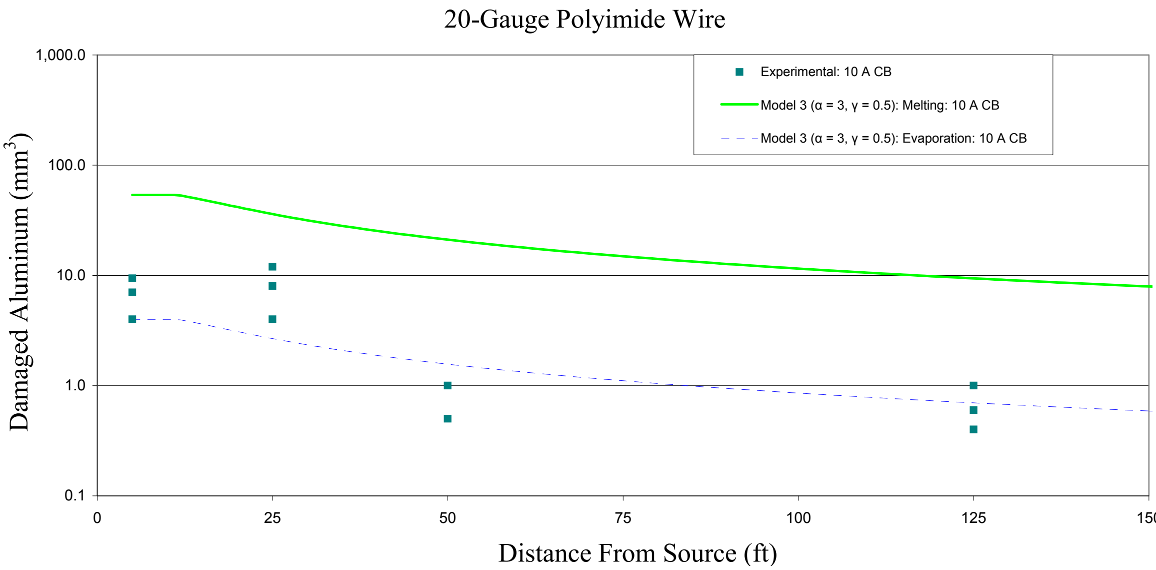

Figure 7. Comparison of Calculated Damage Using Model 3 and Experimental Data

The comparison in figure 7 shows that Model 3 is conservative in that it tends to overestimate the damage that is found experimentally. However, the overestimation is much less than with the simpler models. The model could be made less conservative by reducing the fraction of arc power incident on the target (γ) and using average trip times in the 25°C band of the trip curves instead of maximum values.

2.2.2.8 Finite Volume Thermal Conduction Simulation: Model 4.

In this model, the arc energy is incident into a 3D model of the structure. The structure is divided into many cells, as shown in figure 8. As the arc energy is incident to the cells on the surface of the target, they heat up. The heat energy is conducted away from the surface using a finite volume stimulation. If the arc power is high enough, the cell melts or evaporates before the heat energy is conducted away. The damage calculation is therefore based on the geometry and thermal conductivity of the target material, as well as the heat capacity, melting temperature, arc energy, etc. This eliminates the need for the α value from Model 3 and replaces it with the physical properties of the target.

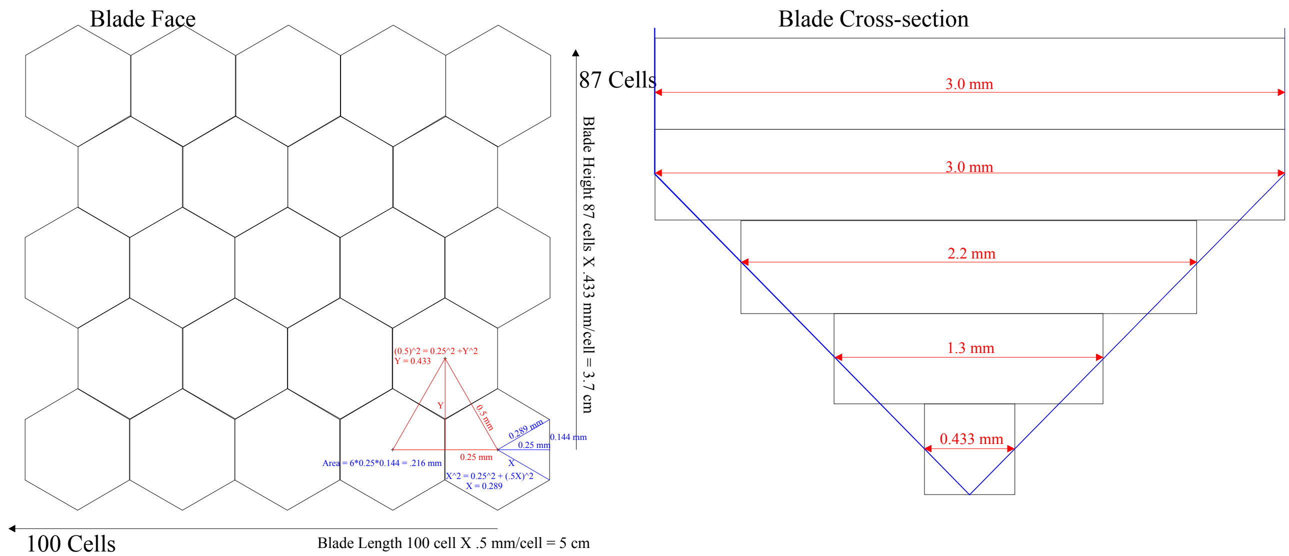

Figure 8. The Cell Structure That Makes up the Blade for the Finite Element Model

Figure 9 shows an example from an arc test with 20 AWG wire, a 10-amp circuit breaker, at a 25-foot distance from the source. The red area is where the blade has been heated above room temperature but below melting temperature. The dark reddish-brown cells are melted and the green cells are evaporated. The total volume melted or evaporated in the simulation was 15 mm^3.

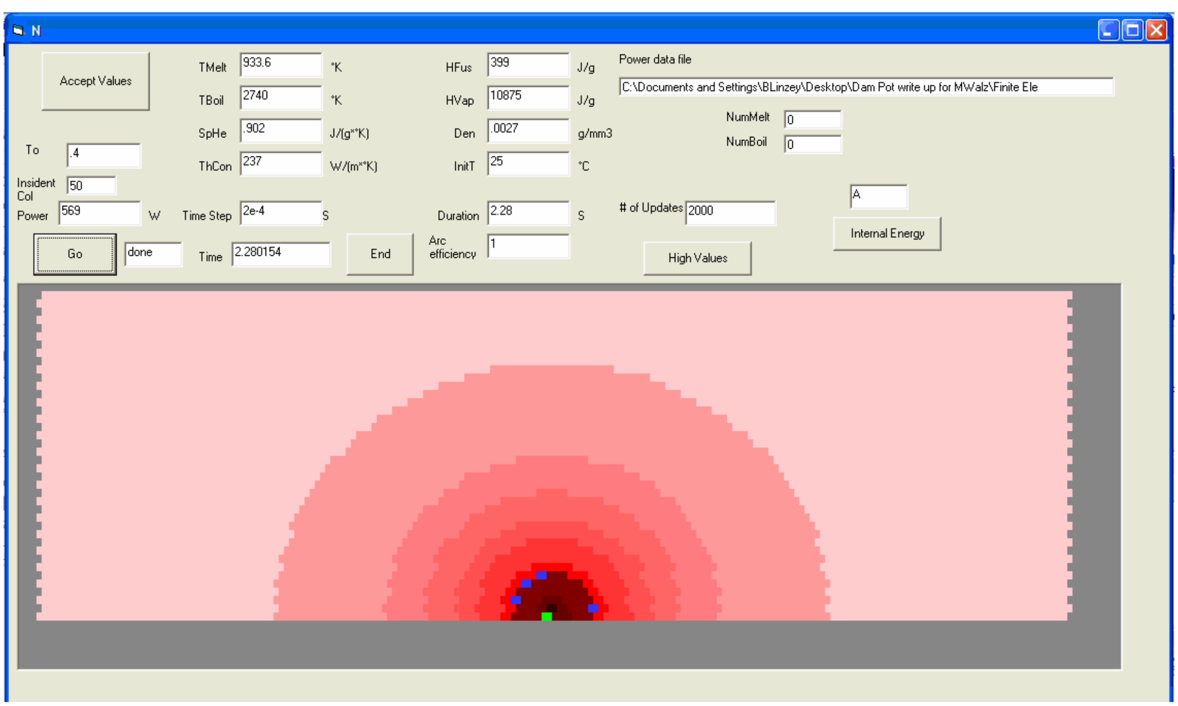

Figure 9. Example for 20 AWG, 10-amp Circuit Breaker With 25 Feet of Resistance

Figures 10 and 11 show comparisons of the damage calculation using the finite volume method with experimental data for 10 and 20 AWG wire. The data in figures 10 and 11 were created using experimental power curves and moving blade. The finite volume results show good agreement with experimental data.

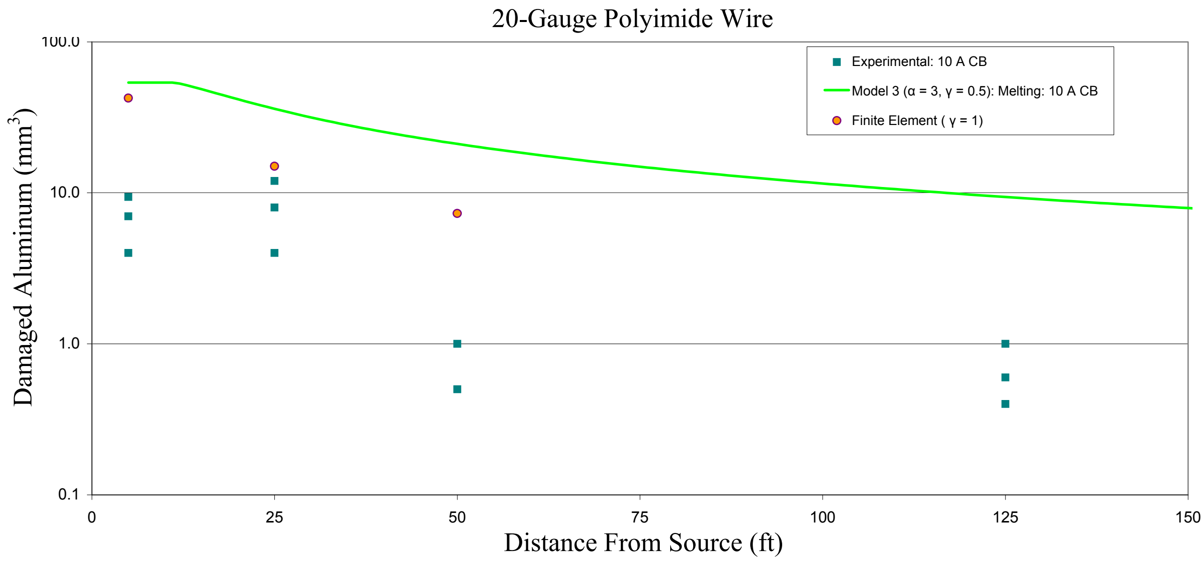

Figure 10. Comparison of Finite Element Method With Experimental Data

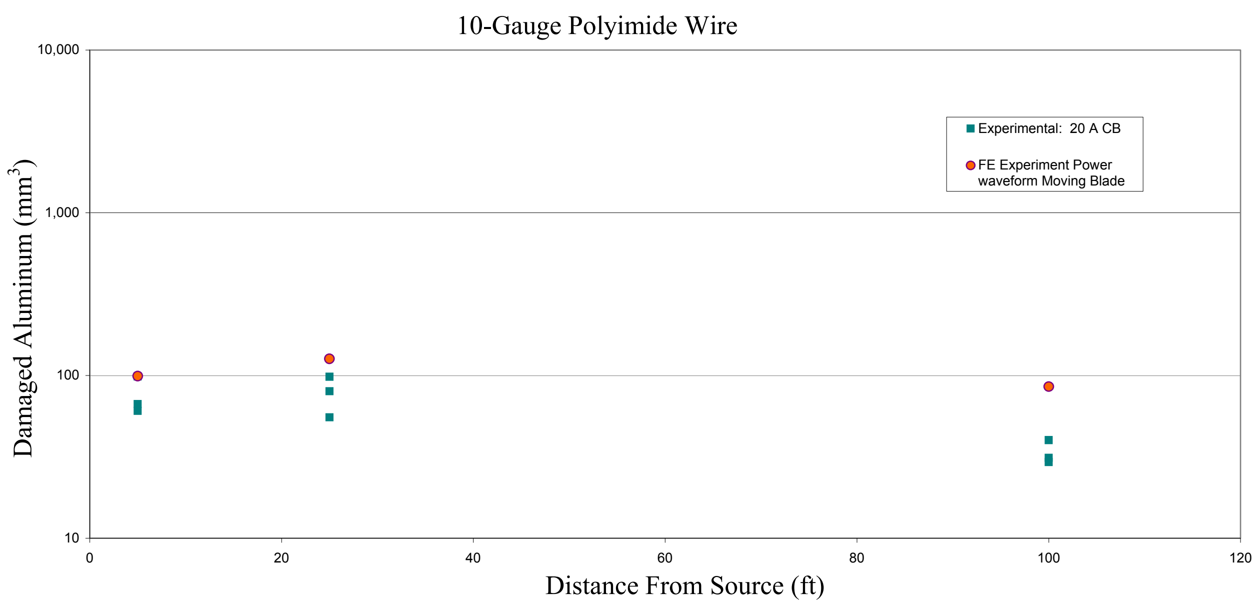

Figure 11. Comparison of Experimental Data and Finite Element Simulation

2.2.2.9 Integration of Damage Potential Into EWIS RAT.

Model 3 was integrated into the EWIS and replaced the damage potential function developed as part of the past effort. Checks were performed on the inputted data; the results from some sample models were evaluated for accuracy. These comparisons were done for a number of sample data sets in the EWIS RAT, and the reported damage potentials were compared with manual calculations for accuracy and reliability.

2.2.2.10 Discussion.

Model 3 is useful in producing a conservative estimate for the damage that could occur to structure if an arc tracking event occurs. Parameters considered in the model are source voltage, circuit protection trip curves, wire gauge, and distance from the source. Two adjustable parameters are α and γ, which are related to heat dissipation in the target and the percentage of the arc energy that enters the target structure. Wire damage can be added to the model, which can extinguish the arc when the distance from the source (wire) and target become too large.

A more detailed analysis of the heat dissipation can be performed using the finite volume method of analysis. This analysis relies on the geometry and thermal constants of the target instead of an adjustable parameter α. Heat dissipation and damage in the source wire can also be calculated using the finite volume analysis method. The results presented here were obtained using a crude cell matrix to represent the blade. Improvements to the finite element technique should improve the results.

2.2.2.11 Validation Plan.

The damage calculated using models developed in this section show general agreement with laboratory arcing data. However, to be useful in assessing damage to items such as hydraulic lines, the models need to be improved. The finite element method can take target geometry and thermal characteristics into account and shows promise that, if developed, could calculate expected damage to a hydraulic line. Validation of the improved model can be shown by comparing the model damage estimates to

- laboratory tests that accurately simulate arcing that occurs in service.
- arcing events that have occurred in the field.

There is work currently being conducted under FAA sponsorship for the development of an arc damage modeling tool.

2.3 SIMPLIFYING DATA COLLECTION AND ENTRY FOR THE EWIS DATABASE.

One issue concerning the feasibility of using the tool was how all the required EWIS data for a certain airplane would be entered into the tool. There are two aspects of this issue.

1. In some cases, required data may not be directly available. This is because the depth of the EWIS risk analysis performed using the tool is greater than what has been normally done by aircraft OEMs. Therefore, some concepts used by the tool are not recognized by

the OEM. For example, the concept of "Bundle Sections," that is basic to the tool, is not generally used by OEMs at this time. Therefore, they do not have this data defined in any of their databases. This data set will have to be created if it is to be imported into the tool.

2. After the data exists, it still needs to be entered into the database in an efficient way. The original tool is built around manual entry of the data. The volume of EWIS data precludes the practicality of manual data entry. Therefore, tools that allow mass data entry into the database need to be created.

The purpose of this task was to develop the methods and software needed to obtain and efficiently enter all of the data required by the EWIS RAT from the data typically available in an aircraft OEM organization. To accomplish this, Lectromec teamed with Cessna Aircraft Company and was granted access to the data from a recently certified aircraft. Cessna also provided engineering assistance in locating where different information could be found and understanding the different data sets.

The software tools developed to import data into the EWIS RAT were incorporated into the tool itself. These tools were kept as general as possible. Delimited files are required; however, the delimiter is the user's choice. The ordering of the columns is flexible, but the user must identify which columns contain the required data.

In some cases, specialized methods and software were created to collect data from sources in a way that is likely to be unique to Cessna data. For example, the form board postscript files were used to extract bundle section data. Other organizations may not have these postscript files or they may not be formatted in the same way. Also, Cessna nomenclature is likely different from other organizations. In these cases, the software was not incorporated directly into the program but collected as a series of independent supplemental programs. Appendix D lists the supplemental programs developed for the data reformat.

Table 9 lists the required data and the sources used to capture and export that data into the EWIS Model. This method allowed data of 6976 wires and 46 systems to be imported into the database.

Table 9. Required Data and Sources

Wire ID	Automatic data extractions from circuit diagrams
Wire Termination	Automatic data extractions from circuit diagrams
Power Type/Circuit Protection	Automatic data extractions from circuit diagrams with additional connectivity mapping
Gauge	Automatic data extractions from circuit diagrams
Insulation Type	Derived from automatic data extractions from circuit diagrams
Conductor Type	Derived from automatic data extractions from circuit diagrams

Table 9. Required Data and Source (Continued)

Jumper/Splice Assigned	Automatic data extractions from circuit diagrams
Multiconductor Cables	Automatic data extractions from circuit diagrams
Failure Effect Data	Not available: Was created for one system fault tree by reviewing circuit diagrams
Bundle Section ID	Automatically generated by form board postscript file interpreter software
Bundle Section Length	Form board postscript file interpreter software
Bundle Section Terminations	Form board postscript file interpreter software
Bundle Section Curvature	Not available: Would be available if CATIA models were used instead of form board postscript files.
Bundle Section Covering	Manually form bundle assembly documents
Objects Within 6″ of Bundle Section	Only done for connectors using data extraction from CATIA models. Would be available if CATIA models were used instead of form board postscript files.
Zonal IDs	Used Cessna knowledge
Subzone IDs	Subzones were not defined beyond zonal level. Would be available if CATIA models were used.
Temperature	Used general knowledge of zones
Vibration	Used general knowledge of zones
Objects in Zones	Bundle Sections were placed in zones based on Cessna nomenclature. More detailed placement of objects (LRUs, hydraulic lines, etc.) would require using 3D CATIA models.
Power Source and Buses	Manually from load report
Connector Specifications	Available in OEM database but was not capture due to the work required to get it.
Fault Tree Cut-Set Data	Automatic data extraction from fault tree software.

2.3.1 Details of Data Mining Process.

Different sources of data often gave additional information about different items needed for the database. For example, the nomenclature of the Wire List provided by Cessna, the data also provided information about connectors and circuit protection devices. This section discusses the data sources at Cessna and how they were used to collect the required data. The following section discusses how the data was ordered and imported into the EWIS RAT model.

2.3.1.1 Circuit Diagram Data Extraction.

A data extraction from the circuit diagrams provided the main sources for wire and system information. This data dump was one of the software features used to create the circuit diagrams. The OEM's existing format was suitable, therefore, the data files already existed. A batch program was written to read the files and create a wire list that could be imported into the model database. The system to which a wire was assigned was based on the circuit diagram. All the electrical system wire information was imported in this way. The avionics systems were not imported to conserve resources, but similar data exists for these systems.

Wire data from these files included wire identification number (ID), wire terminations, wire gauge, wire specification, inclusion in multiconductor cable, and shielding. A list of connector reference designators was formed using wire termination data. This list could be cross-referenced with Wire Book data for connector specification data. Lists of switches, circuit protection, and other electrical devices were created in a similar way.

Determining the power characteristics of wires in the model required an external program that used the to/from wire list data. To assign power wires, the program started with a wire connected to circuit protection. That wire was assigned as a power wire protected by the circuit protection device. The other end of this wire was typically connected to a second wire through a connector, and this wire was also assigned as a power wire protected by the circuit protection device. In this way, the power characteristic was propagated through connectors until a termination device (computer, motor, etc.) was reached. For some devices, such as switches and relays, the power characteristic was propagated through all of the terminals of a given pole (figure 12). Wires A1, A2, A3, and A4 were assigned as power. Pole designation could be determined by Cessna convention in the To/From list.

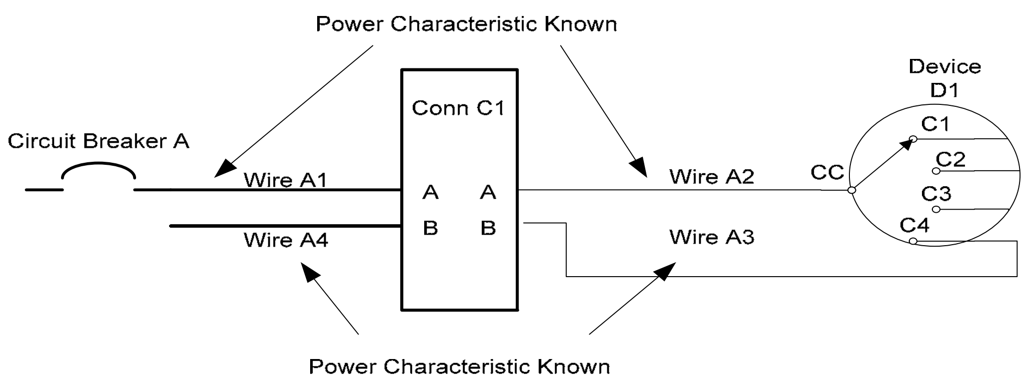

Figure 12. Propagation of Power Characteristics Through a Switch

Propagation of power characteristics through more complicated devices, such as line replacement units (LRU), could be done by creating a library of terminal maps for the different device specification that could be accessed as needed. This was not done in this project.

Ground wires were assigned in a similar manner, starting with wires connected to ground stud or ground blocks. Wires not assigned to power or ground characteristics were assigned to a signal or high impedance wire (low current).

2.3.1.2 Extraction of Form Board Data.

Bundle sections were defined using the computer-aided design (CAD) model of the form boards. Form boards are tools used to manufacture the bundle assemblies by placing wire through a maze of pegs on the board, then grouping the wires into bundles. The wires are then terminated to connectors or other devices.

The postscript files of the CAD models were used to represent the form boards. A supplemental program was written that interpreted the postscript files. This process required the program to recognize drawing abnormalities, such as branch lines coming close to the main trunk of the assembly but not quite touching or overshooting it. Double and triple lines (lines on top of lines) also had to be recognized as well as connecter labels. The bundle assembly was then separated into bundle sections and bundle section terminations (including connectors, circuit breakers, etc.), as shown in figure 13.

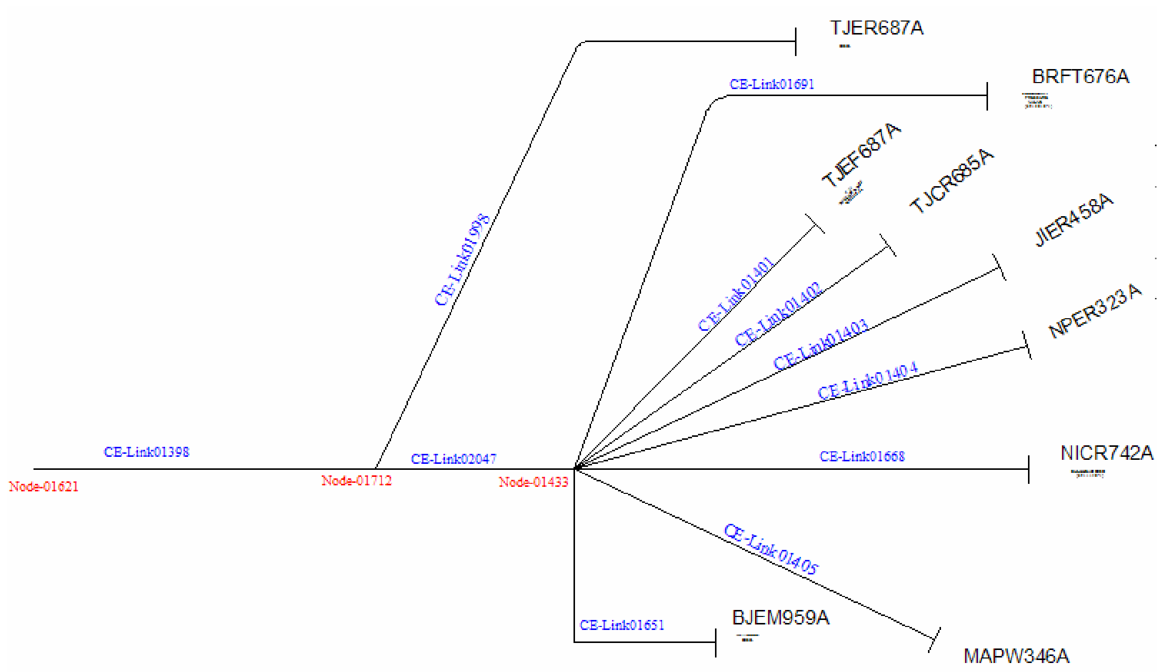

Figure 13. A Section of Postscript File of a Typical Harness Assembly

Table 10 shows an example of some of the resulting bundle sections. The bundle section termination mapping was automatically generated from analysis of the postscript file. Because the postscript files were to scale, bundle section lengths were also captured.

Table 10. Bundle Section and Bundle Section Terminations Mapping

Bundle Section	Bundle Section Termination No. 1	Bundle Section Termination No. 2
CE-Link01398	Node-01621	Node-01712
CE-Link01998	Node-01712	TJER687A
CE-Link02047	Node-01712	Node-01433
CE-Link01691	Node-01433	BRFT676A
CE-Link01401	Node-01433	TJEF687A

Some aspects of the bundle section routing were not available because there were no form board-constructed bundles that went directly from a connector to a device. For these situations, a bundle section of a default length (18″) was created.

Bundle section curvature and EWIS and non-EWIS devices that were within 6″ of the bundle section could not be extracted from the form board data. Both items could be obtained using the 3D bundle assembly models in airplane coordinates. While data extraction from the 3D models is the next logical step in acquiring the required data, it was not pursued further in this project for several reasons:

- The added complexity of interpretation of the 3D models. However, tools that come with the modeling software could aid this pursuit.
- The 3D model of the bundle assemblies was not as complete as the form board data. In some cases, connections to switches and relays or connectors were not shown or they were not labeled with a reference and designation. Three-dimensional modeling of complete bundle assemblies is still relatively new to the organization and it is assumed that as they gain more experience, the modeling will become more complete.

One set of data that allowed some distance from the bundle section data to be collected was the 3D coordinates of the connectors. Cessna had already created a file with this data. This data was analyzed (supplemental program) to determine which connectors were within 6″ of each other. If two connectors were within 6″, then the bundle sections that terminated at those connectors were then taken to be within 6″ of each other. While a limited amount of data was entered into the database using this method, it is a useful model to show how this type of data can be used. Many electrical and nonelectrical devices are modeled using aircraft coordinates and can easily be entered into the database.

2.3.1.3 Routing Wire Into Bundle Sections.

The wires were routed into bundle sections by combining the wire list data with the form board data. To do this, Lectromec developed a module within the EWIS RAT for the automatic routing of the wires within the model. For each wire, two terminations were matched with terminations from the bundle sections. The wire was then routed in successive bundle sections, between the two bundle section terminations, using the Dykstra’s algorithm, which finds the shortest path between two locations within the model. Note that in the overwhelming number of cases, the shortest path was the only path.

For example, referring to figure 13, a wire that terminates at TJER687A and NPER323 would be auto-routed in bundle sections CE-Link01998 - CE-Link02047 - CE-Link01403.

With the wires routed in bundle sections, it is possible to calculate the cumulative resistance of a power wire from the bus to any point on a bundle assembly. A module was built into the EWIS RAT that traces the path from the power bus through the different bundle sections. This provides a means to use the bundle sections' length along with wire gauge data and standard conductor resistance values to sum the resistances to any point in the circuit. The cumulative resistance is used in the damage potential calculation as a limit to the arcing current possible in the circuit.

2.3.1.4 Power Sources, Buses, and Circuit Protection.

It was determined that, given the relatively small number of power sources and buses that exist on an aircraft and the limited information that is required in an EWIS RAT model, no importation interface was necessary, and thus, none was developed. This data was taken from the load analysis report.

There were no electronic files that detailed the circuit protection (including rating). While it is likely that this information could be extracted in a new data dump of the circuit diagrams, because of the relatively low number of protection devices, it was decided to manually extract this data from the power distribution system diagram and then import it to the database. Note, that because power buses are assigned to generators (or other power sources), the voltage type (28 voltage direct current (VDC) or 115 voltage alternating current (VAC) of the generator is also assigned to the buses. In turn, circuit protection devices or wires directly connected to a power bus are assigned to the bus' voltage type.

2.3.1.5 Wire Failure Effect and Fault Tree Data.

The failure effects of wires were not available in any of the OEM databases because such detailed information is not needed in the current method of safety analyses. One method to obtain this data could be to introduce an additional step when creating the individual system fault trees. It was observed that many of the system fault trees did have basic events labeled "wire failure." However, the particular wires and the mode of failure were not indicated. It is reasonable to conclude that when creating the fault tree, the engineer knew, or could easily find, which wires would cause the particular system failure. This data could be captured in a spreadsheet and the data for all of the systems could then be uploaded into the database. This would be the link that connects the EWIS architecture to the structure of the system safety analysis. It would also keep the top-down approach of the safety analysis in tact.

To prove the feasibility of this approach, Lectromec personnel selected a top event categorized as a catastrophic event in the Functional Hazard Assessment in the Electrical Generation and Distribution fault tree. This tree was systematically evaluated and all basic events that could be caused by a wire failure were identified. A spreadsheet was constructed that listed the basic events and the wires and failure modes (open, short to ground, etc.) that would cause each basic event to occur. Table 11 shows part of the spreadsheet.

Table 11. Example of Basic Event—Wire Failure Mode Spreadsheet

Basic Event	Wire ID	Fail Open	Fail GND	Fail High Imp	Fail 28 VDC	Fail 115 VAC
SSA-Electrical-19877	TPCSN881 - NOSIQB880	X	X			X
	UPCSN881 - NOSIQB880	X	X			X
	WPCSN881 - 1CSIQB880	X	X			X
	XPCSN881 - 2CSIQB880	X	X			X
	A4PNEW899 - GNOQ898	X				
	LPCCU867 - TJCSN881	X	X			X
	KPCCU867 - UJCSN881	X	X			X
	DJB002 - XJCSN881	X	X			X
	24PNEW899 - DPBAO898	X	X			X
	\KJCCU867 - 2DCUK859	X	X			X
	\LJCCU867 - 2DCMJ860	X	X			X
	KJCCU867 - \KJCCU867	X	X			X
	LJCCU867 - \LJCCU867	X	X			X
B1RD-SI3111	2HCJC870 - YJCEB869	X	X			X
	NJAHK885 - DJCAW883	X	X			X
	RJAHK885 - PJCAW883	X	X			X
	CJCAW883 - YPCEB869	X	X			X
	PPCAW883 - A3SISF789	X	X			X
	*SPTUE841 - NPAHK885	X	X			X
	KPTUE841 - RPAHK885	X	X			X
SSA-Electrical-5451	EUDWM892 - GTDX875	X				
	BUDWM892 - 1HZWP867	X	X			X

Once the link between basic events and wires was created, it was important to determine which combination of basic events would lead to the catastrophic event. This was done using the fault tree cut-set report for the top event. A cut-set is a list of basic events and if each basic event in the cut-set occurs, the top-level event occurs. A cut-set for a catastrophic event is typically comprised of two, three, or more basic events. A cut-set report is made up of many lines, and each line is a cut-set for the top event. A file of the cut-set report is a standard output of the commercial program used by Cessna to construct the system fault trees. The cut-set report of the catastrophic events was roughly 280 pages long. This file was formatted to a delimited text file and placed in a folder associated with EWIS RAT. In this way, the structure of the system analysis, with associated wire failure modes, was made available to the program and could be called as required.

When constructing the basic event–wire failure mode spreadsheet, there were cases in which no wire failure basic event existed under a certain fault tree logic gate. However, it was possible that a wire failure could cause the gate to be satisfied. For example, if a switch failure was listed as a basic event, then, obviously, failure in the wires connecting the switch would have the same effect. For this example, the wire failures were simply associated with the switch basic event. This allows the use of the cut-set reports generated by the fault trees. However, this practice could cause confusion if it were done in general, especially when assigning failure probabilities to basic events.

In the future, an EWIS Failure Modes and Effects Summary (FMES) could be created to capture and document the wire identifications and failure modes that cause a given system effect. The EWIS FMES would then become a basic event in the fault tree and would be listed along with the other basic events in the fault tree cut-sets.

A check can be run on the wire failure data to probe for inconsistencies in the assignment of failure effects to the wires. Like the assignment of power type to wires, the program looks at wires connected to each through connector and similar devices. If there is a difference in failure effects, the program will ask the user if the failure effect assignments are correct. Note, in the case of open failures and because of branching, the failure effects on one wire do not have to match the failure effects of an adjacent or downstream wire.

2.3.1.6 Zonal Data.

The zones and the specific conditions of the zones are evaluated as part of the aircraft certification program. From this, Lectromec was able to define the environmental conditions that would be experienced in various zones within the aircraft. Again, since Lectromec focused on the two-dimensional representation of the wire harness, placing the wire harnesses into particular subzones, as is defined for the program, was impractical. However, the wire harnesses that were imported into the program were broken down into aircraft-specific sections (left wing, tail cone, etc.).

2.3.2 Importation of Data Into the EWIS RAT.

Figure 14 shows a flowchart of how the information from the OEM was handled and imported into the program. This is a general case and some modification would likely need to be made for a different OEM implementing the tool. The raw data that exists within the organization was first reviewed and a determination was made on the usefulness of developing a full EWIS model. The next stage was the Reformat Layer; in this layer, the raw data was modified and reformatted for the importation to the program. Additionally, certain characteristics of the data may need to be cross-correlated, but this will be dependent upon how the OEM maintains their data.

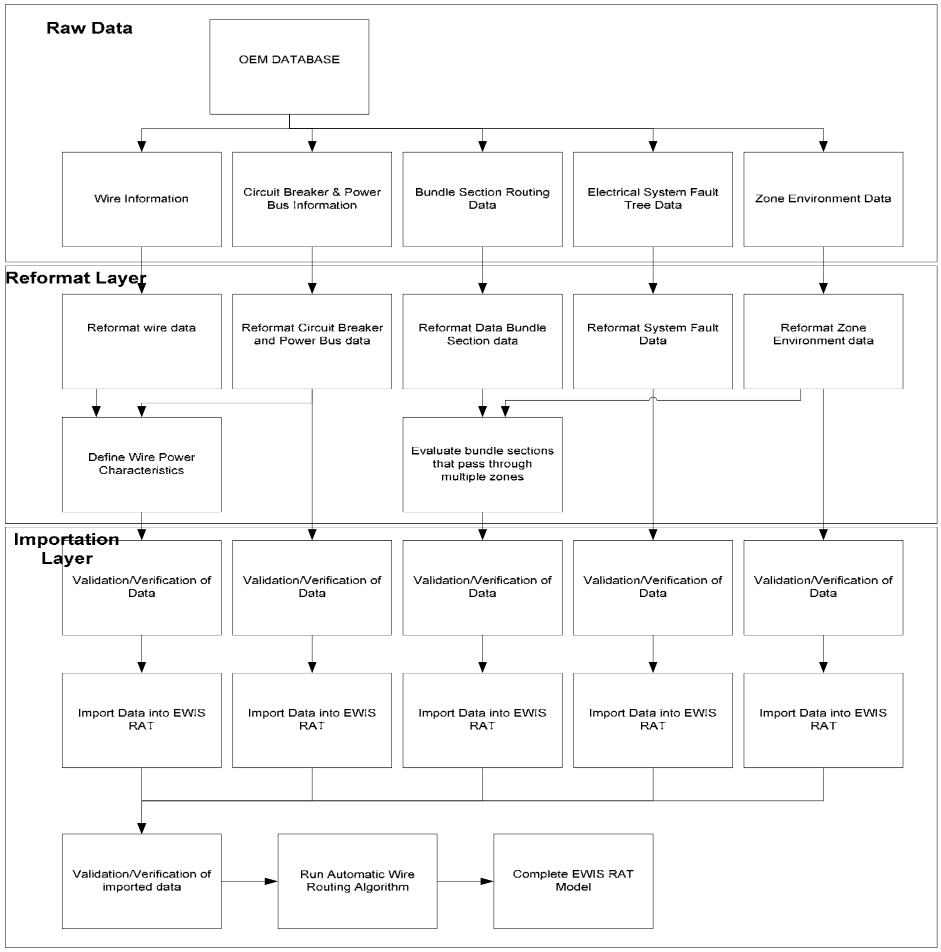

Figure 14. Flowchart of Information Extraction and Importation Into the EWIS RAT

The importation layer starts with the verification/validation of the data to be imported. Unless the data is verified for consistency prior to importation, problems may emerge during the analysis of the reports. Once verified, the data can then be imported to the program.

After going through the data and different importation mechanisms, it was determined that the order of importation of data into the EWIS RAT is best served using the outline that follows:

1. Circuit Breaker Information
2. System Information
3. Device Information (Electrical and Nonelectrical)
4. Connector Information
5. Connector Specification Information
6. Wire Information
7. Pin-to-Pin Information
8. Cable Information
9. Bundle Section Information
10. Zone/Subzone Information

Because there is such a great deal of interconnection between the different segments of information within a model (a system has a subsystem, a subsystem has a wire, a wire is in a cable, the cable is in a bundle section, the bundle section is in a subzone, etc.), the information should be built systematically such that all of the data and information relationships are self-consistent.

2.3.3 Validity of the Data.

After the data from the form board and wire interconnection data sets were imported into the EWIS RAT, the wires were then placed into the appropriate bundle sections using the automatic wire routing feature that was built into the program. To validate these results, 100 wires were selected at random and were manually compared against what one would expect the routing of the wire to be given a particular form board layout. The results of this validation are shown in table 12.

Table 12. Results of Validation of Automatic Routing Modules

Result	Number of Occurrences
Routed	
Correct	68
Not Shortest Path	3
Known Problem	4
Not Routed	
No Data	24
Incorrect Info	1

Of the 100 wires that were analyzed, 68% were routed correctly. This figure includes wires that ran from connector to connector, jumpers, and connectors to devices.

Three of the wires were routed in a way that was not the ideal or shortest path, although the variation in the length of the wire was found to be no more than 6″ in each case.

The “Known Problem” category, in which there were four wires, was an issue known to Lectromec during design. As the form boards were analyzed, certain assumptions had to be made with the data that slightly altered the data that was imported into the EWIS RAT vis-à-vis the “true” form board. This variation caused the four wires to be routed incorrectly. However, it is the consensus of Lectromec that if the bundle section routing data were to be gathered from a three-dimensional model, this particular error would not appear.

Twenty-four wires were not routed because not all the form boards and bundle assemblies were gathered from the OEM. Since the wires that were routed demonstrated the feasibility of this method and to conserve resources, the rest of the bundle assembly data was not obtained from the OEM. One wire was not routed and was classified as “Incorrect Info”’ because of a typo in the OEM's data set. This matter was resolved and the wire was properly routed after a second attempt.

2.4 IMPROVED CORRESPONDENCE WITH ACO EXPECTATIONS.

One of the primary goals of the EWIS RAT is to generate reports that will be useful in the Type Certification process. This is especially important for the new rules relating to EWIS, specifically 14 CFR 25.1709. To evaluate the usefulness of the reports, the OEM data that was loaded into the EWIS RAT tool and used to generate several different analysis reports. These reports were then integrated into a prototype EWIS Safety Assessment report. The intentions were to have an Aircraft Certification Officer (ACO) review the report and provide feedback. However, due to the especially heavy workload of the ACO, the evaluation of the prototype report could not be performed. Section 2.4.1 describes the prototype report.

The prototype report, Model B1RD Electrical Wiring Interconnection Safety Assessment, is provided in appendix G. The outline of the EWIS Safety Assessment report is based on other system safety reports that were reviewed by Lectromec.

The data from a recently certified aircraft was used, which included wire lists, form board data, 3D CAD models of the EWIS, fault trees, and cut-set data. Because some of this data is proprietary to the OEM, the IDs on connectors, wires, circuit breakers, and fault tree basic events were changed to protect the proprietary information. However, the basic structure and the relationship between the elements were not modified.

The failure effects of wire data were not available in any of the OEM databases because such detailed information was not needed in the previous safety analyses. Lectromec personnel developed this data for one catastrophic event in the Electrical Generation and Distribution fault tree. To conserve resources, this was not done for the other catastrophic events in that fault tree or any other system trees; therefore, the analysis shown in the prototype report is based only on this event and related faults. In an actual certification, the hazardous and catastrophic events for all of the systems would have to be analyzed in this manner.

Note, because this prototype report is meant to represent a report that would be submitted for certification, the language used is what would appear in an actual report. Therefore, in some cases it states that "all systems" were analyzed when, in fact, for this project only the Electrical Generation and Distribution System were analyzed. However, when this language is used, there is a note in italic that states what was actually done.

2.4.1 Review of the Sections of the EWIS Safety Assessment Prototype Report.

The Prototype EWIS Safety Assessment Report is divided into six sections and three appendices. A brief review of these follows. This report is provided in appendix G of this report. The variables definitions are provided in appendix B.

2.4.1.1 Sections 1 and 2: Introduction, References, and System Description.

The introduction, reference, and system description are self-explanatory. The EWIS RAT will not affect these sections except that it may aid in the description of the system in terms of numbers of wires, bundle sections, etc.

2.4.1.2 Section 3: Electrical Wiring Interconnection System Safety Requirements.

In general, the EWIS safety assessment will not have failure conditions passed to it from the Aircraft Functional Hazard Assessment (AFHA), System Functional Hazard Assessment (SFHA) or the Preliminary System Safety Assessments (PSSA). However, 14 CFR 25.1705 requires that the effects of EWIS failures on the safety all of the other aircraft systems be evaluated. Further, a common cause analysis of the EWIS is required.

2.4.1.3 Section 4: Safety Requirement Verification.

Section 5 describes the analyses that were performed to show compliance to the requirements described in Section 4. In general, the text in this section briefly describes the analysis done and then points to an appendix where the detailed report is found. In this case, three analyses were done:

1. The Failure Matrix Report was run to show that EWIS functional failure effects would not impact other systems in a way that prevents those systems from meeting the safety requirements. One set of data needed to support this is the EWIS Failure Modes and Effects Summary Events Table, which is found in Appendix A of the prototype report. This table lists all of the EWIS FMES events with all the particular wire segments (and failure modes) that cause the event. The table in Appendix B of the prototype report shows the results of the Failure Matrix analysis and lists the failure probabilities for each FMES event. These failure probabilities would then be fed into the various system fault trees. If these fault trees meet their failure probability requirements with the EWIS failure event taken into consideration, then the requirement for showing that EWIS failure would not cause other systems to miss their safety requirements is met. Note, because the time required to run the failure probability analysis on system fault trees is long (up to a week) and because it takes valuable OEM computer resources, the Electrical Generation and Distribution System fault trees were not rerun with this new data.

2. The second analysis performed was the Cut-Set Collocation Analysis of catastrophic events. This is a common cause analysis using the cut-set for a catastrophic event, in this case PSSA-Ele-7540, as the basis of a collocation analysis. The purpose of the analysis is to show that no combination of wire failures that cause the top event to occur, exist together in any of the wire bundle sections. (The report is found in Appendix C of the prototype report.) It lists the cut-sets in which all of the elements (basic events) have an EWIS failure mode. It then shows the results of the collocation analysis. When the OEM data were analyzed, no collocations were found. However, to show what the report would look like if collocations were found, the analysis was rerun with an artificial collocation added to the database. The results are shown in the second table of Appendix C of the prototype report along with possible comments the OEM may use to

show that the EWIS event with the collocation is still safe. It would be the judgment of the ACO to accept or reject these arguments.

3. The third analysis is also a common cause analysis that examines the potential damage that can be done to or by the wire bundle. The Bundle Section Report (Appendix F of the prototype report) analyzes each bundle section and evaluates the potential damage due to shorting or arcing. It uses the methodology described in section 2.4 of this report. It also brings together other significant information needed to evaluate the safety of the bundle section. This information includes:

   - harsh environmental conditions.
   - specially designated zones such as a fire zone.
   - systems that have wires routed in the bundle section.
   - EWIS and non-EWIS devices routed within 6″ of the bundle section.

   With these issues combined in one table, the user comments on why the bundle section is acceptable in terms of safety. The report shows an example of comments that may be used, but it would be at the discretion of the ACO as to whether the comments would be accepted.

   Because there are many bundle sections in the EWIS (at least 1774 in this case), it is impractical to show and comment on each bundle section. Therefore, filtering mechanisms are used to show the bundle section with a threshold of potential damage. In this report, the threshold was taken as a bundle section that contained enough power that an arcing event could cause damage of approximately 1/8 in^3 in a hydraulic line or, if the bundle section was within 6″ of a hydraulic line, 1.0 mm^3. Other criteria were used to determine which bundles were reported. These included such things as bundle sections that contain redundant systems or are within 6″ of redundant systems.

3. CONCLUSIONS AND RECOMMENDATIONS.

The goal of this project was to continue the development of the Electrical Wiring Interconnection Systems (EWIS) Risk Assessment Tool (RAT) so that it would be more useful to Type Certificate and Supplemental Type Certificate (STC) applicants in meeting the requirements of Title 14 Code of Federal Regulations (CFR) 25.1709. The specific areas of research were validity of the data, entry of required data into the model database, and improve the correspondence of reports generated with Aircraft Certification Officer (ACO) expectations.

Wire probability density functions for open and shorting faults were developed that depend on the wire properties, routing considerations, and zonal environment. The failure equations were developed using expert judgment that was elicited using a paired comparison process and analyzed using the Bradley-Terry and Negative Exponential Life models. The failure functions were scaled using service difficult data for the emergency path lighting system. The failure functions still need to be validated.

A model was developed to estimate the potential damage to structure caused by an electrical arcing event. The model was based on the power available in the arc, heat dissipation, and thermal mass of the target. Agreement between the model and damage measured in laboratory arcing tests was good. However, areas to improve the model have been identified.

Developments have been made in the EWIS RAT to simplify the collection and entry of required wire and routing data. This was done in coordination with an aircraft manufacturer. Some tools are general and can be applied to any application. However, other tools are specific to the organization and will have to be modified when used with different organizations.

The prototype EWIS Safety Report was generated based on the reports generated by the EWIS RAT. The report addresses the requirements that the original equipment manufacturer (OEM) will need to meet to satisfy 14 CFR 25.1709, but this still needs to be reviewed by Federal Aviation Administration personnel.

3.1 IMPROVING ARC DAMAGE MODELS.

The arc damage methods in the current version of the EWIS RAT attempt to model the damage to structure caused by an electrical arc. Other damage and effects that need to be quantified include:

- Damage to other wires in the harness.
- Damage to EWIS and non-EWIS devices at a distance away from the arc caused by the spew of ejected material and the hot plume of ion gas above the arc.
- The effect of mitigation techniques, such as the use of Teflon tape to protect other wires in the bundle.
- The ability of the arc to ignite nearby objects, dirt, and lint.

In addition, the initial work with the finite element modeling suggests that the issue of heat energy transfer away from the arc by the target material could be calculated using the thermal properties of the target and not by empirical equations. This will increase the accuracy and confidence of the results, which will be required when dealing with smaller-scale damage, such as the rupture of pressurized hydraulic or pneumatic lines.

3.2 EXPANDING THE CAPABILITY OF THE EWIS RAT TO INTEGRATE AND ANALYZE 3D CAD MODELS OF EWIS AND NON-EWIS ELEMENTS.

Currently, the EWIS RAT is designed to meet the needs of OEM in the certification of new aircraft, but cannot directly evaluate the three-dimensional (3D) computer-aided design (CAD) models that have been made of the aircraft. These models include the location of devices, the positions of nonelectrical items such as fuel tanks, and information on the wire routing. Evaluation of the models in a 3D environment would be the next logical step in the evaluation of the EWIS.

The full integration of 3D CAD data would allow the generated reports to identify EWIS and non-EWIS better and to eliminate interaction for such things as distance from hydraulic lines, fuel lines, flight control cables, and safety-critical equipment. Currently, this information has to be generated outside the EWIS RAT, but it can still be imported into the program. From the knowledge of EWIS and non-EWIS proximity, the values reported as part of the damage potential reports and bundle section reports are shown. If deemed applicable, modifications can be made to the routing or protection of the wire bundle based on what system may be impacted by the damage.

This would aid OEMs in the integration of the EWIS RAT into their organizations and help reduce the amount of work that would be required for full integration. Some methodologies for the incorporation of 3D CAD models have been investigated and preliminary designs for modifications to the EWIS RAT have been developed.

3.3 FIELD TEST EWIS RAT FOR AN STC APPLICATION.

The EWIS RAT has focused on meeting the needs of OEMs in the certification of new aircraft, and is dependent upon a significant amount of data that is only available to the OEM. For those performing STCs on aircraft, the consideration of EWIS-related safety concerns is limited, but could be greatly improved with the assistance of a defined software approach, similar to the one defined by the EWIS RAT. However, because there is a limitation on the amount of data available to those modifying aircraft who are not the OEM, considerations need to be made as to the level of completeness to which aircraft-modifying organizations will be held.

Methods and procedures need to be developed to provide a clear means of proving that the modifications that are made to the aircraft have not adversely affected the safety of the wiring system.

This could be best accomplished with the on-site application of the EWIS RAT to an aircraft that is undergoing the process for an STC. This would help determine the different levels of feasibility and which aspects of the EWIS RAT are impractical to require from a modifier during the STC process. From this on-site effort, some modifications to the EWIS RAT may need to be performed based on the level of detail or quality of the information reported. Further, as part of this, the expectations of regulatory bodies would be considered as to what level of information would be deemed sufficient for certification of the aircraft modification.

3.4 VALIDATION OF FAILURE RATE EQUATIONS USING U.S. NAVY WIRE FAILURE DATA.

The wire failure rate equations derived using the paired comparison need to be validated before they can be used for certification. In general, there is a lack of historical data to validate these equations. However, in recent years, the U.S. Navy has placed emphasis on recording wire failures. It may be possible to validate these equations using the U.S. Navy data.

Several different zones would be selected and characterized in terms of the 14 variables used in the paired comparison. Using the U.S. Navy databases, the wire failure rates for these zones could be calculated and compared to those generated by the failure rate equations. If there was good agreement for those selected environments, then it is likely that the failure rates calculated for the other environments would also be correct. While military transport aircraft are not identical to commercial aircraft in both design and mission, there are enough similarities that the comparison would be valid.

3.5 THE ACO REVIEW OF EWIS RAT REPORTS.

Although originally part of this project, the reports generated by the EWIS RAT were not evaluated by an ACO. For this tool to be accepted by the aviation community, the reports that are generated should correlate with the expectations of the regulatory bodies that will be viewing the final products. Without this correlation between the expectations and the reports, OEMs will be less likely to use the tool and the associated work if they cannot be certain that the end product will be of any use in the certification process. Efforts not directly related to the certification process are discouraged by the ACOs. Therefore, the format and scope of the output must be useful to the ACO reviewing it. If the data overwhelm or are not understood by the ACO, the report is much less useful. In addition, if the reports do not directly address the issues that are of concern to the ACO, they also are much less useful.

3.6 POTENTIAL ADDITION OF OTHER AGING MODEL.

Although the paired comparison results from this work generated failure functions, these failure functions were for the random probability of failure, and they cannot be applied as an aging model (i.e., the failures were independent of time); aging is considered when the likelihood of a failure changes with respect to time.

The only aging model currently available in the tool is a Hydrolysis Aging Model, which was developed by Lectromechanical Design Company. This model was developed based on laboratory tests and examination of polyimide-insulated wiring systems. As such, the parameters for input into the aging model are rather limited and the application to other wire types is subject to question.

Because of the varying chemical compositions of wire insulating materials that are used on aircraft, any aging model would have to be able to combine various aspects of the material properties such as melting temperature, hydrolytic resistance, and crack propagation. Other items, such as modifiers for things like good maintenance practices, might have to be considered as part of the aging models.

There have been some research efforts in the past to quantify the aging and degradation of insulating materials in aircraft environments, and these may be good locations from which future aging models may be developed.

An aging model would help designers and regulators define maintenance intervals for the wiring in aircraft and, if integrated as part of the EWIS failure matrix report, would hopefully provide a definition of when one could expect the failure probabilities to exceed acceptable levels.

4. REFERENCES.

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APPENDIX A—OVERVIEW OF ELECTRICAL WIRING INTERCONNECTION SYSTEMS RISK ASSESSMENT TOOL

A software Risk Assessment Tool (RAT) was developed by Lectromechanical Design Company that aids the user in the risk assessment of the aircraft Electrical Wiring Interconnection System (EWIS). While the tool is still in its beta version, it appears that it may be a significant help in the performance, understanding, and standardization of the EWIS risk assessment for a Type Certificate or Supplemental Type Certificate (STC).

The tool is composed of two databases that feed the analysis/report generator module. Significant aircraft design data are collected and organized in the EWIS Model Database; and non-aircraft-specific data are kept in the EWIS Failure Rate and General Information Database. Information in these databases is used in the analysis of the EWIS. The results of the analysis are presented in a series of reports that are designed to be useful in the certification and safety analysis process. The flow of information through the tool is shown in figure A-1.

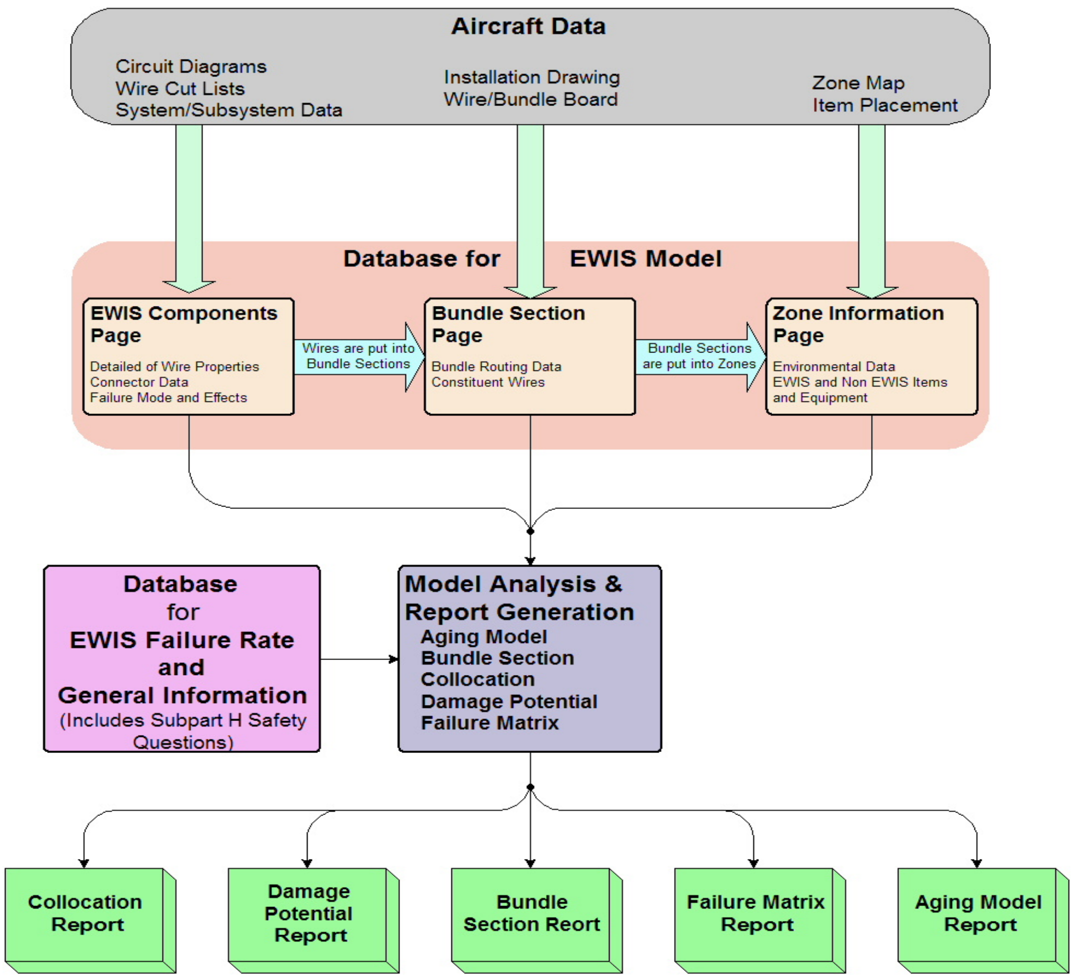


Figure A-1. Flow Diagram of EWIS RAT

Descriptions of the databases in figure A-1 are given below.

- The EWIS database contains aircraft design-specific data that can be queried at three distinct levels:

    - Wire Level
    - Bundle Level
    - Zonal Level

- The EWIS Failure and General Information Database is called by the various analytical modules of the code to provide:

    - EWIS failure data
    - Damage potential data
    - Air Transport Association system codes
    - Environmental and operational levels, etc.

    The database can be easily updated as more data becomes available.

- The calculation and report generation module queries the EWIS database, and/or calculates failure probabilities, etc., and then arranges the results into one or several reports, depending on the desired analysis. The following are descriptions of the reports and analyses that the tool can be asked to perform.

    - Collocation reports: There are several different collocation analyses available in the tool. Collocation of systems, subsystems, failure effects, etc., can be performed at the bundle or zonal level. In general, they should be used during development of the EWIS, and the Bundle Section Report will be used as certification documentation. However, when performing the common mode analysis, the failure effect collocation report can be used to show independence of certain basic EWIS events.

    - Damage Potential Report: This analysis calculates the amount of damage that can result from an arcing or an arc-tracking event in the bundle. Key bundle variables include the number and gauge of power wires, circuit protection, voltage, and wire insulation type. Damage includes potential damage to the bundle itself, adjacent bundles, adjacent equipment, structures, and flammable material. The potential damage should be considered in the Particular Risk and Zonal Analysis and, depending on the analysis, could require actions such as separation, segregation, or other mitigation techniques.

    - Bundle Section Report: This is the integration of the Damage Potential, Collocation Reports and specific EWIS separation and safety issues. In this module, each bundle section is analyzed. Therefore, a risk analysis is performed on the entire EWIS system. This report documents the physical failure analysis requested in proposed Title 14 Code of Federal Regulations (CFR) 25.1705 and the common mode analysis of the functional failures.

- Failure Matrix Report: A list of all basic events (corresponding to those events from the individual system fault trees) and the probability that those basic events will occur due to an EWIS failure is generated. These basic events can be placed into the system fault trees to obtain more accurate failure rates of the system. This report is meant to satisfy the requirements of proposed 14 CFR 25.1705 to include the EWIS effects on the functional failure of the system for an aircraft. With the addition of the EWIS failures, the system fault tree will delineate how, and the probability that, an EWIS failure can result in aircraft level hazards.

- Aging Model Report: This analysis models how different environments can change the rate of EWIS failures, and therefore, the probability of basic events. If these probabilities are used in the system fault trees, then the reduction of system reliability due to an EWIS failure can be calculated as a function of aircraft age. At this time, an aging model in the database is a hydrolytic deterioration model that is applicable for aromatic polyimide insulation.

These reports are meant to be used in the safety analysis required by 14 CFR 25.1309, further defined in Aerospace Recommended Practice 4761, and again developed in proposed 14 CFR 25.1705. The reports are designed such that the safety analysis can be performed in a straightforward and broadly understood manner.

APPENDIX B—EXPLANATION OF VARIABLES

The following is the breakdown of the variables that were used for the paired comparison workshop. These assumptions, variables, and break points were used to explain to the experts the break points in each of the variables.

B.1 ASSUMPTIONS.

- When filling out this survey, it may be helpful to visualize a 6- to 10-foot section of a bundle assembly. This bundle will run through several clamps and may include branches and shorter breakouts leading to devices.

- Wire Installations are assumed to have been done adhering to best practices such as found in AS50881A, Chapter 20 of Aircraft Maintenance Manual, Advisory Circular (AC) 43-13-1b, Job Aid 1.0, etc. This does not mean that the installations are prefect, only that they were installed by competent personnel who attempted to use accepted procedures.

- Connectors, while important, are not included in this survey.

- There are two modes of failure considered in this survey:

  - Opens: This refers to a breakdown of the conductor. It includes the total failure or breaking of the conductor and also the development of a high resistance in the conductor such that the wire cannot perform its intended function.

  - Shorts: This is a breakdown of the insulation and a shorting of the conductor, either to the structure or to another wire. Breaches in the insulation are not failures unless shorting is present.

  Note that under certain circumstances, either of these failure modes can develop further into arcing and fire failures. While very important, this situation is not subject of this survey. This survey deals with the initial failure of the wire.

- Answers should not be based on the results of one or two bad batches of a particular item of material, but instead on what is generally expected from a product.

B.2 PHYSICAL AND ENVIRONMENTAL VARIABLES.

WIRE PROPERTIES

Wire Gauge:

00-14 AWG:
16-22 AWG:
24-26 AWG:

Conductor Type:

Aluminum:

Copper:

High Strength Copper Alloy:

Insulation Type:

Polyimide:

Hybrid (PI/FP composite):

ETFE & other FP: ETFE and other flouropolymers

Splices:

None: There are no wire splices

Environmental: There is an environmental (sealed) wire splice

Non-environmental: There is a non-environmental (sealed) wire splice

BUNDLE PROPERTIES

Bundle Size

Large (>1.25 in): The Bundle Diameter is greater than 1.25 inches

Moderate (0.5-1.25 in: The Bundle Diameter is between 0.5 and 1.25 inches

Small (0.2-0.5 in): The Bundle Diameter is between 0.2 and 0.5 inches

Very Small (<0.2 in): The Bundle Diameter is less than 0.2 inches

Bundle Protection:

Some Level of Protection: There is some type of chafing protection on the bundle

Not protected (Open There is no chafing protection on the bundle

Curvature of the wire:

Low (> 10x): The radius of curvature is greater than 10 times the diameter of the bundle.

High (<= 10x): The radius of curvature is less than or equal to 10 times the diameter of the bundle.

Bundle Orientation (Shock)

Horizontal/Vertical Wire

Longitudinal

ZONAL PROPERTIES

Operation/Maintenance Traffic

Low: Wire that rarely comes in contact with human either during operation or maintenance.

Moderate: Wire that rarely comes in contact with human either occasional maintenance actions.

High: Areas of high operations and maintenance traffic

Ops Temp/Alt: Operational Temperature and Altitude

Benign (P & T Controlled*):* Pressure and Temperature are controlled

D1 (P Control. but not T): Pressure is controlled but Temperature is **not** controlled

D2 (P & T not controlled): Pressure and Temperature are **not** controlled

D3 (High T & P not control): The temperature is high and Pressure is **not** controlled

Vibration*:* These break point descriptors are taken from RTCA DO-160

Low: (Fuselage): Vibration levels are low similar to what may be expected in the fuselage

Moderate: (Inst Panel): Vibration levels are moderate similar to what may be expected in an instrument panel.

High: (Nacelle etc.): Vibration levels are high similar to what may be expected in a nacelle.

Extreme: (Engine): Vibration levels are extreme similar to what may be expected near an engine.

Exposure to Corrosive Fluids

Yes: The wire is routinely exposed to fluids that are corrosive.

No: The wire is not exposed to fluids that are corrosive.

Exposure to Conductive fluids

Yes: The wire is routinely exposed to fluids that are conductive.

No: The wire is not exposed to fluids that are conductive.

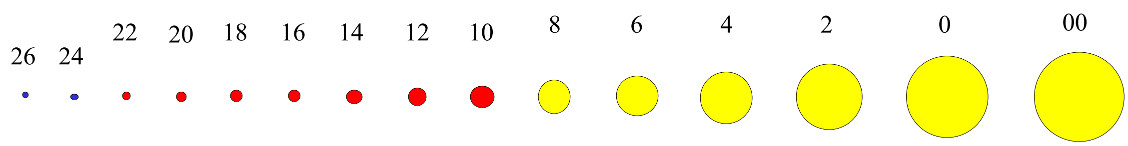
B.3 PHYSICAL AND ENVIRONMENTAL VARIABLE.

WIRE PROPERTIES

Wire Gauge:

00-14 AWG: Many of the larger diameter wires have a thicker insulation than the smaller diameter wire. This can be considered when evaluating wire gauge as a factor.

16-22 AWG:



24-26 AWG:

Conductor Type: For the purposes of this survey the different plating (i.e. Tin, Silver or Nickel) on the wires are not considered.

Aluminum: This refers to aluminum conductors in power feeder cables and not to general-purpose wire

Copper:

High Strength Copper Alloy: For the purposes of this survey this is only used in 24-26 gauge wire.

Insulation Type:

Polyimide: This refers to construction made with aromatic polyimide tape such as Mil-W- 81381, BMS-13-51. It includes construction that have a flouropolymers topcoat (1mil or less in thickness). This category does not include Poly X, which is an aliphatic polyimide

Hybrid (PI/FP composite): This refers to constructions with a single wrap of aromatic polyimide (possibly with a flouropolymer layer) and then a substantial layer of flouropolymer material that is several mils thick. This includes the AS 22759/80-92, BMS 13-60 and similar constructions where the flouropolymer is at least several mils thick.

ETFE & other FP**: ETFE and other flouropolymers. These includes**

ETFE (Tefzel)
XL-ETFE (Cross-linked Tefzel, spec 55)
Teflon
X-linked Polyalkene/Kynar (spec 44)

It does not include PVC/glass /nylon, Mil-W- (not a flouropolymer), Poly X

Splices:

None: This assumes a wire with no splices either repair or production.

Environmental: This assumes a sealed splice made by a qualified electrician that is either a production or repair splice

Non-environmental: This assumes a non-sealed splice made by a qualified electrician that is either a production or repair splice.

BUNDLE PROPERTIES

Bundle Size

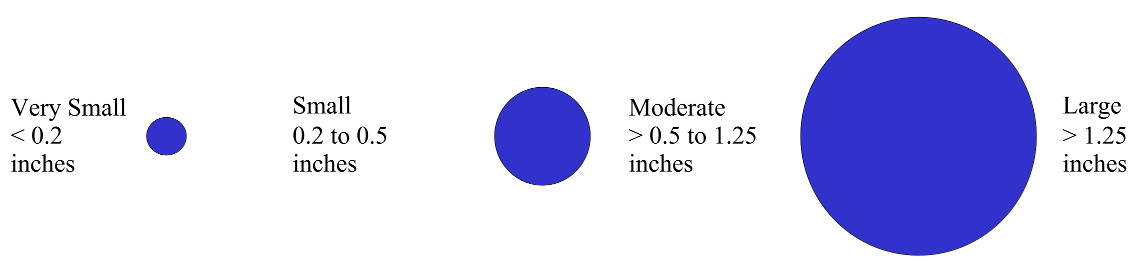
Any wire that is routed in small bundles including breakouts that connect to instruments or devices.

Large (>1.25 in): The diameter of the bundle is greater than 1.25 inches.

Moderate (0.5-1.25 in): The diameter of the bundle is greater than 0.5 inches but less than or equal to 1.25 inches.

Small (0.2-0.5 in): The diameter of the bundle is greater than 0.2 inches but less than or equal to 0.5 inches.

Very Small (<0.2 in): The diameter of the bundle is less than or equal to 0.2 inches. Foe example a bundle of seven 20 gauge wires.



Bundle Protection: This refers to physical protection it does not refer to lightening protection.

Some Level of Prot.: Examples of protection include chafing tape, metal or plastic conduit, Nomex over-braid.

Not protected: This refers to an open bundle

Curvature of the wire:

Low (> 10x): The radius of curvature is greater than 10 times the diameter of the bundle.

High (<= 10x): The radius of curvature is less than or equal to 10 times the diameter of the bundle.

B.4 ZONAL PROPERTIES.

Operation/Maintenance Traffic

Low: Wire that rarely comes in contact with human either during operation or maintenance.

Moderate: Wire that rarely comes in contact with human either occasional maintenance actions.

High: Areas of high maintenance traffic include Equipment bays where LRUs are continuously being changed out. Also passenger entertainment, emergency path lighting etc where there is maintenance (changing seating configurations) and operations traffic (passenger interactions)

Operation Temperature and Pressurization: These break point descriptors are taken from RTCA DO-160

Benign (P & T Controlled*):* Such as in the cabin or the cockpit inside the pressure vessel.

D1 (P Control. but not T): Some baggauge compartments

D2 (P & T not controlled): Such as the wings or tail cone outside of the pressure vessel.

D3 (High T & P not control): This assumes general purpose wire near or on the engine not specialty wire designed for very high temperature application.

Vibration: These break point descriptors are taken from RTCA DO-160

Low: (Fuselage):

Moderate: (Inst Panel)

High: (Nacelle etc.)

Extreme: (Engine)

Exposure to Corrosive Fluids

Yes: Assume the wire in routinely exposed to one or more corrosive fluids such as Hydraulic fluid (skydrol)

Cleaning fluid
Fuel
Blue water
Anti-ice fluids
Anti-corrosion fluid (for the airplane metal components)

No: In the normal course of operation the wire is not exposed to corrosive fluids

Exposure to Conductive fluids

Yes: Assume the wire in routinely exposed to one or more conducting fluids such as

Water
Salt Water Spray
Lavatory fluids
Spilled beverages (soft drinks, coffee, Alcohol)
New (Green) anti-ice fluids

No: In the normal course of operation the wire is not exposed to conducting fluids

APPENDIX C—DESCRIPTION OF EXPERTS

C.1 INTRODUCTION.

All those who participated (see table C-1) in the workshop had more than 5 years of experience with wiring systems on aircraft. Eight had experience with civilian aircraft, three had experience with military aircraft, and three had experience on both types of aircraft.

Table C-1. Experts Participating in the Paired Comparison Workshop (One person requested that their name not be listed)

Name	Position	Company/Organization
Richard Anderson	Director, Maintenance	Air Transport Association
Jerome Collins	Branch Manager	NAVAIR
Luci Crittenden	Flight Operations Engineer	National Aeronautics and Space Administration-Langley
Keith Fairley	Managing Director	Cable Connect Solutions
Bryce Fenton	Design and Regulatory Specialist	Cessna
Tony Heather	Senior Airworthiness Surveyor	Civil Aviation Authority
Bjorne Jakobsson	Avionic Systems Engineer	Airtran Airways
George Slenski	Principle Engineer	United States Air Force
Larry Stevick	Senior Specialist Engineer	Not available
Dane Swenson	Avionics Wiring Analyst	Delta
Mark Thomas	Not available	Not available
Kirk Thornburg	VP Maintenance Engineering	Airtran Airways
Glenn White	Program Analyst	Federal Aviation Administration

C.2 DESCRIPTION OF EXPERTS.

The following is a list of the experts' credentials in terms of specific experience with wiring on aerospace vehicles. These are listed in no particular order.

Expert A Credentials: A reliability engineer, electrical & electronics shift member on the company's DNS, STC. Also has worked as a design engineer for several large avionics retrofits.
Years of experience handling wire and wiring issues: 22 years.
Primary type of aircraft wire experience: Commercial aircraft.

Expert B Credentials: Naval Vehicle Systems engineering for over 15 years, +7 years electrical power systems engineering +3 years of air vehicle wiring systems engineering.
Years of experience handling wire and wiring issues: Over 10 years.
Primary type of aircraft wire experience: Military aircraft.

Expert C Credentials: Have been involved in the installation, design, maintenance, involving various the various wire types found on aircraft.

Years of experience handling wire and wiring issues: 18 years.

Primary type of aircraft wire experience: Military aircraft.

Expert D Credentials: Working on military tactical and civilian transport a/c for 36 yrs as troubleshooter, repair and engineer. Member of ATSRAC Non-Intrusive and intrusive inspection working groups.

Years of experience handling wire and wiring issues: 36 years.

Primary type of aircraft wire experience: Commercial and Military aircraft.

Expert E Credentials: Experience with wire installations for both new aircraft and aircraft modifications. Years of hands on experience with the troubleshooting of wire problems.

Years of experience handling wire and wiring issues: 30 years.

Primary type of aircraft wire experience: Commercial aircraft.

Expert F Credentials: Has a general knowledge, not specific, of aircraft wiring systems. Also had experience with the overall safety considerations of the wire systems relevant to flight test. ATSRAC exposure,

Years of experience handling wire and wiring issues: Less than 6 years.

Primary type of aircraft wire experience: Commercial and Military aircraft

Expert G Credentials: Previous Electrical Inspection course instructor, Develop Electrical course training material, Aircraft Accident Investigator, Harmonization working group 13 team member.

Years of experience handling wire and wiring issues: 10 years in depth, 37 years of aircraft maintenance experience.

Primary type of aircraft wire experience: Commercial aircraft.

Expert H Credentials: 24 years of service in the Royal Air force from actually carrying out maintenance to specifying policy.

Years of experience handling wire and wiring issues: 14 years.

Primary type of aircraft wire experience: Military Aircraft.

Expert I Credentials: Assisted engineering on development and installation of several modifications to aircraft, and was personally involved in the full aircraft wiring inspections on 727 and MD 88/90 aircraft. Currently using automated Wiring Analysis Equipment on preventative maintenance and troubleshooting of wiring issues.

Years of experience handling wire and wiring issues: 12 years.

Primary type of aircraft wire experience: Commercial aircraft.

Expert J Credentials: Had over five years of experience on ATSRAC and over 35 years of experience in commercial transport category aircraft; particularly in the creation and modification of maintenance programs.

Years of experience handling wire and wiring issues: 35 years.

Primary type of aircraft wire experience: Commercial aircraft.

Expert K Credentials: Was formerly an aircraft avionics installer and technical electrical systems design engineer. Current works on avionics and electrical systems certification and addresses field issues.

Years of experience handling wire and wiring issues: 18 years.
Primary type of aircraft wire experience: Commercial aircraft.

Expert L Credentials: Has worked as an electrical and avionics aircraft engineer since 1970. Current roles specifically related wire wiring issues include participation in ATSRAC and as Chairman of the EASA European Rule drafting Group for EWIS regulations.

Years of experience handling wire and wiring issues: 36 years.
Primary type of aircraft wire experience: Commercial aircraft.

Expert M Credentials: Twenty-six years of experience with developing, acquiring and maintaining aircraft electrical systems. The primarily experience was with military aircraft with moderate experience and familiarity with commercial aircraft.

Years of experience handling wire and wiring issues: 26 years.
Primary type of aircraft wire experience: Commercial and Military aircraft.

Expert N Credentials: Aging Wiring Maintenance Program on DC9s, IFE systems Installations - A330, B917, Post Aircraft Delivery - in service modifications to A/C Systems.

Years of experience handling wire and wiring issues: 10 years.
Primary type of aircraft wire experience: Commercial aircraft.

APPENDIX D—FURTHER DETAILS OF PAIRED COMPARISON WORK

D.1 INTRODUCTION.

An accurate Electrical Wiring Interconnection Systems (EWIS) Component failure rate data is needed when the EWIS failure effects are represented by system fault trees in the system safety analyses as the backbone of the failure matrix report. This failure rate depends on the component environment and the properties. The EWIS Risk Assessment Tool (RAT) software must be able to assess the failure rates for the different EWIS component failure modes under different environmental and operational conditions.

To improve the data in the beta version tool, the goal was to develop a multivariant function that calculated wire failures dependent on wire properties, routing considerations, and environmental conditions (Note, wire properties, routing considerations, and environmental conditions will hereafter be referred to as the wire environment). Therefore, a formal pair comparison using an expert opinion experiment was applied to the problem of wire failure. This methodology was employed because the wire failure data for the many different environmental and operational conditions found on aircraft are sparse. Therefore, a failure function cannot be created based on only historical data. Using this technique, historical data is supplemented by expert opinion in creating a wire failure function.

D.2 MODEL FOR WIRE FAILURE.

The goal of this effort was to develop a theoretically sound model for wire failure. In this model, “Wire failure” specifically referred to two modes of failure: fail to ground (including wire to wire and wire to structure failure) and fail to open (broken conductors).

D.3 TIME TO FAILURE DISTRIBUTION.

The development of a time to failure Probability Density Function (PDF) for wire failure based on environmental factors was considered. The PDF for T_g and T_o, the time to wire failure “fail to ground” and “fail to open,” respectively, is assumed to be the exponential distribution given by

$$f(t_i|\lambda_i) = \lambda_i e^{-\lambda_i t_i} \tag{D-1}$$

where $i = g, o$ and the parameter $\lambda_i > 0$ is referred to as the failure rate for failure mode i. To completely specify the distribution, this parameter must be estimated, usually from past data. The exponential distribution has been applied successfully for years in reliability and risk analyses to model the failure behavior of electronic components [D-1]. Assuming that the individual failure modes behave independently (which is a common assumption unless a particular dependence model can be specified), it is well known that the time to wire failure (regardless of failure mode), $T = \min\{T_g, T_o\}$ has an exponential PDF with failure rate $\lambda_g + \lambda_o$. Thus, each failure mode may be considered separately in the analysis.

D.4 INCORPORATION OF PHYSICAL AND ENVIRONMENTAL FACTORS.

Through review of industry documents and discussion with industry experts, a list of physical and environmental factors and their critical values was compiled. This list is presented in table D-1. This table shows the physical and environmental variables and the break points of those variables. The variables are separated into Wire Properties, Bundle Properties, and Zonal Properties. Wire Properties include Wire Gauge, Conductor Type, Insulation Type, and Presents of Splices. Bundle Properties include Bundle Size, Bundle Protection, Curvature of Bundle, and Bundle Orientation. Zonal Properties include Operations and Maintenance Traffic, Operation Temperature and Altitude or Pressure, Vibration, Exposure to Corrosive Fluids, and Exposure to Conducting Fluids. While most of the variable break points are self-explanatory, definitions for the break points of the variables Ops/Main Traffic, Vibration, and Ops/Pressurization can be found in reference D-2.

Table D-1. Environmental Factors Contributing to Wire Failure

Category	Variables	Levels			
		1	2	3	4
Wire properties	Wire gauge	4/0-8 AWG	10-16 AWG	18-22 AWG	24-28 AWG
	Conductor type	Aluminum	Copper	High-strength copper alloy	
	Insulation type	Polyimide	Hybrid (PI/FP composite)	ETFE and other FPs	
	Splices	No	Environmental	Nonenvironmental	
Bundle properties	Bundle size	Large (>1.25 in.)	Medium (0.5-1.25 in.)	Small (0.2-0.5 in.)	Very small (<0.2 in.)
	Bundle protection	Some level of protection	Not protected (open)	Protected metal conduit	
	Curvature of wire	Low (diameter >10x)	High (diameter ≤10x)		
	Bundle orientation	Horizontal/ vertical wire	Longitudinal wire		
Zonal properties	Operations/main traffic	Low	Moderate	High	
	Operation temperature/ Pressure	Benign (pressure and temperature control)	D1 (pressure but no temperature control)	D2 (no pressure or temperature control)	D3 (power plant high temperature and pressure not controlled)
	Vibration	Low	Moderate	High	Extreme
	Exposure corrosive fluid	Yes	No		
	Exposure conducting fluid	Yes	No		

PI = Polyimide
FP = Fluorescent penetrant
ETFE = Ethylene tetrafluoroethylene
AWG = American Wire Gauge

Incorporating physical and environmental factors into a time to failure PDF is a common practice in reliability and biometry. A common model for incorporating these variables is the Proportional Hazards Model [D-2]. The basic idea of the model is to write the failure rate as a function of the covariates, a common form being

$$\lambda = e^{\beta_0+\beta_1 X_1+\ldots+\beta_{15} X_{13}} \tag{D-2}$$

where the X_i represents the quantitative effect of covariate i, and β_i represents regression parameters relating the influence of covariate i on the failure rate. For example, rewrite equation D-1 as

$$f(t|\beta_0, \beta_1, \ldots, \beta_{14}) = [e^{\beta_0+\Sigma_{j=1,13}\beta_j X_j}] \exp\{-[e^{\beta_0+\Sigma_{j=1,13}\beta_j X_j}]t\} \tag{D-3}$$

and now, the parameters $\beta_0, \beta_1, \ldots, \beta_{13}$ must be estimated from past data. Note that the index i for the failure mode was suppressed.

Usual estimation of the parameters requires an extensive amount of failure data in many environments. As this is currently impossible, the use of expert judgment was employed. Expert judgment, or subjective data, has been used successfully in risk analysis for years [D-3], and there are several techniques in practice for collecting, combining, and using expert judgment. One of these methodologies is called the Negative Exponential Life (NEL) model, which is based on a popular expert judgment elicitation method known as paired comparison [D-3]. The approach consists of four steps:

1. Obtain a single failure environment for which there exists significant exposure time and failure data. From this environment, obtain a failure rate estimate.

2. Select an additional number of failure environments to compare via paired comparison. The result of the paired comparison will be a set of failure rate estimates obtained to within proportionality constant.

3. Given the failure rate estimates obtained using the previous two steps, obtain the parameters estimates of $\beta_0, \beta_1, \ldots, \beta_{15}$ based on a regression analysis of the failure rate estimates obtained in step 2 and coded values for the physical environmental variables.

4. By comparing the failure rate estimate for the failure environment selected in step 1 to the failure rate estimate using the paired comparison and regression results in steps 2 and 3, the constant of proportionality for all failure rate estimates can be estimated.

Once the estimates for the parameters $\beta_0, \beta_1, \ldots, \beta_{13}$ are obtained, the complete failure rate and corresponding PDF may be specified for any environment.

D.5 THE EXPERTS' JUDGMENT EXPERIMENT.

Fourteen wiring experts attended a one-day workshop in which the expert opinion elicitation took place. Table D-2 lists the experts who granted approval for their names to be cited.

Table D-2. List of Selected Experts

Name	Position	Company/Organization
Richard Anderson	Director, Maintenance	Air Transport Association
Jerome Collins	Branch Manager	NAVAIR
Luci Crittenden	Flight Operations Engineer	National Aeronautics and Space Administration-Langley
Keith Fairley	Managing Director	Cable Connect Solutions
Bryce Fenton	Design and Regulatory Specialist	Cessna
Tony Heather	Senior Airworthiness Surveyor	Civil Aviation Authority
Bjorne Jakobsson	Avionic Systems Engineer	Airtran Airways
George Slenski	Principle Engineer	United States Air Force
Larry Stevick	Senior Specialist Engineer	Not available
Dane Swenson	Avionics Wiring Analyst	Delta
Mark Thomas	Not available	Not available
Kirk Thornburg	Vice President Maintenance Engineering	Airtran Airways
Glenn White	Program Analyst	Federal Aviation Administration

Initially, the experts were given an overview of how the wiring environments and the variable break points were determined and how a paired comparison is conducted. Experts were asked to compare the 15 sample environments given in table D-3. These environments were selected in consultation with experts not participating in the elicitation. The selection was based on realism, minimal change in environment comparisons, and wide-encompassing of the total set of wiring environments.

The experts were asked to reply to 105 survey questions for both the open and shorting failure analysis. Each question compared two environments, and the experts were asked to indicate the environment that would produce a failure sooner. It was also possible for the experts to specify that the environments are equally severe. The questions were presented in the form shown in figure D-1, where for ease of comparison, the environments were categorized according to wire, bundle, and zonal properties and the changes from environment 1 to environment 2 were shaded.

		COMPARISON 11		
WIRE ENVIRONMENT 1			**WIRE ENVIRONMENT 2**	
WIRE PROPERTIES			**WIRE PROPERTIES**	
Wire Gauge	18-22 awg		Wire Gauge	
Conductor Type	Copper		Conductor Type	
Insulation Type	Hybrid (PI/FP Composite)		Insulation Type	
Splices	None		Splices	
BUNDLE PROPERTIES			**BUNDLE PROPERTIES**	
Bundle Size	Moderate (0.5-1.25 in)		Bundle Size	
Bundle Protection	Not Protected (Open)		Bundle Protection	Some Level of Prot.
Curvature of Bundle	Low (> 10x)		Curvature of Bundle	
Bundle Orientation (Shock)	Horizontal/Vertical Wire		Bundle Orientation (Shock)	
ZONAL PROPERTIES			**ZONAL PROPERTIES**	
Ops/Main Traffic	High		Ops/Main Traffic	
Ops Temp/Alt	Benign (P&T Controlled)		Ops Temp/Alt	
Vibration	Moderate		Vibration	High
Exposure to Corrosive Fluid	No		Exposure to Corrosive Fluid	
Exposure to Conductive Fluid	Yes		Exposure to Conductive Fluid	

Figure D-1. Paired Comparison Question Format

Table D-3. Comparison Environment Description

Environment	Wire Guage	Insulation Type	Conductor Type	Splices	Bundle Size	Bundle Protection	Curvature of Bundle	Shock Dam. Pot.	Ops/Main Traffic	Ops temp\altitude	Vibration	Exp Corrosive Fluid	Exp Conducting Fluid
1	18-22 awg	Hybrid (PI/FP Composite)	Copper	None	Moderate (0.5-1.25 in)	Not Protected (Open)	Low (> 10x)	Horizontal/Vertical Wire	High	Benign (P&T Controlled)	Moderate	No	Yes
2	24-26 awg	Hybrid (PI/FP Composite)	High Streng. Copper Alloy	None	Very Small (< 0.2 in)	Not Protected (Open)	Low (> 10x)	Horizontal/Vertical Wire	High	Benign (P&T Controlled)	Moderate	No	Yes
3	24-26 awg	Hybrid (PI/FP Composite)	Copper	None	Moderate (0.5-1.25 in)	Not Protected (Open)	Low (> 10x)	Horizontal/Vertical Wire	Moderate	Benign (P&T Controlled)	Moderate	No	Yes
4	18-22 awg	Hybrid (PI/FP Composite)	Copper	None	Moderate (0.5-1.25 in)	Some Level of Prot.	Low (> 10x)	Horizontal/Vertical Wire	High	Benign (P&T Controlled)	High	No	Yes
5	18-22 awg	Hybrid (PI/FP Composite)	Copper	None	Large (> 1.25 in)	Not Protected (Open)	Low (> 10x)	Horizontal/Vertical Wire	High	Benign (P&T Controlled)	Moderate	Yes	Yes
6	18-22 awg	Hybrid (PI/FP Composite)	Copper	Non-environmental	Moderate (0.5-1.25 in)	Not Protected (Open)	Low (> 10x)	Horizontal/Vertical Wire	High	Benign (P&T Controlled)	Low	No	Yes
7	18-22 awg	ETFE & other FPs	Copper	None	Moderate (0.5-1.25 in)	Not Protected (Open)	Low (> 10x)	Horizontal/Vertical Wire	High	Benign (P&T Controlled)	Low	No	Yes
8	18-22 awg	Hybrid (PI/FP Composite)	Copper	None	Moderate (0.5-1.25 in)	Not Protected (Open)	High (<= 10x)	Horizontal/Vertical Wire	High	Benign (P&T Controlled)	Moderate	No	No
9	18-22 awg	Hybrid (PI/FP Composite)	Copper	None	Moderate (0.5-1.25 in)	Some Level of Prot.	Low (> 10x)	Horizontal/Vertical Wire	High	D2 (P&T not controlled)	Moderate	No	Yes
10	18-22 awg	Hybrid (PI/FP Composite)	Copper	None	Moderate (0.5-1.25 in)	Not Protected (Open)	High (<= 10x)	Horizontal/Vertical Wire	High	Benign (P&T Controlled)	Low	No	Yes
11	18-22 awg	Hybrid (PI/FP Composite)	Copper	None	Moderate (0.5-1.25 in)	Not Protected (Open)	Low (> 10x)	Longitudinal Wire	High	Benign (P&T Controlled)	Moderate	No	No
12	18-22 awg	Hybrid (PI/FP Composite)	Copper	None	Moderate (0.5-1.25 in)	Not Protected (Open)	Low (> 10x)	Horizontal/Vertical Wire	Low	Benign (P&T Controlled)	High	No	Yes
13	18-22 awg	Polyimide	Copper	None	Moderate (0.5-1.25 in)	Not Protected (Open)	High (<= 10x)	Horizontal/Vertical Wire	High	Benign (P&T Controlled)	Moderate	No	Yes
14	4\0-8 awg	Hybrid (PI/FP Composite)	Aluminum	None	Moderate (0.5-1.25 in)	Not Protected (Open)	Low (> 10x)	Horizontal/Vertical Wire	High	Benign (P&T Controlled)	Moderate	No	No
15	4\0-8 awg	Hybrid (PI/FP Composite)	Copper	None	Moderate (0.5-1.25 in)	Not Protected (Open)	Low (> 10x)	Horizontal/Vertical Wire	High	D2 (P&T not controlled)	Moderate	No	Yes

D.6 INDIVIDUAL EXPERTS.

The first analysis conducted was to see if each expert was specifying a true preference structure in his/her answers or just assigning answers in a random fashion. Let E_1, …, E_n denote the test environments whose failure rates are desired from experts. Experts were asked to assess a series of paired comparisons as to which environment was more severe, that is, more likely to produce a failure sooner. A preference structure can be determined by analyzing the number of circular triads in his/her comparisons. A circular triad occurs when the expert suggests, for example, that E_1 is more severe than E_2, E_2 is more severe than E_3, and E_3 is more severe than E_1, thus violating the transitivity property. When experts compare a large number of events, however, it is not surprising that a few circular triads may result.

It was determined an expression for $c(r)$, the number of circular triads in expert r's preferences [D-4]. Tables were developed of the probability that certain values of $c(r)$ are exceeded under the null hypothesis that the expert answered in a random fashion for n = 2, …, 10 [D-5]. In addition, a chi-squared statistic has been developed for comparing n items in a random fashion [D-4]. This statistic can be used to test the null hypothesis that an expert answered randomly versus the alternative hypothesis that his/her answers form a real preference structure. If the null hypothesis of random response for any expert cannot be rejected at the 5% level of significance, the expert should be dropped from the analysis. For the specific case considered here, it was determined that the null hypothesis could not be rejected at the 5% level of significance for any expert whose number of circular triads exceeded 97.

Table D-4 summarizes the performance of the 14 experts. The experts were labeled 1-15, with expert 4 missing. This is because there were 15 elicitation books created and only 14 experts attended the meeting. The books were randomly assigned, and thus, book 4 was unassigned. Table D-3 shows that experts 1, 6, 7, 8, and 10 were dropped from the "open failures" analysis and experts 1, 6, and 10 were dropped from the "shorting failures" analysis. This means that their data was not considered. In addition, as experts 1, 6, and 10 were dropped from both analyses, their data was not considered from any of the surveys.

From the analysis of each expert's answers and the resultant circular triads, the experts could be partitioned into three groups: those that are effective in both open and shorting failure analysis, those that are effective in one analysis but not the other, and those that are effective in neither. For the open failure analysis, there was a clear separation of experts with a solid preference and those without a preference (see figures D-2 and D-3). However, for the shorting failure analysis, the division was less clear.

Table D-4. Summary of Experts' Circular Triads

Expert No.	Open Failures		Shorting Failures	
	Number of Circular Triads	Null Hypothesis	Number of Circular Triads	Null Hypothesis
1	106	Fail to Reject	122	Fail to Reject
2	59	Reject	97	Reject
3	37	Reject	26	Reject
5	49	Reject	43	Reject
6	121	Fail to Reject	102	Fail to Reject
7	114	Fail to Reject	75	Reject
8	100	Fail to Reject	57	Reject
9	58	Reject	41	Reject
10	113	Fail to Reject	102	Fail to Reject
11	35	Reject	32	Reject
12	14	Reject	27	Reject
13	35	Reject	79	Reject
14	55	Reject	45	Reject
15	46	Reject	37	Reject

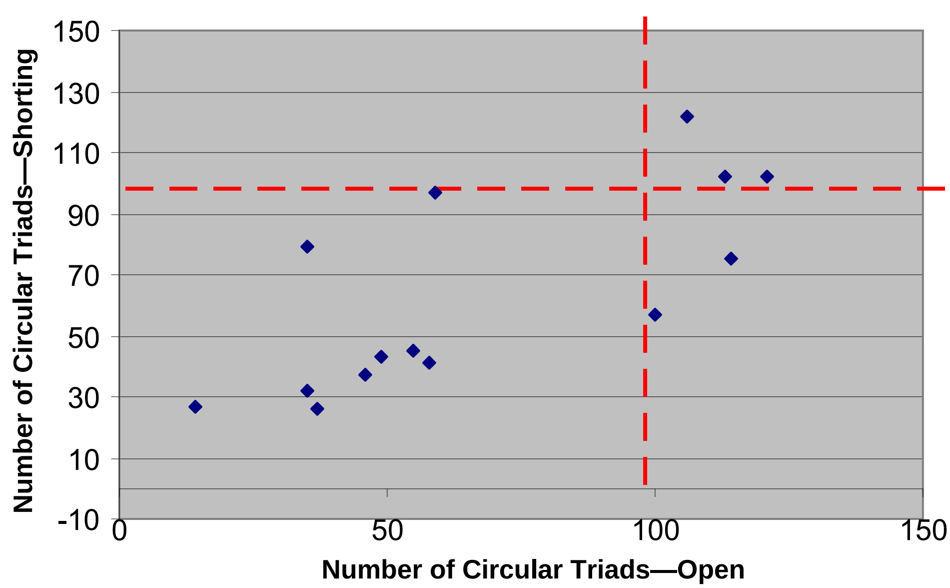


Figure D-2. Comparison of Individual Expert Performance

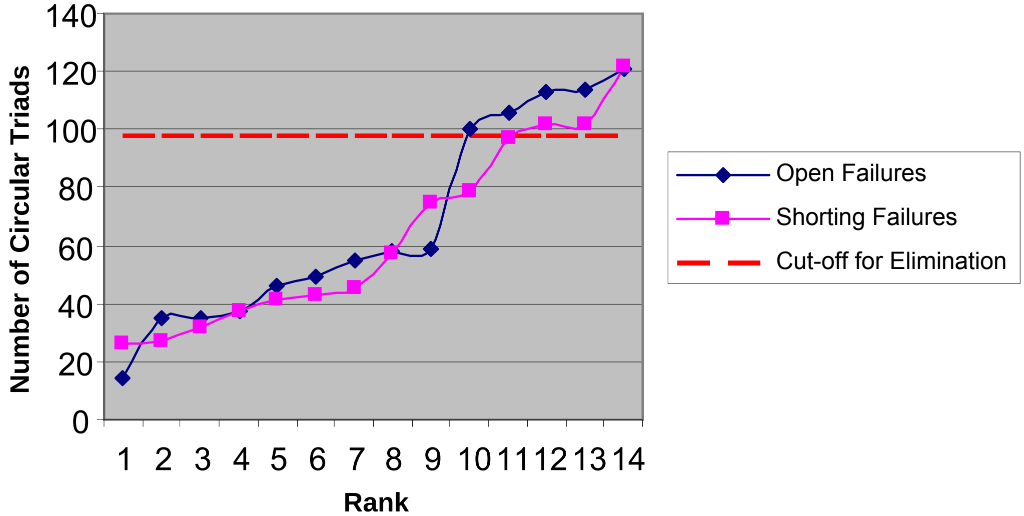


Figure D-3. Comparison of Overall Expert Performance

D.7 EXPERTS AS A GROUP.

The agreement of the experts as a group can also be statistically tested. To test the hypothesis that all agreements of experts are due to chance, the coefficient of agreement defines the tabulated distributions of a function of this value for small values of n and e under the hypothesis that all agreements of the experts are due to chance [D-5]. Let $N(i,j)$ denote the number of times some expert ranked E_i more severe than E_j. To test the hypothesis that all agreements of experts are due to chance, the coefficient of agreement is

$$u = \frac{2\sum_{i=1}^{n} \sum_{j=1\, j \neq i}^{n} \binom{N(i,j)}{2}}{\binom{e}{2}\binom{n}{2}} - 1 \tag{D-4}$$

and tabulated distributions of

$$\frac{2\sum_{i=1}^{n} \sum_{j=1\, j \neq i}^{n} \binom{N(i,j)}{2}}{\binom{e}{2}\binom{n}{2}} - 1$$

for small values of n and e under the hypothesis that all agreements of the experts are due to chance.

These distributions were used to test the hypothesis concerning the coefficient of agreement. For large values of n and e, a statistic has been developed, which, under the null hypothesis that all agreements of experts is due to chance, has (approximately) a chi-squared distribution [D-5]. Again, the hypothesis that all agreements are due to chance was rejected at the 5% level of significance for confidence in the expert estimates.

From the open failure analysis, after dropping experts 1, 6, 7, 8, and 10 and using the above statistics, the hypothesis may reject that the agreement was due to chance at the <0.001 level of significance. For shorting failure analysis, after dropping experts 1, 6, and 10, the hypothesis may reject that the agreement was due to chance at the <0.001 level of significance.

D.8 OBTAINING THE FAILURE RATE ESTIMATES.

The NEL model uses the fact that given two environments, say E_i, and E_j, with respective failure rates h_i and h_j, the probability that environment E_i produces a failure before environment E_j is given by

$$r(i,j) = \frac{h_i}{h_i + h_j} \qquad \text{(D-5)}$$

Let $N(i)$ denote the number of times some expert ranks E_i more severe than other environments, that is $N(i) = \sum_{r=1}^{e} N_r(i)$, David [D-4] shows that the failure rates $h_1, \ldots, h_n$ for all environments compared can be obtained as the solution to the system of equations

$$h_i = \frac{N(i)}{e \sum_{j=1, j \neq i}^{n} \left[h_i + h_j \right]^{-1}}, \ i = 1, \ldots, \mathrm{n} \qquad \text{(D-6)}$$

and Ford [D-6] shows that the following iterative solution procedure can be used to solve for the h_i up to a scale constant.

$$h_i^{(k+1)} = \frac{N(i)/e}{\sum_{j=1}^{i-1} \left[h_i^{(k)} + h_j^{(k+1)} \right]^{-1} + \sum_{j=i+1}^{n} \left[h_i^{(k)} + h_j^{(k)} \right]^{-1}}, \ i = 1, \ldots, \mathrm{n} \qquad \text{(D-7)}$$

where $h_i^{(k)}$ is the kth iteration estimate of h_i (thus, initial estimates must be specified) and by convention

$$\sum_{j=1}^{0} \left[h_1^{(k)} + h_j^{(k+1)} \right]^{-1} = \sum_{j=n+1}^{n} \left[h_n^{(k)} + h_j^{(k)} \right]^{-1} = 0 \qquad \text{(D-8)}$$

The PC-based computer program, WCOMPAR (available from Delft University of Technology), employs this procedure and was used to obtain the estimates (to within a scale constant) of the candidate wiring environment failure rates combined with their joint 90% bounds, which are provided in table D-5. Note that even within the candidate environments, there is a 2 order of magnitude separation in the failure rate estimates.

Table D-5. Bradley-Terry (NEL) Estimates and Joint 90% Confidence Bounds for the 15 Candidate Wiring Environments

	Open Failures			Shorting Failures		
Environment	Lower	Bradley-Terry Estimate	Upper	Lower	Bradley-Terry Estimate	Upper
1	0.016	0.039	0.068	0.020	0.045	0.067
2	0.060	0.121	0.260	0.047	0.085	0.160
3	0.007	0.026	0.047	0.007	0.019	0.039
4	0.017	0.042	0.073	0.031	0.070	0.130
5	0.068	0.119	0.190	0.077	0.150	0.220
6	0.150	0.265	0.420	0.057	0.102	0.170
7	0.004	0.014	0.029	0.006	0.017	0.032
8	0.021	0.050	0.089	0.012	0.028	0.044
9	0.018	0.042	0.063	0.030	0.059	0.110
10	0.019	0.048	0.080	0.019	0.044	0.075
11	0.004	0.020	0.040	0.003	0.012	0.022
12	0.005	0.018	0.041	0.007	0.024	0.038
13	0.110	0.158	0.260	0.160	0.252	0.430
14	0.001	0.008	0.018	0.004	0.012	0.019
15	0.010	0.030	0.055	0.047	0.081	0.120

Bradley developed a statistic to test the appropriateness (goodness of fit) of the Bradley-Terry (or NEL) model [D-7]. Using this statistic, the Bradley-Terry (NEL) model could not be rejected based on the data at the 5% level of significance.

D.9 OBTAINING A REGRESSION FIT.

To determine the values for the covariates X_i that are needed for the regression analysis, the experts were also asked to fill out survey questions presented in figure D-4, where for each failure type and each variable, the expert was given a base variable level (assigned a value of 1) and asked by what ratio the environment would become more or less severe as a single variable value was moved to its other possible values.

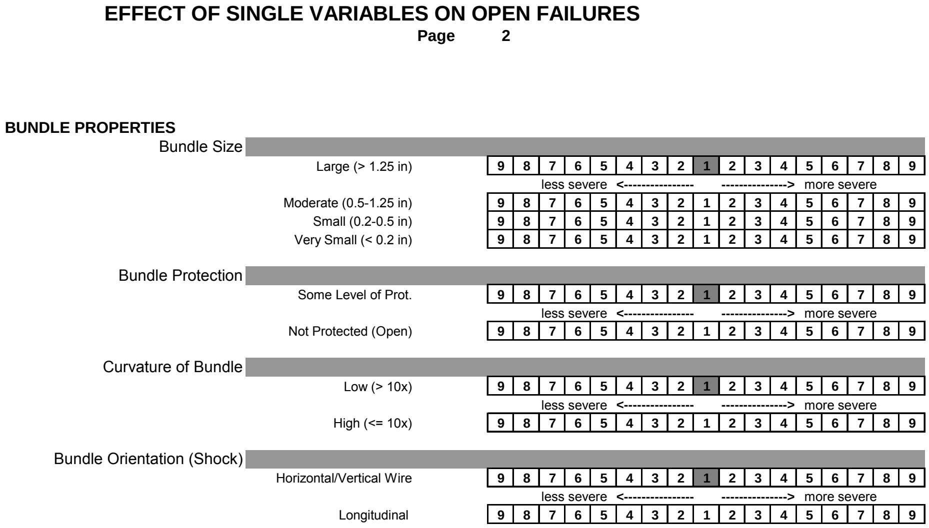


Figure D-4. Example Survey for Determining the Values for X_i

These results are graphically shown in figures D-5 to D-17. These data display the points of agreement and disagreement between the experts. By way of clarification of the graph legends, note that experts were randomly assigned numbers 1 through 15, thus there was no Expert 4. In addition, only the expert scores provided by those experts that passed the consistency test were used in this analysis. Thus, as shown in the legends in figures 6 and 7, experts 1, 6, 7, 8, and 10 were dropped from the open failures values and experts 1, 6, and 10 were dropped from the shorting failures analysis.

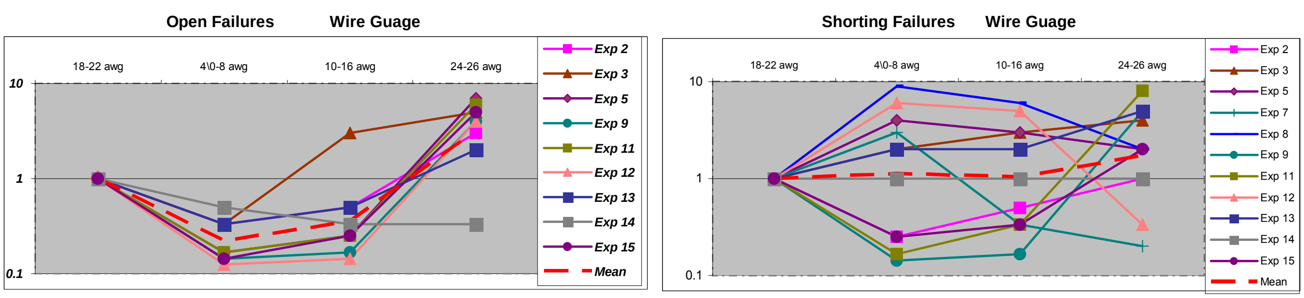


Figure D-5. Expert Values for Wire Gauge Levels

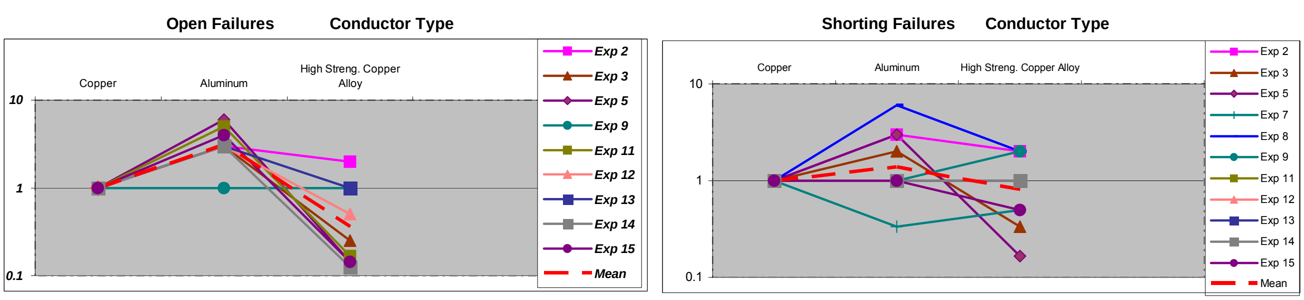


Figure D-6. Expert Values for Conductor Type Levels

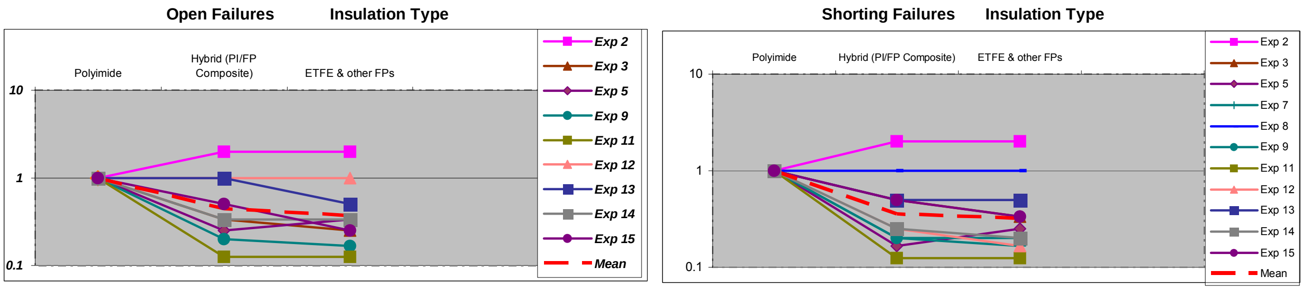


Figure D-7. Expert Values for Insulation Type Levels

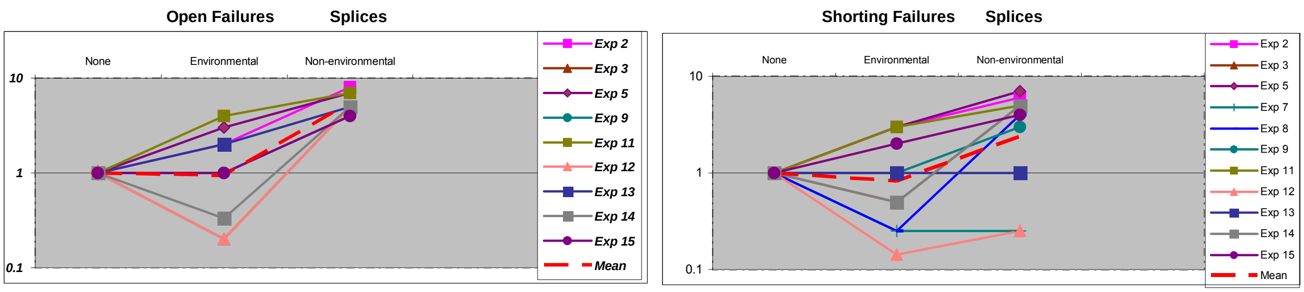


Figure D-8. Expert Values for Splices Levels

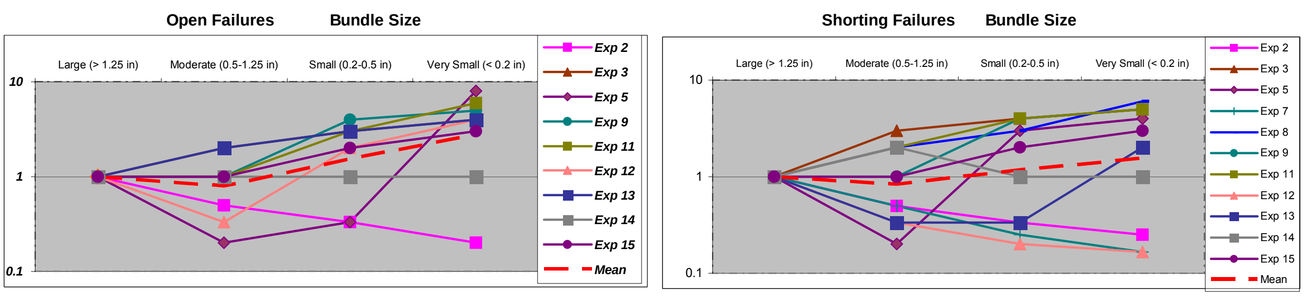


Figure D-9. Expert Values for Bundle Size Levels

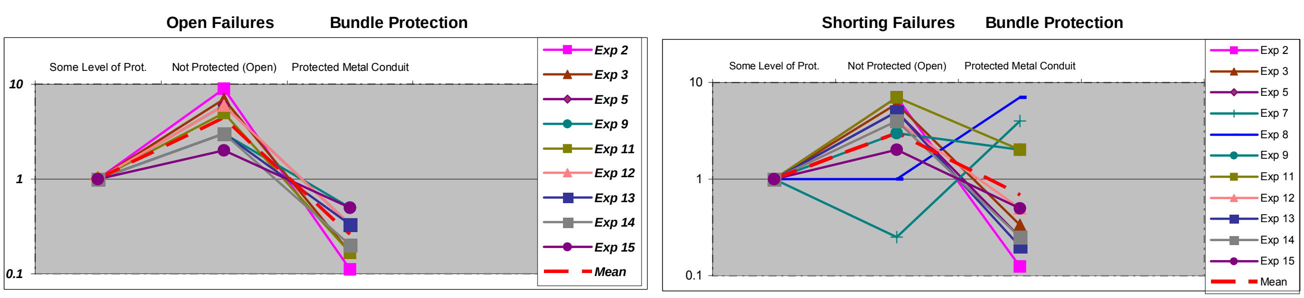


Figure D-10. Expert Values for Bundle Protection Levels

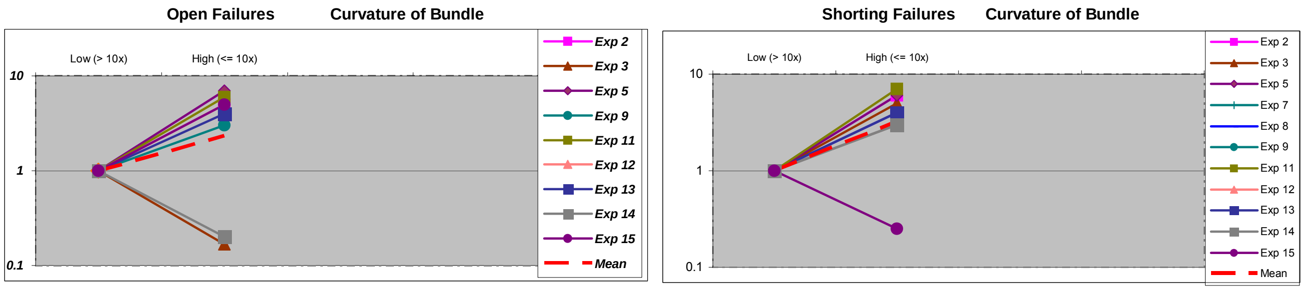


Figure D-11. Expert Values for Curvature of Bundle Levels

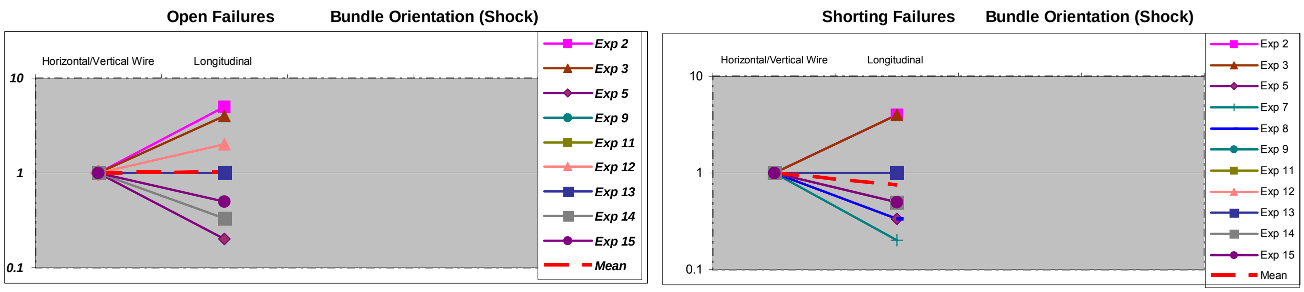


Figure D-12. Expert Values for Bundle Orientation Levels

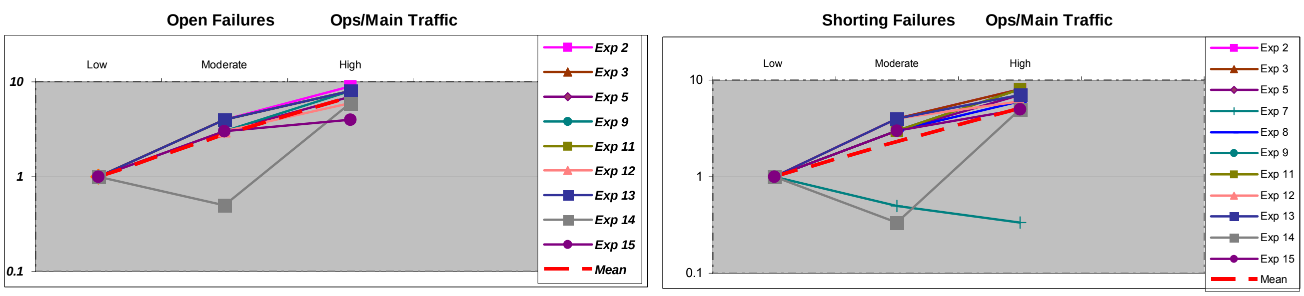


Figure D-13. Expert Values for Operations and Maintenance Traffic Levels

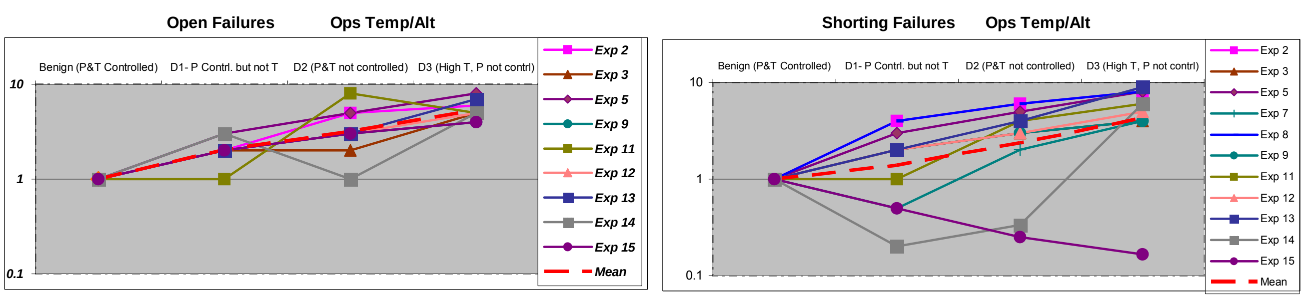


Figure D-14. Expert Values for Operations Temperature and Altitude Levels

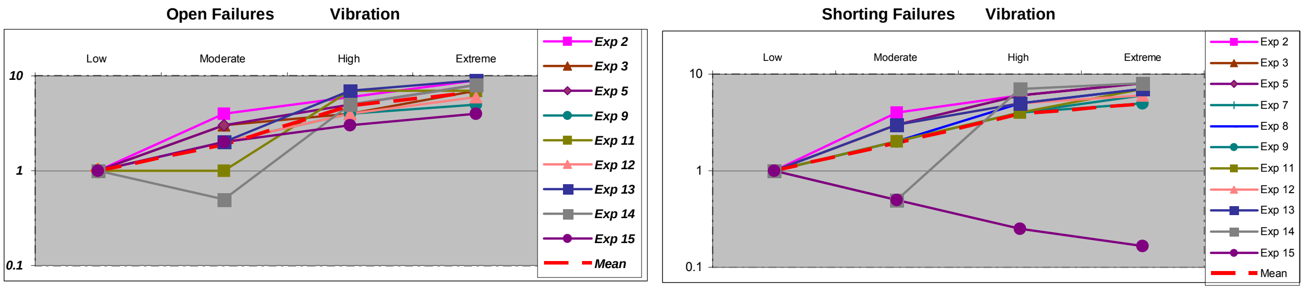


Figure D-15. Expert Values for Vibration Levels

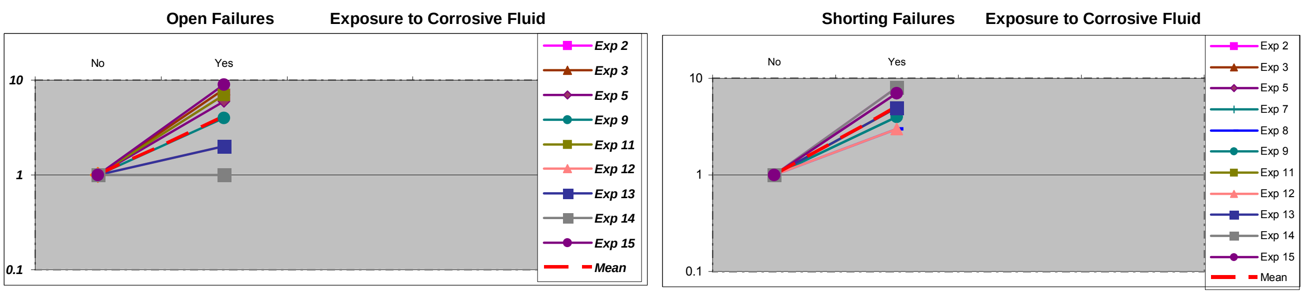


Figure D-16. Expert Values for Exposure to Corrosive Fluid Levels

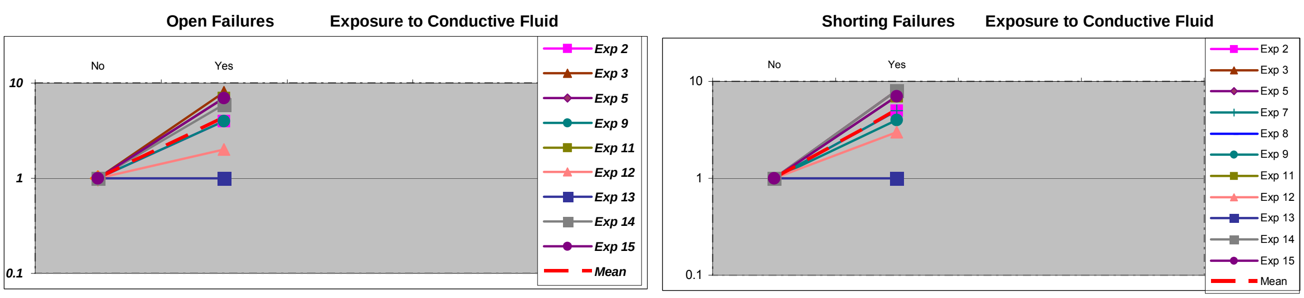


Figure D-17. Expert Values for Exposure to Conductive Fluid Levels

Note also that the geometric mean of the values is plotted as a dashed line in these figures. The geometric mean for a set of values $y_1, \ldots, y_n$ is given by

$$geom\ mean(y_1,\ldots,y_n) = \prod_{i=1}^{n} (y_n)^{1/n} \tag{D-9}$$

and is the appropriate measure of central tendency for ratio values.

Estimates were made of the magnitude of the increase/decrease in severity of each variable value for both open and shorting failure using the geometric mean. These are shown in table D-6. These are used as the coded values for the environmental variables in the regression analysis and are presented in table D-6.

Given the candidate environment failure rate estimates in table D-6 and the coded values for the environmental variables in table D-5, a backwards selection method was used to determine the most appropriate model relating the expert responses to the coded environmental variable values for both open and shorting failures. This method proceeds by starting with all variables in the model and then removing variables one at a time if the p-value for the t-statistic is greater than a preselected cutoff value. The value of 0.20 was used in this procedure. This is a generous cutoff value by comparison to standard practice, but the goal of the analysis was to provide a relationship to as many variables as possible. After the 0.20 value, the next opportunity for a cutoff value was significantly greater. These regression results are presented in table D-7. Variables that do not appear in the figures were deemed insignificant in their contribution to the regression in explaining the Ln (failure rate) variation as a function of the environment and are thus assigned a coefficient value of 0. Variables were dropped whose p-value was significantly above 0.20 during the backward elimination process. While this is fairly lenient, emphasis was placed on including as many variables as possible and within reason. The unusually high multiple R square value is to be expected due to the small number of degrees of freedom. However, the graphical fit appears to be more than reasonable, as shown in figures D-18 and D-19.

Table D-6. Coded Values for Environmental Variables

Variable	Level	Geometric Mean	
		Open	Shorting
Wire Gauge	18-22 AWG	1.00	1.00
	4/0-8 AWG	0.22	1.13
	10-16 AWG	0.36	1.05
	24-26 AWG	3.18	1.73
Conductor Type	Copper	1.00	1.00
	Aluminum	3.13	1.39
	High Strength Copper Alloy	0.36	0.82
Insulation Type	Polyimide	1.00	1.00
	Hybrid (PI/FP composite)	0.45	0.36
	ETFE and other FPs	0.37	0.32
Splices	None	1.00	1.00
	Environmental	0.95	0.83
	Nonenvironmental	5.40	2.41
Bundle Size	Large (>1.25 in.)	1.00	1.00
	Moderate (0.5-1.25 in.)	0.80	0.83
	Small (0.2-0.5 in.)	1.54	1.18
	Very small (<0.2 in.)	2.76	1.55
Bundle Protection	Some level of protection	1.00	1.00
	Not protected (open)	4.40	3.00
	Protected metal conduit	0.26	0.68
Curvature of Bundle	Low (>10 times)	1.00	1.00
	High (≤10 times)	2.34	3.24

Table D-6. Coded Values for Environmental Variables (Continued)

Variable	Level	Geometric Mean	
		Open	Shorting
Bundle Orientation	Horizontal/vertical wire	1.00	1.00
	Longitudinal	1.03	0.75
Operations and Maintenance Traffic	Low	1.00	1.00
	Moderate	2.79	2.32
	High	6.94	5.10
Operations Temperature and Altitude	Benign (P&T controlled)	1.00	1.00
	D1-P controlled but not T	2.03	1.39
	D2-P&T not controlled	3.17	2.37
	D3-high T, P not controlled	5.31	4.28
Vibration	Low	1.00	1.00
	Moderate	1.88	1.92
	High	4.82	3.88
	Extreme	6.79	4.93
Exposure to Corrosive Fluid	No	1.00	1.00
	Yes	4.12	5.07
Exposure to Conductive Fluid	No	1.00	1.00
	Yes	4.32	5.03

PI = Polyimide
FP = Fluorescent penetrant
AWG = American Wire Gauge
P = Pressure
P&T = Pressure & Temperature
ETFE = Ethylene tetrafluoroethylene
T = Temperature

Table D-7. Regression Coefficients From Paired Comparison Analysis for Opens and Shorting Failures

Open	Dependent Var														
								Independnet Variables							
Environ	Ln(Rel Fail Rate)	Wire Guage	Insulation Type	Conductor Type	Splices	Bundle Size	Bundle Protection	Curvature of Bundle	Shock Dam Pot.	Ops/Main Traffic	Ops temp\altitude	Vibration	Exp Corrosive Fluid	Exp Conducting Fluid	
1	-3.251915679	1	0.45	1	1	0.8	4.4	1	1	6.94	1	1.88	1	4.32	
2	-2.110313205	3.18	0.45	0.36	1	2.76	4.4	1	1	6.94	1	1.88	1	4.32	
3	-3.665162927	3.18	0.45	1	1	0.8	4.4	1	1	2.79	1	1.88	1	4.32	
4	-3.165335058	1	0.45	1	1	0.8	1	1	1	6.94	1	4.82	1	4.32	
5	-2.131155977	1	0.45	1	1	1	4.4	1	1	6.94	1	1.88	4.12	4.32	
6	-1.326517157	1	0.45	1	5.4	0.8	4.4	1	1	6.94	1	1	1	4.32	
7	-4.283086687	1	0.37	1	1	0.8	4.4	1	1	6.94	1	1	1	4.32	
8	-2.987764104	1	0.45	1	1	0.8	4.4	2.34	1	6.94	1	1.88	1	1	
9	-3.165335058	1	0.45	1	1	0.8	1	1	1	6.94	3.17	1.88	1	4.32	
10	-3.040729639	1	0.45	1	1	0.8	4.4	2.34	1	6.94	1	1	1	4.32	
11	-3.922073341	1	0.45	1	1	0.8	4.4	1	1.03	6.94	1	1.88	1	1	
12	-4.000854219	1	0.45	1	1	0.8	4.4	1	1	1	1	4.82	1	4.32	
13	-1.844527535	1	1	1	1	0.8	4.4	2.34	1	6.94	1	1.88	1	4.32	
14	-4.828313737	0.22	0.45	3.13	1	0.8	4.4	1	1	6.94	1	1.88	1	1	
15	-3.519980918	0.22	0.45	1	1	0.8	4.4	1	1	6.94	3.17	1.88	1	4.32	

Shorting	Dependent Var														
								Independnet Variables							
Environ	Ln(Rel Fail Rate)	Wire Guage	Insulation Type	Conductor Type	Splices	Bundle Size	Bundle Protection	Curvature of Bundle	Shock Dam Pot.	Ops/Main Traffic	Ops temp\altitude	Vibration	Exp Corrosive Fluid	Exp Conducting Fluid	0.000
1	-3.101092789	1	0.36	1	1	0.83	3	1	1	5.1	1	1.92	1	5.03	
2	-2.469821012	1.73	0.36	0.82	1	1.55	3	1	1	5.1	1	1.92	1	5.03	
3	-3.9633163	1.73	0.36	1	1	0.83	3	1	1	2.32	1	1.92	1	5.03	
4	-2.664990712	1	0.36	1	1	0.83	1	1	1	5.1	1	3.88	1	5.03	
5	-1.895121982	1	0.36	1	1	1	3	1	1	5.1	1	1.92	5.07	5.03	
6	-2.282782466	1	0.36	1	2.41	0.83	3	1	1	5.1	1	1	1	5.03	
7	-4.098352584	1	0.32	1	1	0.83	3	1	1	5.1	1	1	1	5.03	
8	-3.57912859	1	0.36	1	1	0.83	3	3.24	1	5.1	1	1.92	1	1	
9	-2.826833737	1	0.36	1	1	0.83	1	1	1	5.1	2.37	1.92	1	5.03	
10	-3.11451581	1	0.36	1	1	0.83	3	3.24	1	5.1	1	1	1	5.03	
11	-4.431216879	1	0.36	1	1	0.83	3	1	0.75	5.1	1	1.92	1	1	
12	-3.717278929	1	0.36	1	1	0.83	3	1	1	1	1	3.88	1	5.03	
13	-1.377532855	1	1	1	1	0.83	3	3.24	1	5.1	1	1.92	1	5.03	
14	-4.414549826	1.13	0.36	1.39	1	0.83	3	1	1	5.1	1	1.92	1	1	
15	-2.515778313	1.13	0.36	1	1	0.83	3	1	1	5.1	2.37	1.92	1	5.03	

SUMMARY OUTPUT OPEN FAILURE ANALYSIS					
Regression Statistics					
Multiple R	0.9987				
R Square	0.9975				
Adjusted R Square	0.7929				
Standard Error	0.2868				
Observations	15				
ANOVA					
	df	*SS*	*MS*	*F*	*Significance F*
Regression	10	161.4031	16.1403	196.2824	0.0001
Residual	5	0.4112	0.0822		
Total	15	161.8142			
	Coefficients	*Standard Error*	*t Stat*	*P-value*	
Intercept	0	#N/A	#N/A	#N/A	
Wire Guage	0.4535	0.1343	3.3770	0.0197	
Insulation Type	2.0738	0.6439	3.2209	0.0234	
Conductor Type	-0.4380	0.1701	-2.5745	0.0498	
Splices	0.5639	0.0781	7.2246	0.0008	
Curvature of Bundle	0.5013	0.2000	2.5061	0.0541	
Shock Dam. Pot.	-8.1221	0.9121	-8.9051	0.0003	
Ops/Main Traffic	0.2014	0.0560	3.5950	0.0156	
Ops temp/altitude	0.2050	0.1236	1.6585	0.1581	
Vibration	0.2239	0.0924	2.4218	0.0600	
Exp Corrosive Fluid	0.4742	0.1026	4.6237	0.0057	

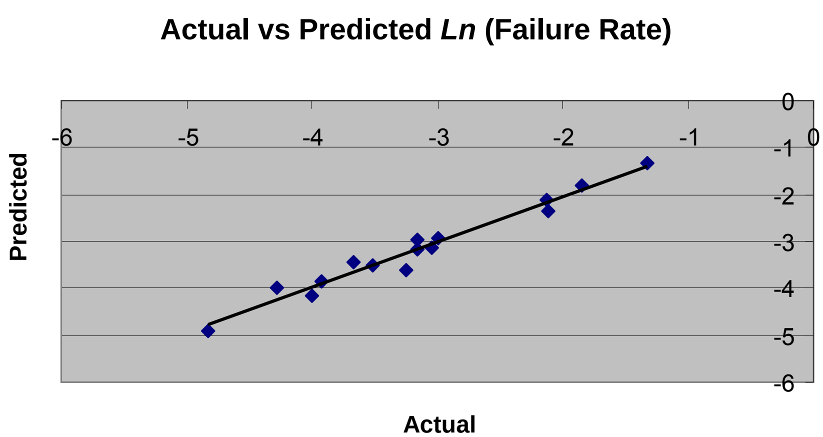


Figure D-18. Regression Output for Open Failures

SUMMARY OUTPUT SHORTING FAILURE ANALYSIS

Regression Statistics	
Multiple R	0.9923
R Square	0.9846
Adjusted R Square	0.9462
Standard Error	0.2143
Observations	15

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	10	11.7579	1.1758	25.6012	0.0034
Residual	4	0.1837	0.0459		
Total	14	11.9416			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	-13.0056	1.0868	-11.9666	0.0003
Wire Guage	0.9203	0.2697	3.4119	0.0270
Insulation Type	1.7154	0.4447	3.8577	0.0182
Splices	1.1536	0.1902	6.0654	0.0037
Bundle Protection	0.2512	0.1276	1.9692	0.1203
Curvature of Bundle	0.3723	0.0880	4.2288	0.0134
Ops/Main Traffic	0.4368	0.0717	6.0928	0.0037
Ops temp/altitude	0.5998	0.1470	4.0796	0.0151
Vibration	0.6605	0.1202	5.4976	0.0053
Exp Corrosive Fluid	0.3456	0.0613	5.6373	0.0049
Exp Conducting Fluid	0.2873	0.0419	6.8593	0.0024

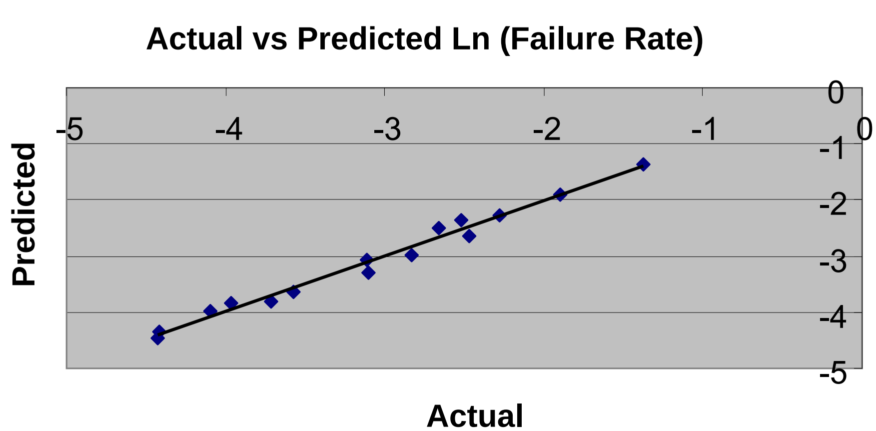


Figure D-19. Regression Output for Shorting Failures

A comparison of expert to model results is presented in figure D-20. Note again that five experts were dropped from the open failures case, while only three experts were dropped from the shorting failures case. The model matches the group expert choice (by simple majority) 91.4% of the time for the open failures case and 86.7% of the time for shorting failures.

Open Failures

Comparison Env	Comparison Env	Expert data: # Left More Severe	Expert data: # Left Equal Severeity	Expert data: # Right More Severe	Expert to Model Comparison: Expert Choice	Expert to Model Comparison: Model Choice	Expert to Model Comparison: Difference
1	2	2	2	5	2	2	No
1	3	4	0	5	3	3	No
1	4	4	1	4	4	4	No
1	5	2	0	7	5	5	No
1	6	2	1	6	6	6	No
1	7	8	1	0	1	1	No
1	8	2	0	7	8	8	No
1	9	4	0	5	9	9	No
1	10	2	2	5	10	10	No
1	11	6	1	2	1	1	No
1	12	8	0	1	1	1	No
1	13	0	1	8	13	13	No
1	14	8	0	1	1	1	No
1	15	3	2	4	15	15	No
2	3	8	1	0	2	2	No
2	4	8	0	1	2	2	No
2	5	5	0	4	2	5	Yes
2	6	3	0	6	6	6	No
2	7	9	0	0	2	2	No
2	8	6	0	3	2	2	No
2	9	7	0	2	2	2	No
2	10	7	0	2	2	2	No
2	11	8	0	1	2	2	No
2	12	7	0	2	2	2	No
2	13	3	0	6	13	13	No
2	14	8	0	1	2	2	No
2	15	5	1	3	2	2	No
3	4	1	0	8	4	4	No
3	5	2	0	7	5	5	No
3	6	1	0	8	6	6	No
3	7	3	1	5	7	3	Yes
3	8	3	0	6	8	8	No
3	9	3	0	6	9	9	No
3	10	3	0	6	10	10	No
3	11	5	0	4	3	3	No
3	12	5	0	4	3	3	No
3	13	2	0	7	13	13	No
3	14	8	0	1	3	3	No
3	15	7	0	2	3	3	No
4	5	0	1	8	5	5	No
4	6	2	1	6	6	6	No
4	7	5	3	1	4	4	No
4	8	4	0	5	8	8	No
4	9	4	0	5	9	4	Yes
4	10	3	1	5	10	4	Yes
4	11	6	0	3	4	4	No
4	12	7	1	1	4	4	No
4	13	2	0	7	13	13	No
4	14	8	0	1	4	4	No
4	15	5	0	4	4	4	No
5	6	2	0	7	6	6	No
5	7	9	0	0	5	5	No
5	8	6	0	3	5	5	No
5	9	7	0	2	5	5	No
5	10	6	1	2	5	5	No
5	11	7	0	2	5	5	No
5	12	7	1	1	5	5	No
5	13	2	0	7	13	13	No
5	14	9	0	0	5	5	No
5	15	8	0	1	5	5	No
6	7	9	0	0	6	6	No
6	8	9	0	0	6	6	No
6	9	8	0	1	6	6	No
6	10	7	1	1	6	6	No
6	11	8	1	0	6	6	No
6	12	8	1	0	6	6	No
6	13	7	1	1	6	6	No
6	14	9	0	0	6	6	No
6	15	6	0	3	6	6	No
7	8	1	1	7	8	8	No
7	9	2	1	6	9	9	No
7	10	1	0	8	10	10	No
7	11	3	1	5	11	11	No
7	12	5	1	3	7	7	No
7	13	1	0	8	13	13	No
7	14	7	0	2	7	7	No
7	15	2	1	6	15	15	No
8	9	4	0	5	9	8	Yes
8	10	6	1	2	8	8	No
8	11	7	2	0	8	8	No
8	12	5	0	4	8	8	No
8	13	0	1	8	13	13	No
8	14	8	1	0	8	8	No
8	15	4	0	5	15	8	Yes
9	10	5	0	4	9	10	Yes
9	11	6	0	3	9	9	No
9	12	3	1	5	12	9	Yes
9	13	3	0	6	13	13	No
9	14	7	0	2	9	9	No
9	15	6	0	3	9	9	No
10	11	6	2	1	10	10	No
10	12	7	1	1	10	10	No
10	13	0	0	9	13	13	No
10	14	7	0	2	10	10	No
10	15	7	0	2	10	10	No
11	12	5	0	4	11	11	No
11	13	0	0	9	13	13	No
11	14	6	1	2	11	11	No
11	15	6	0	3	11	15	Yes
12	13	2	0	7	13	13	No
12	14	5	0	4	12	12	No
12	15	4	0	5	15	15	No
13	14	7	1	1	13	13	No
13	15	5	0	4	13	13	No
14	15	2	2	5	15	15	No

Shorting Failures

Comparison Env	Comparison Env	Expert data: # Left More Severe	Expert data: # Left Equal Severeity	Expert data: # Right More Severe	Expert to Model Comparison: Expert Choice	Expert to Model Comparison: Model Choice	Expert to Model Comparison: Difference
1	2	5	2	4	1	2	Yes
1	3	8	1	2	1	1	No
1	4	3	1	7	4	4	No
1	5	2	0	9	5	5	No
1	6	3	2	6	6	6	No
1	7	10	1	0	1	1	No
1	8	6	0	5	1	1	No
1	9	4	0	7	9	9	No
1	10	4	2	5	10	10	No
1	11	8	1	2	1	1	No
1	12	7	0	4	1	1	No
1	13	0	0	11	13	13	No
1	14	8	2	1	1	1	No
1	15	2	2	7	15	15	No
2	3	8	2	1	2	2	No
2	4	9	0	2	2	4	Yes
2	5	5	0	6	5	5	No
2	6	5	1	5	6	6	No
2	7	10	0	1	2	2	No
2	8	7	1	3	2	2	No
2	9	6	0	5	2	2	No
2	10	7	2	2	2	2	No
2	11	11	0	0	2	2	No
2	12	8	0	3	2	2	No
2	13	1	1	9	13	13	No
2	14	9	1	1	2	2	No
2	15	3	1	7	15	15	No
3	4	0	0	11	4	4	No
3	5	1	0	10	5	5	No
3	6	2	0	9	6	6	No
3	7	2	1	8	7	3	Yes
3	8	5	0	6	8	8	No
3	9	2	1	8	9	9	No
3	10	5	0	6	10	10	No
3	11	7	0	4	3	3	No
3	12	5	0	6	12	12	No
3	13	1	1	9	13	13	No
3	14	8	0	3	3	3	No
3	15	4	0	7	15	15	No
4	5	2	0	9	5	5	No
4	6	4	2	5	6	6	No
4	7	6	4	1	4	4	No
4	8	9	0	2	4	4	No
4	9	6	0	5	4	4	No
4	10	7	0	4	4	4	No
4	11	8	1	2	4	4	No
4	12	7	2	2	4	4	No
4	13	2	1	8	13	13	No
4	14	10	0	1	4	4	No
4	15	5	1	5	15	15	No
5	6	5	1	5	6	5	Yes
5	7	11	0	0	5	5	No
5	8	10	0	1	5	5	No
5	9	7	0	4	5	5	No
5	10	9	0	2	5	5	No
5	11	11	0	0	5	5	No
5	12	8	0	3	5	5	No
5	13	3	0	8	13	13	No
5	14	11	0	0	5	5	No
5	15	6	1	4	5	5	No
6	7	8	3	0	6	6	No
6	8	8	0	3	6	6	No
6	9	5	0	6	9	6	Yes
6	10	7	2	2	6	6	No
6	11	9	0	2	6	6	No
6	12	10	0	1	6	6	No
6	13	6	1	4	6	13	Yes
6	14	10	1	0	6	6	No
6	15	5	0	6	15	6	Yes
7	8	4	0	7	8	8	No
7	9	3	2	6	9	9	No
7	10	1	1	9	10	10	No
7	11	5	1	5	11	7	Yes
7	12	6	2	3	7	12	Yes
7	13	1	0	10	13	13	No
7	14	5	1	5	14	7	Yes
7	15	0	2	9	15	15	No
8	9	3	1	7	9	9	No
8	10	4	0	7	10	10	No
8	11	9	2	0	8	8	No
8	12	5	0	6	12	8	Yes
8	13	0	0	11	13	13	No
8	14	6	3	2	8	8	No
8	15	3	0	8	15	15	No
9	10	5	0	6	10	9	Yes
9	11	8	1	2	9	9	No
9	12	7	0	4	9	9	No
9	13	3	0	8	13	13	No
9	14	9	0	2	9	9	No
9	15	4	0	7	15	15	No
10	11	8	0	3	10	10	No
10	12	8	0	3	10	10	No
10	13	0	0	11	13	13	No
10	14	8	0	3	10	10	No
10	15	6	0	5	10	15	Yes
11	12	4	0	7	12	12	No
11	13	0	0	11	13	13	No
11	14	4	1	6	14	14	No
11	15	3	0	8	15	15	No
12	13	3	0	8	13	13	No
12	14	5	0	6	14	12	Yes
12	15	4	0	7	15	15	No
13	14	11	0	0	13	13	No
13	15	8	0	3	13	13	No
14	15	0	1	10	15	15	No

Figure D-20. Comparison of Expert and Model Results

D.10 RESCALING THE FAILURE RATE SURFACE.

The analysis of the expert opinion elicited during the paired comparison workshop produced a wire failure function that gives relative failure rates for different aircraft environments. To obtain absolute failure rates, these functions need to be scaled using wire failure rate data for one or more of the test environments. It was decided to use the Service Difficulty Reports (SDR) to capture wire failures in the Emergency Path Lighting (EPL) System, because the EPL is checked daily and must be repaired if inoperable; it appears that the SDRs capture a high percentage of the wire total failures in that system. Also, the environment for the EPL is fairly uniform and corresponds to test environment 10 in the paired comparison workshop. The failure rate for the EPL was calculated using the SDR Database, the Federal Aviation Administration (FAA) Utilization Database, and an estimation of the total amount of wire in the system.

The FAA Utilization Database organizes the flight hour data into monthly intervals by aircraft model (and serial number) and airline. Therefore, the failure rate for two different model aircraft was calculated for the period 1999 to 2005 (1999-2001 in some cases) for several different airlines. The two model aircraft chosen (referred to as Model A and Model B, subsequently) are large transport airplanes with over 1000 of each manufactured. Five different airlines were included (airlines 1 through 5).

D.11 FLIGHT HOUR DATA.

The flight hours were collected for the combination of airline and models using the FAA Utilization reports, and the totals are shown in table D-8. In some cases, data was missing for a particular month or months. To resolve this, an average of the months surrounding the missing data was used.

Table D-8. Flight Hours for the Airline/Model Combinations for the Period Indicated

Airline	Period	Model	Usage (Flight hours)
1	1999-2005	A	2,618,435
2	1999-2005	A	1,125,715
3	1999-2005	A	1,295,112
		Total Model A	5,039,261
1	1999-2005	B	2,424,053
2	1999-2001	B	1,974,499
4	1999-2001	B	3,300,155
5	1999-2001	B	1,834,025
		Total Model B	9,532,732

D.12 FAULT DATA.

The fault data was gathered using the SDR database using search tools from the National Aviation Safety Data Analysis Center website. A search of the SDR narrative was done using the keywords wire(s), wiring, cable, harness, bundle, short, open, arc, etc. This returned over 9000 SDRs. This dataset was grouped according to airline and model number for the years in which utilization data was available. The SDRs were then read in detail and placed in one of four categories:

- Emergency Path Lighting: Open Fault
- Emergency Path Lighting: Shorting Fault
- Emergency Path Lighting: Unspecified Fault
- Other

For an SDR to be counted as a fault, it had to have explicit reference to a broken or shorted wire or reference to a function failure of the wire and/or repair to wire. SDRs with indications such as "Checked Harness," "Harness Repositioned," or issues with "Safety Wire," etc., were removed from the dataset. In some cases, it was not stated whether the fault was an open or a short, but a system functional fault traced to a wire or a repair was indicated. To resolve this, the SDR was placed in the undetermined fault category. Failures in the connectors or terminals were not considered, while failures at splices were considered as wire failures. This corresponds to instructions given to the experts during the paired comparison workshop. Table D-9 shows the number of open, shorting, and unspecified wire faults found for the model/airline combinations of interest.

Table D-9. The Number of Opens, Shorts, and Unspecified Wire Failures for the Model Number/Airline Combinations of Interest

Airline	Period	Model	Open	Short	Unspecified	Total	Other (Wire)	Rate: Total	Rate: Open	Rate: Short
1	1999-2005	A	17	3	4	24	16	9.17E-06	7.79E-06	1.37E-06
2	1999-2005	A	3	5	3	11	3	9.77E-06	3.66E-06	6.11E-06
3	1999-2005	A	2	1	1	4	2	3.09E-06	2.06E-06	1.03E-06
Total Model A			22	9	8	39	21	7.74E-06	4.37E-06	4.17E-06
1	1999-2005	B	6	9	3	18	36	7.43E-06	2.97E-06	4.46E-06
2	1999-2001	B	6	5	3	14	2	7.09E-06	3.87E-06	3.22E-06
4	1999-2001	B	27	7	67	101	23	3.06E-05	2.43E-05	6.30E-06
5	1999-2001	B	11	3	10	24	10	1.36E-05	1.00E-05	3.63E-06
Total Model B			50	24	83	157	71	1.65E-05	5.25E-06	7.45E-06

D.13 ESTIMATE OF THE AMOUNT OF WIRE IN THE EPL SYSTEM.

The amount of wire in the EPL system is dependent on the airplane model and series. It was found that changes to the system could occur throughout the life cycle of the fleet and were airline-dependent. For example, in some fleets, path lighting was moved from the floor to seat mountings; in other cases, the EPL system was replaced with photoluminescent systems.

It was beyond the scope of this project to perform a detailed analysis of the amount of EPL wire for each model/series/airline. However, generically, they consist of the following elements:

- Power from a cockpit circuit breaker panel powers one or two distribution boxes.
- The distribution boxes supply power to the light strips that are on either side of the aisle (both models have a single aisle). These strips vary in length but are approximately 10 ft long.
- In addition, there are emergency exits lights at each of the emergency exits.

The lengths for some of these wire segments were obtained from one of the airlines and the other lengths were estimated from the dimensions of the cabin. From these estimates, lengths from 763 to 1431 feet were estimated for the EPL.

D.14 CALCULATION OF EPL WIRE FAILURE RATE.

The failure rate was calculated for open and shorting failures by taking the number of failures of each type and dividing by the exposure, which, in this case, was the number of flight hours multiplied by the length wire in the EPL system. Table D-10 shows the failure rates for the airline/model combinations investigated. The open failure rate for the EPL is $1.1*10^{-8}$ opens per flight hour*foot of wire, and the shorting rate is $4.3*10^{-9}$ shorts per flight hour*foot of wire.

Table D-10. Open and Shorting Failure Rates

Model	Airline	Total Wire Faults EPL	Faults Open	Faults Short	Exposure (hr*ft)	Open Fail Rate Opens/(hr*ft)	Shorts Fail Rate Shorts/(hr*ft)
A	1	24	20.4	3.6	2,395,867,568	8.5E-09	1.5E-09
A	2	11	4.1	6.9	1,072,760,435	3.8E-09	6.4E-09
A	3	4	3.0	1.0	1,269,781,137	2.4E-09	7.9E-10
B	1	18	6.9	11.1	1,946,962,446	3.5E-09	5.7E-09
B	2	14	7.6	6.4	1,592,952,814	4.8E-09	4.0E-09
B	4	101	80.6	20.5	2,704,349,215	3.0E-08	7.6E-09
B	5	24	19.9	4.1	1,549,750,703	1.3E-08	2.6E-09
Total		196	142.5	53.5	12,532,424,316	1.1E-08	4.3E-09

The “Unspecified” failures (table D-9) were divided between shorts and opens using the ratio of specified shorts to opens. For example, if there were 10 opens, 5 shorts, and 3 unspecified, the 3 unspecified would by divided into 2 opens and 1 short for a total of 12 opens and 6 shorts.

D.15 SCALING OF THE WIRE FAILURE FUNCTION AND DISCUSSION.

The wire failure rates from table D-10 were used to scale the wire failure functions developed from the analysis of the data from the paired comparison workshop resulting in the following failure functions for opens and shorts.

- Failure Rate Open Failures =
  exp{0.0-(-3.1354) + 0.4535*Wire Gauge Code + 2.0738*Insulation Type Code
  –0.4380*Conductor Type Code + 0.5639*Splices Code
  +0.5013*Curvature of Bundle Code - 8.1221*Bundle Orientation Code
  +0.2014*Ops/Main Traffic Code + 0.2050*Ops Temp/Altitude
  +0.2239*Vibration Code + 0.4742*Exp Corrosive Fluid Code}
  * 2.53035×10^{-7} failures per flight hour per foot of wire

- Failure Rate Shorting Failures =
  exp{-13.0056-(-3.0756) + 0.9203*Wire Gauge Code + 1.7154*Insulation Type Code
  +1.1536*Splices Code + 0.2512*Bundle Protection Code
  +0.3723*Curvature of Bundle Code + 0.4368*Ops/Main Traffic Code
  +0.5998*Ops Temp/Altitude + 0.6605*Vibration Code
  +0.3456*Exp Corrosive Fluid Code + 0.2873*Exp Conductive Fluid Code}
  * 9.31508×10^{-8} failures per flight hour per foot of wire

There are several issues of concern regarding the validity of the scaled failure functions. From analysis of the SDR data, the EPL appears to be a very harsh environment for wire. In fact, there were more wire faults reported in the EPL (196) than in all the other systems combined (92). While this may be, in part, due to underreporting of wire faults in the other systems, clearly, the EPL wire is located in one of the most severe environments for wire. However, when the failure functions are examined, environment 10 is actually one of the more benign environments in terms of failure rates with more than half of the other environments having higher rates of failure. The most probable reason for this is that during the paired comparison workshop, environment 10 was not described to the participants in a manner that suggested in their minds that the emergency path lighting wire was located in environment 10. If this is the case, then it would not be appropriate to scale the failure function by using this data.

D.16 ALTERNATIVE WIRE FAILURE FUNCTION.

An alternative method for scaling the wire failure function would be to use the overall wire failure rate of all systems. Using this method, the wire failure function would be scaled so that the environment with the median failure rate would have a failure rate equal to the overall failure rate. Table D-11 shows the overall failure rate using wire failures from the EPL and all other systems. The exposure is the flight hours multiplied by the entire length of wire on the airplane.

Table D-11. Overall Failure Rate Calculated Using Wire Failures From EPL and all Other Systems

Model	Airline	All Wire Faults	Exposure (hr*ft)	Wire Failure Rate Faults/(hr*ft)
A	1	40	688,501,641,168	5.8E-11
A	2	14	247,307,195,520	5.7E-11
A	3	6	350,488,045,776	1.7E-11
B	1	54	489,519,470,880	1.1E-10
B	2	16	400,238,561,818	4.0E-11
B	4	124	677,886,079,200	1.8E-10
B	5	34	379,503,131,568	9.0E-11
Total		288	3,233,444,125,930	8.9E-11

If this failure rate is used to scale the failure function, they become:

- Failure Rate Open Failures =
  exp{0.0-(-3.1354)+0.4535*Wire Gauge Code + 2.0738*Insulation Type Code
  −0.4380*Conductor Type Code + 0.5639*Splices Code
  +0.5013*Curvature of Bundle Code - 8.1221*Bundle Orientation Code
  +0.2014*Ops/Main Traffic Code + 0.2050*Ops Temp/Altitude
  +0.2239*Vibration Code + 0.4742*Exp Corrosive Fluid Code}
  * 3.33920*10^{-10} failures per flight hour per foot of wire

- Failure Rate Shorting Failures =
  exp{-13.0056-(-3.0756) + 0.9203*Wire Gauge Code + 1.7154*Insulation Type Code
  +1.1536*Splices Code + 0.2512*Bundle Protection Code
  +0.3723*Curvature of Bundle Code + 0.4368*Ops/Main Traffic Code
  +0.5998*Ops Temp/Altitude + 0.6605*Vibration Code
  +0.3456*Exp Corrosive Fluid Code + 0.2873*Exp Conductive Fluid Code}
  * 1.34751*10^{-10} failures per flight hour per foot of wire

Note, here, the wire failure rate found in table D-11 was divided into open and shorting failure rates using the ratio of open and shorting failures found in table D-10.

There is a question if the failure rate is related to the age of the aircraft. Again, it is beyond the scope of this study to do a detailed analysis of the age of the fleets for the airline/model combination used here. However, the series of an aircraft often gives a good indication of the aircraft's age. The series for Model B can be grouped into older series and newer series. If the overall wire failure rate is calculated for these groups (table D-12), the failure rate is 6 to 7 times higher for the older series. This indicates that aging probably is a factor in wire failures. Aging may include environment (or chemical) aging of the wire component themselves, or the accumulation of minor traumas throughout the life of the aircraft. Another explanation of the reduced failure rate in the newer series could be an improvement in wire installation designs, maintenance practice, the wire properties, etc.

Table D-12. Comparison of Wire Failure Rates for Older and Newer Series Aircraft

Model B Series Group	All Wire Faults	Exposure (hr*ft)	Wire Fail Rate Faults/(hr*ft)
Older Series	216	1,419,224,395,248	1.5E-10
Newer Series	12	527,922,848,218	2.3E-11

D.17 REFERENCES.

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APPENDIX E—ARC DAMAGE MODELING

Four models were developed to represent the damage that could be done in an electrical arcing event. The following describes each of these models and the results obtained from each.

E.1 MODEL 1.

The simplest calculation of the damage to structure is to assume that all of the arcing energy is used to melt the structural material. It is assumed that this will overestimate the damage caused to the structure, but the results can be checked against experimental results to determine the extent of the overestimation.

To perform this calculation, several assumptions are made that tend to be conservative (i.e., overestimate damage):

1. The arc voltage is such that the maximum power is dissipated in the arc.
2. The arc continues until the circuit protection trips.
3. All of the energy (power integrated over time) goes to melting structure.

The current in the arc is regulated by the impedance in series with the arc (or the source impedance plus the resistance of the wire from the source to the arc). Therefore, the power in the arc is:

$$P_{arc} = V_{arc} I_{arc} = V_{arc} \frac{(V_0 - V_{arc})}{R_{series}}$$

where V_0 is the source voltage.

The maximum power in the arc occurs when V_{arc} equals $V_0/2$. This will generally overestimate the power in the arc, e.g., for a 115-volt circuit, a typical arc voltage will be 30 to 40 volts, not 115/2 or 57.5 V.

Using the maximum power assumption, the current in the arc is $V_0/(2*R_{series})$. For thermal circuit breakers and fuses, the trip time was taken as the upper limit on the standard 25°C trip band (see appendix H of this report for parameterization of trip curve). For arc fault circuit breakers, the trip time was taken to be 10 ms after the arc initiation.

With the arc power (P_{arc}) and trip time (τ), the energy dissipated in the arc (E_{arc}) can be calculated using $E_{arc} = P_{arc}*\tau$.

The calculation of the amount of structure that is melted by this energy is based on the temperature of the structure being raised from ambient to the melting temperature and then the energy to overcome the heat of fusion. The mass melted (M) by E_{arc} is

$$M = \frac{E_{arc}}{((T_m - T_a)C + H_{fus})}$$

where

T_m = Melting temperature
T_a = Ambient temperature
C = Specific heat
H_{fus} = Heat of fusion

The results can be converted from mass to volume melted using the density. Figure E-1 shows the results of volume melted for several common circuit protections versus wire gauge pairs. To help visualize the amount of damage, the volume of some common items is indicated on the scale. The curves are for a 115-voltage alternating current (VAC) source, with a 0.1-ohm internal resistance, arcing to aluminum structure.

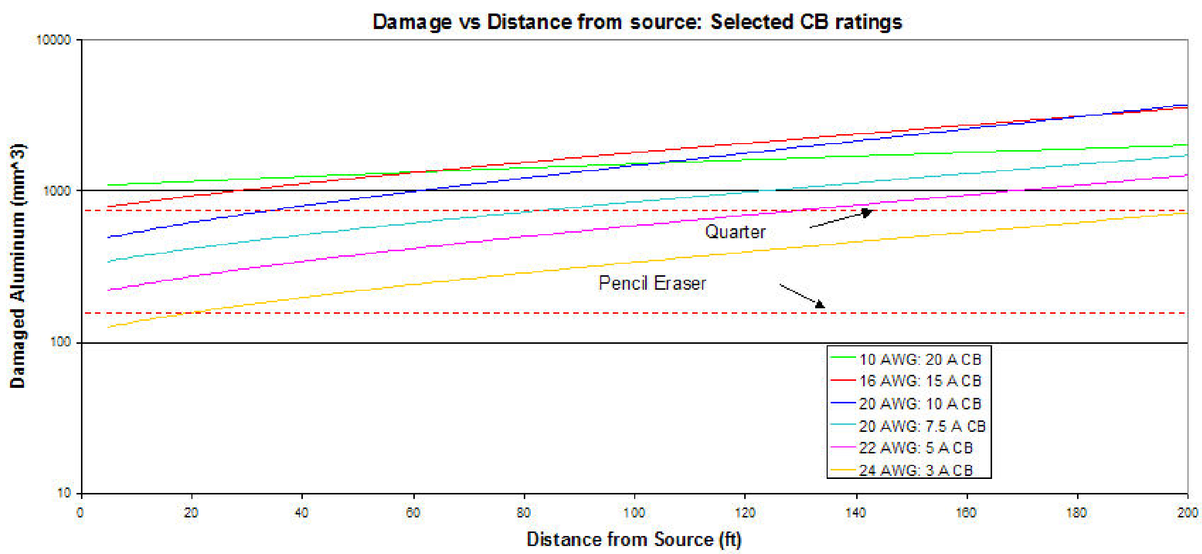

Figure E-1. Damage Curves From Model 1 for 115 VAC

E.2 DISCUSSION OF MODEL 1 RESULTS.

Figure E-1 shows a general characteristic that is expected in that the damage increases as the wire gauge and circuit protection increases. However, there are two characteristics of the curves in figure E-1 that do not match what is expected. First, the theoretical volume of damage is much higher than observed. In practice, it would be unexpected that a 24-gauge wire with a 3-amp circuit breaker would create damage larger than a pencil eraser. Second, the volume of damage increased as the distance from the source increased.

Both conflicts are shown in figure E-1 where the curve for a 20-gauge wire and a 10-amp circuit breaker with a 28-voltage direct current (VDC) source is compared to blade damage from a laboratory dry arc test similar to the AS4373.301 test in which a moving blade cut the insulation. The damage to the test's blades are more than a magnitude lower than that predicted by the model. In addition, the damage tends to decrease as the distance from the arc to power source is increased. The dotted line represents the results of Model 1 with all of the energy going into evaporating the aluminum rather than melting it. Evaporation of the aluminum probably does occur to some extent. However, beads of resolidified aluminum, either still attached to the blade or in the test chamber, suggest that a combination of melting and evaporation damaged the blade.

Note also that in many of the experiments, the circuit breaker did not trip and that the arc was stopped by wire evaporation or movement away from the blade. Measuring blade damage less than 1 mm^3 is difficult, and these damage levels should be considered approximations.

Figure E-2 shows the comparison between model and experimental results. In Model 1, the increase in damage with increasing distance from the power source is due to nonlinear trip curves of the circuit breakers. For example, if the distance from the power bus is doubled, the circuit resistance is approximately doubled. Therefore, the arc current is halved and so is the arc power. However, the trip time is more than doubled when the current is halved, so the overall energy dissipated in the arc is increased, and thus, the volume melted is increased. In practice, the increase in trip time is observed but what is not considered in this model is that, as the arc time increases, the heat energy from the lower power arc has more time to dissipate in the thermal mass of the target. The fact that this model does not consider the dissipation of heat in the structure is one of the main reasons the model generally overestimates the damage to the structure.

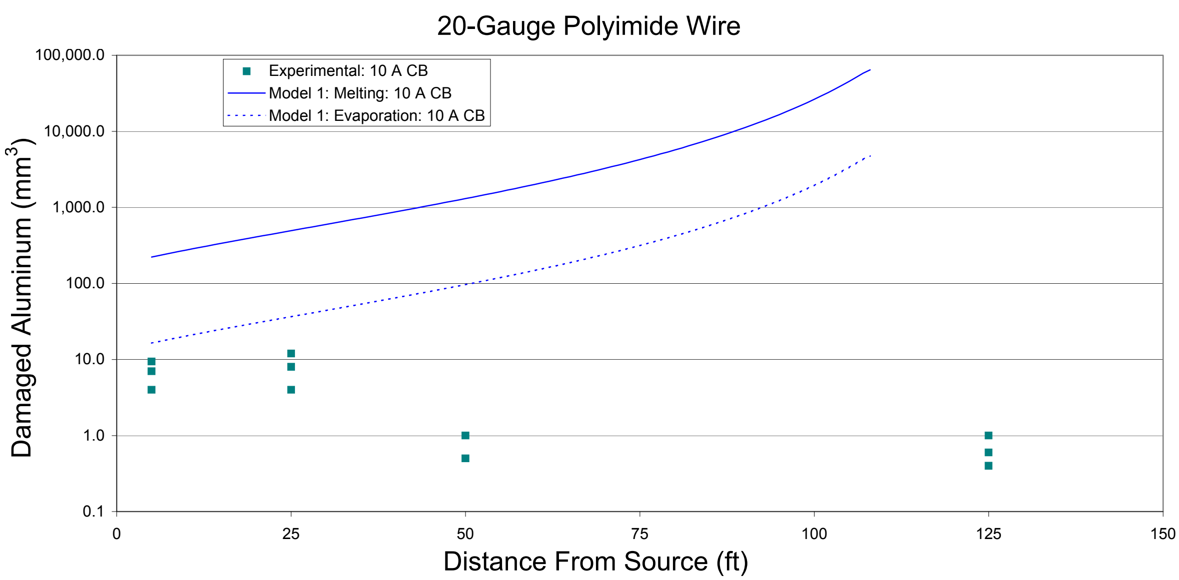

Figure E-2. Comparison Between Model 1 and Experimental Results

A second cause of the overestimation of damage in the model is that all of the arc energy is assumed to be incident on the structure. This is not the case in practice, as often there is quite a bit of damage to the wire that was arcing (i.e., some of the arc energy is dissipated in the wire). Some energy is also radiated by the arc away from the structure and wire. (Note that because of the low source voltages, the distance of the gap between the wire and structure cannot be very long if an arc is to occur. Therefore, the energy lost due to radiation will be less than in the high voltage arc that can be several inches, or even feet, long.)

The third reason the model overestimates the damage to structure is the fact that the arcing section of the wire can be destroyed. If enough of the wire is destroyed, then the distance between the wire and the structure becomes too large and the arc extinguishes before the circuit protection trips. Less energy than the model predicts is incident to the structure, and therefore, the damage to structure will be less than predicted by the model. This is particularly true for the smaller gauge wire.

From this discussion, it can be concluded that there are three main shortcomings in this simple model:

1. Heat dissipation is not considered.
2. All the arc energy is not incident onto the structure.
3. Damage to the arcing wire can extinguish the arc before the circuit protection trips.

E.3 MODEL 2.

One of the unsatisfactory aspects of Model 1 is that the damage increases as the distance from the power source increases. As previously discussed, this is because the model does not account for heat dissipation. The following model takes this into account in a simple way. The expression below shows the energy balance of Model 2.

$$P_{arc} \longrightarrow \boxed{E'} \longrightarrow \alpha E'$$

where $E' = E\text{-}E_0$ and E_0 is the energy at ambient temperature.

The arcing energy enters the structural element and the heat dissipation is proportional to the accumulated energy. (Note: heat dissipation is proportional to the temperature difference and the temperature difference is proportional to the energy difference.) The energy balance equation is

$$\frac{dE'}{dt} = P_{arc} - aE'$$

This equation shows that there is a steady state ($dE'/dt = 0$) reached when $E' = P_{arc}/\alpha$. The solution to this equation is

$$E' = \left(\frac{P_{arc}}{\alpha}\right)\left(1 - e^{(-\alpha\tau)}\right) \tag{E-1}$$

This expression is used to replace $E' = (P_{arc})*\tau$ that was used in Model 1. This does not let energy continue to accumulate unchecked as arcing time increases. Figure E-3 shows the results of Model 2 for the same 28-VDC arc with 20-gauge wire and 10-amp circuit breaker. The results shown are for $\alpha = 3$, and the results of Model 1 are shown for reference.

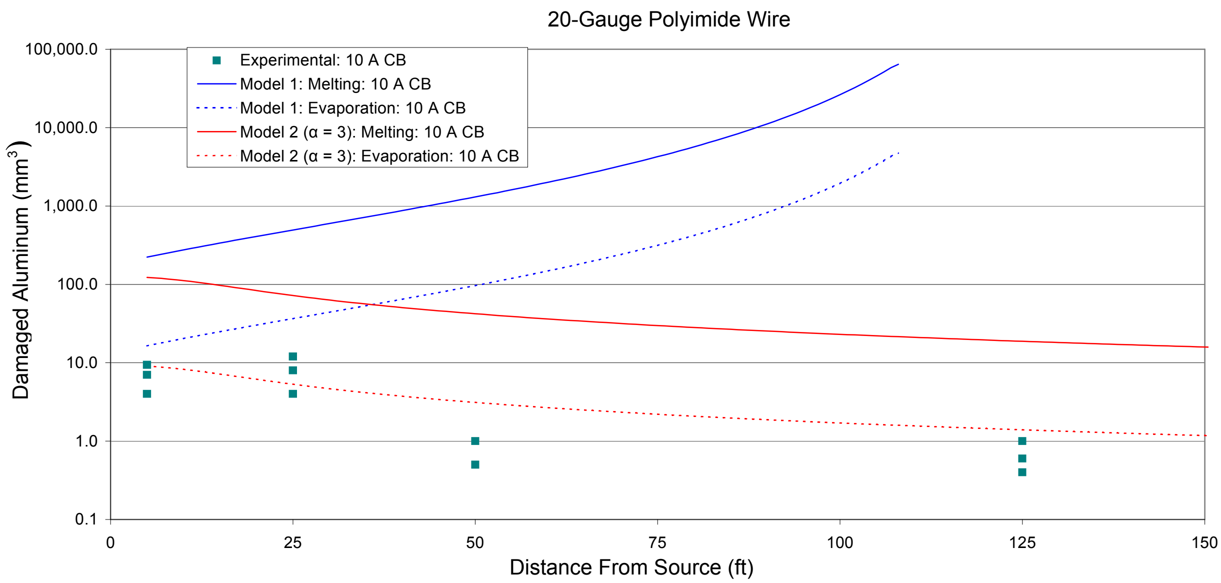

Figure E-3. Comparison Between Models 1 and 2 and Experimental Results

E.4 DISCUSSION OF MODEL 2 RESULTS.

As expected, Model 2 changed the shape of the damage versus distance curve to reflect the experimental and common sense results much better than Model 1. It also reduced the magnitude of the damage, which also tends to agree better with the experimental results.

Shortcomings of Model 2:

1. The value of α is not directly related to the size or geometry of the damaged area or the physical constants of the material, such as thermal conductivity. Therefore, the value of α is chosen to get the best empirical fit to the data.

2. The mixture of material that is melted and the material that is evaporated is uncertain.

3. Wire damage extinguishing the arc is still not considered.

E.5 MODEL 3.

Model 3 accounts for the damage to the wire. This affects the model in two ways. First, because the wire is damaged, it is evident that not all the arc energy actually enters and heats the target. The arc energy is partitioned between the target, the wire, and radiation (spew, ionized gas plume, etc.). Second, when the length of damaged and removed wire (conductor) is large enough, the arcing length becomes too long and the arc is extinguished.

E.6 ARC ENERGY PARTITION.

The effect of sharing the arc energy between damaging wire, damaging structure, and radiation is that it effectively reduces the amount of energy incident to the structure. This reduction is a function of many variables, such as wire and structure geometry, arc length, and arc power. A first approximation is to use a fraction (γ) of the arc power. Applying this to the equations from Model 2:

$$E' = \left(\frac{\gamma P_{arc}}{\alpha}\right)\left(1 - e^{(-\alpha\tau)}\right) \tag{E-2}$$

The value of γ is not directly tied to the physics of the arc and so the value of γ is chosen for the best empirical fit to the data.

It is assumed that the level of wire damage needed to extinguish the arc is that 3 mm of wire must be evaporated. For a given power level, the time required to evaporate 3 mm of wire will be compared to the trip time of the circuit protection. The lower time will be used to determine the duration of the arc.

The effect of heat dissipation should also be applied to the wire destruction. In this case, equation E-2 is solved for τ, and E' is the energy required to evaporate 3 mm of the wire, E_w.

$$\tau_m = \left(\frac{-1}{\alpha'}\right) ln\left(1 - \frac{\alpha' E_w}{\gamma' P_{arc}}\right)$$

where τ_m is the time required to melt the wire.

Note, if $\gamma'\ P_{arc}$ is too small, then the expression inside the *ln* becomes negative, indicating that the wire does not melt. In this equation, the α and γ are primed because these constants used for wire damage can be different from those used for structural damage. Figure E-4 shows the results of Model 3 compared with the experimental results. Note that the same α and γ were used for both the structure and wire ($\alpha = 3$ and $\gamma = 0.5$). The results for Model 3 agree better with experimental data than the results of Model 2, although they still overestimate the damage. Much of the improvement is due to setting $\gamma = 0.5$, which means that only half of the total arc energy is used to damage the blade.

The effect of wire evaporation is evident at the beginning of the Model 3 curve. The flat section from 5 to 10 feet of the distance curve is caused by the wire evaporating before the circuit protection trips.

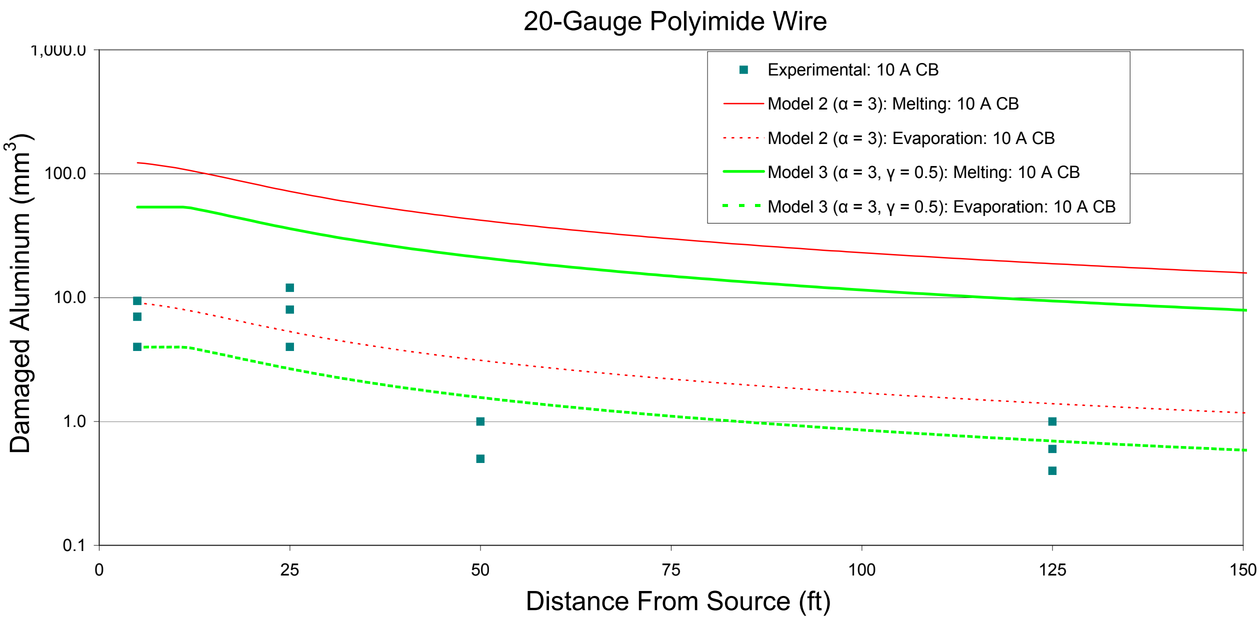

Figure E-4. Comparison of Model 3 With Experimental Data

E.7 DISCUSSION OF MODEL 3 RESULTS.

Some problems with this model include:

1. The heat dissipation factor, α, is still not calculated directly from fundamental properties of the structure, such as structure geometry, size and shape of the melted area, thermal conductivity, and specific heat.

2. The model does consider that the temperature of the material outside the melted area rises above ambient (heat is dissipated but E_0 does not change).

E.8 FINITE VOLUME THERMAL CONDUCTION SIMULATION: MODEL.

In this model, the arc energy is incident into a three-dimensional model of the structure. The structure is divided into many cells, as shown in figure E-5. As the arc energy is incident to the cells on the surface of the target, they heat up. The heat energy is conducted away from the surface using a finite volume stimulation. If the arc power is high enough, the cell melts or evaporates before the heat energy is conducted away. The damage calculation is therefore based on the geometry and thermal conductivity of the target material as well as the heat capacity, melting temperature, arc energy, etc. This eliminates the need for the α value in Model 3 and replaces it with physical properties of the target.

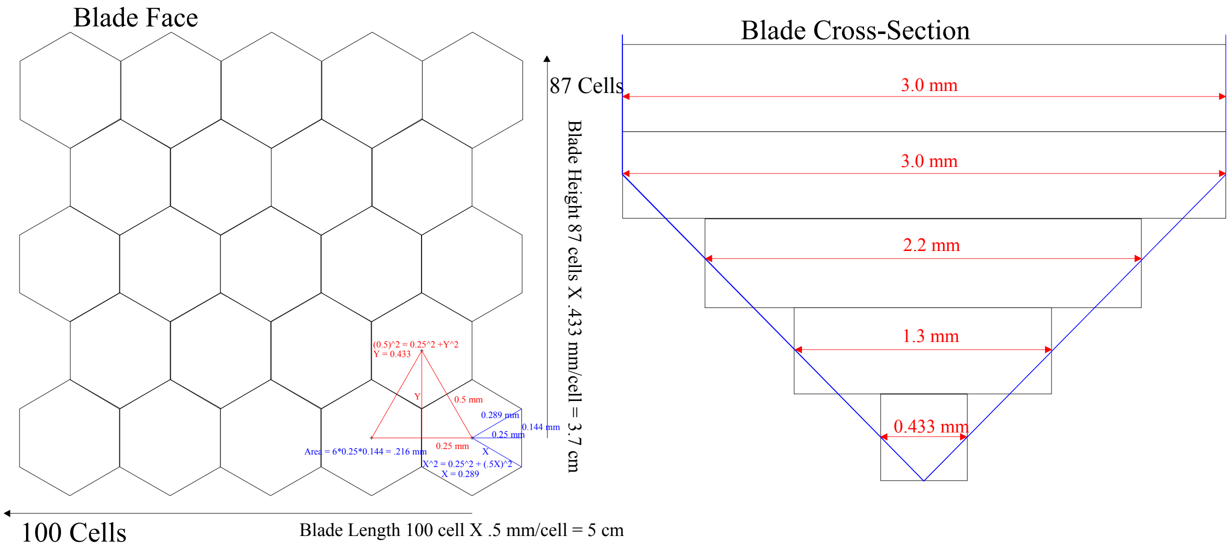

Figure E-5. The Cell Structure That Makes up the Blade for the Finite Element Model

Figure E-6 shows an example from an arc test with 20-AWG wire, a 10-amp circuit breaker, at a 25-foot distance from the source. The red area is where the blade has been heated to above room temperature but below melting temperature. The dark reddish-brown cells are melted and the green cells are evaporated. The total volume melted or evaporated in the simulation was 15 mm^3.

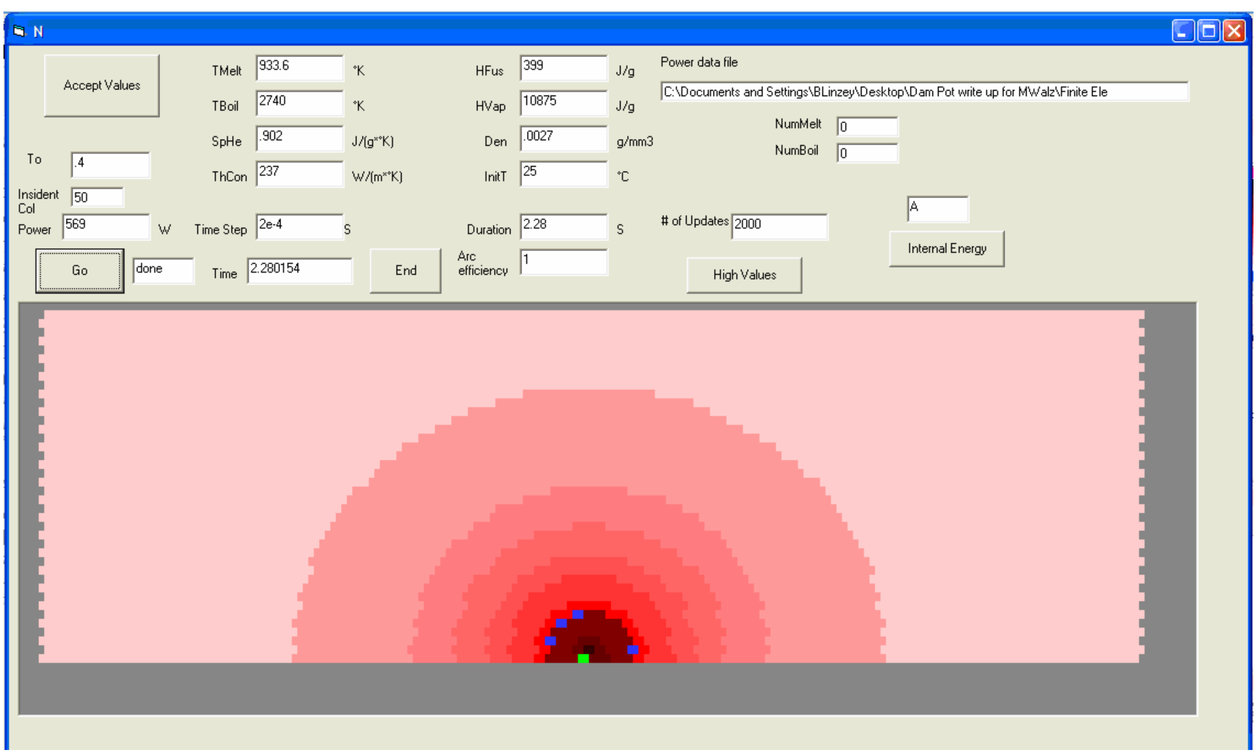

Figure E-6. Example for 20-AWG, 10-Amp Circuit Breaker With 25 Feet of Resistance

Figure E-7 shows the comparison of finite element method with experimental data and other models.

Notes:

1. Energy is based on maximum arcing power and arc duration based on circuit protection trip time.

2. 100% of the arc energy goes to damaging the structure (γ=1). There are no other assumed variables (i.e., no assigned α), and heat dissipation is based on book value thermal conductivity of aluminum.

3. Damage is the sum of both melted and evaporated cells.

4. Rise in damage at 75 feet is due to the long duration of the arc (at 100 seconds, the circuit protection trips). The arc slowly heats the entire blade. It is unrealistic for an arc to last this long and improvements need to be made to the arc model.

Figure E-7 shows comparisons of the damage calculation using the finite volume method with experimental data for 20-AWG wire. The finite volume results show good agreement with experimental data.

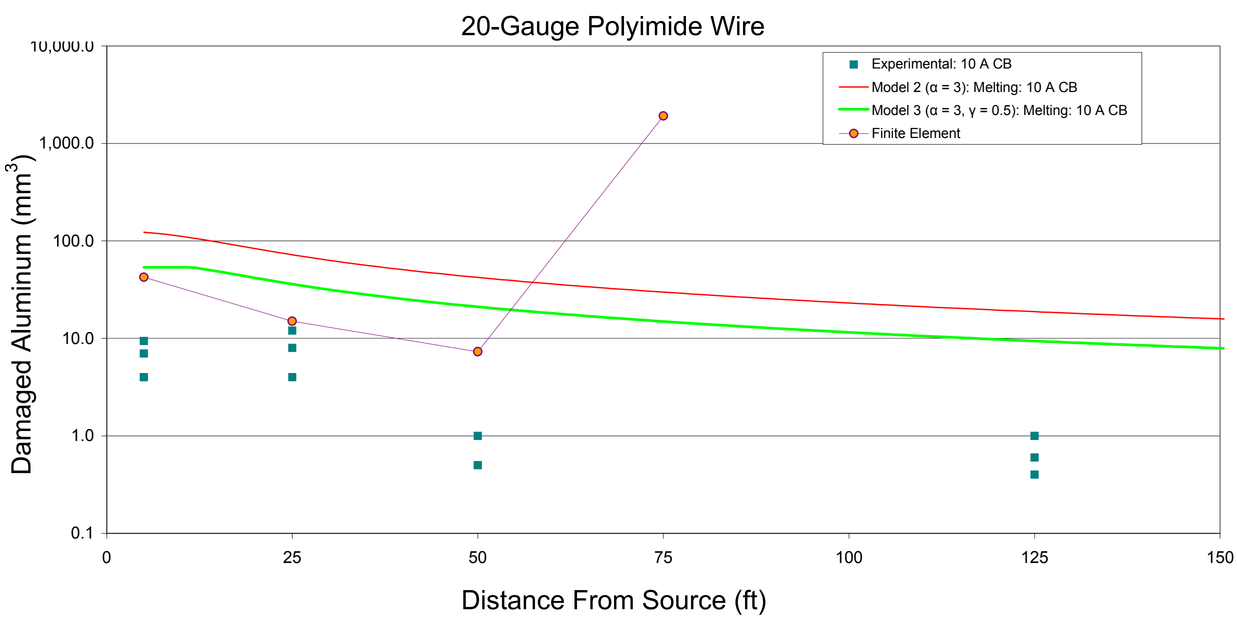

Figure E-7. Comparison of Finite Element Method With Experimental Data

E.9 DISCUSSION OF MODEL 4 RESULTS.

To test how well the models could be used for different gauge wires, the four models were tested using the blade dry arcing test results on 10-gauge wire with a 20-amp circuit breaker. Figure E-8 shows the results of those comparisons.

1. Model 1 with the 20-gauge wire, overestimated the damage by over an order of magnitude.

2. Model 2 showed the same shape as the experimental data but overestimated the damage done to the blade.

3. Model 3 showed a relatively good fit to the experimental data.

4. Model 4, the finite element model, tended to overestimate the damage. This is due to two effects that can be reduced with a better arcing model:

    a. Long trip times as series resistance increases
    b. All of the arc energy goes into the blade; there is no partition of the energy.

To understand how the damage levels predicted by the finite element method would improve if a more accurate arc model was used, several simulations were done using the power data from the experiments. The movement of the blade during the arc event was also simulated. This data is compared with experimental data in figure E-9. It shows an improvement in the agreement between damage levels. However, the simulations still overestimated the damage. Note that in this example, all the arc energy is still assumed to go into the blade.

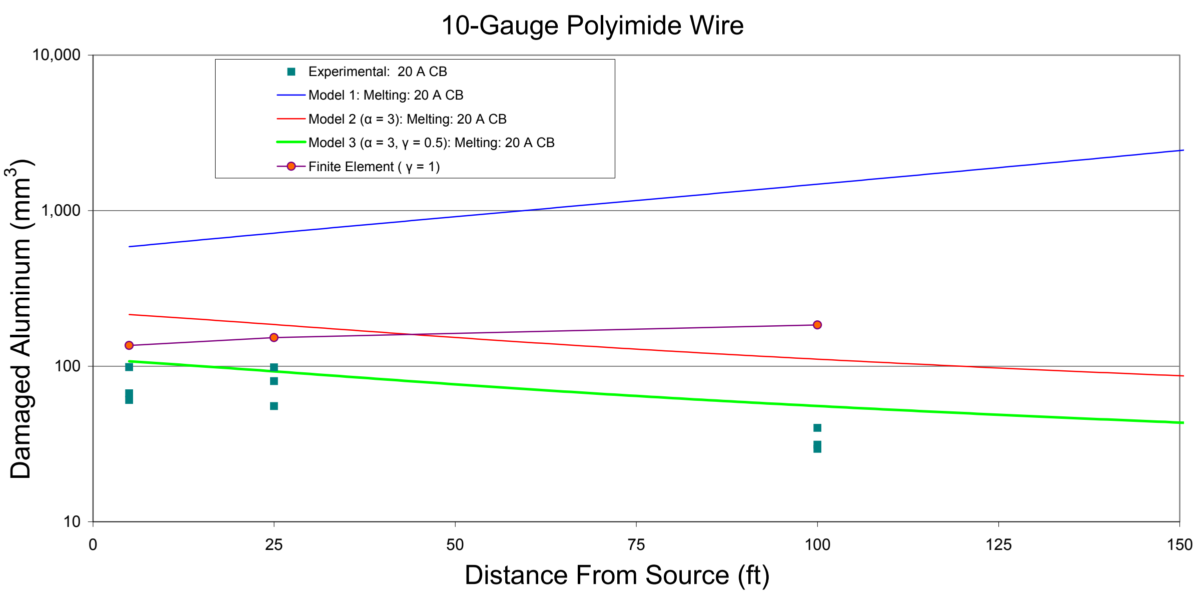

Figure E-8. Comparison of Models for Arcing With 10-AWG Wire and a 20-Amp Circuit Breaker

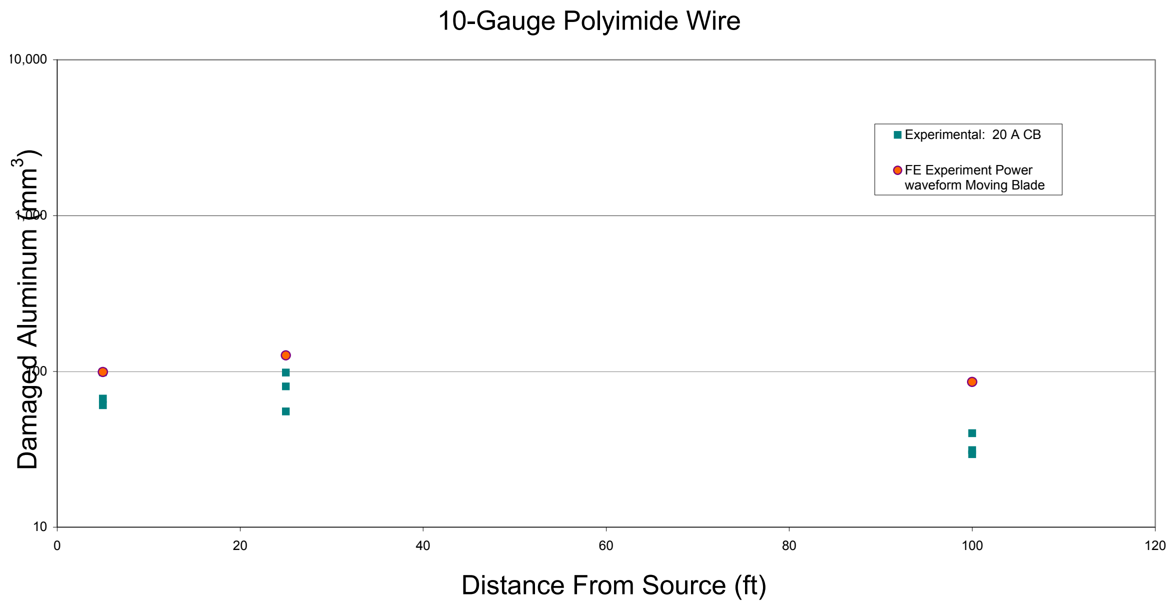

Figure E-9. Comparison of Experimental Data and Finite Element Simulation Using Experimental Power Curves and a Moving Blade

APPENDIX F—SUPPLEMENTAL PROGRAMS DEVELOPED

Project Name: CessnaBSConnectorRename
Details: This project takes in the data that comes from the CessnaBundleSec project and renames the node locations of the links such that they are consistent with the ready determined nomenclature that is being used. This nomenclature is determined by the connectors that appear in the wire list data.

Project Name: CessnaBundleSec
Details: This project takes in a filtered post script file (*.ps) – described later – and creates a graph in memory to interpret the data and define specific bundle sections and nodes. The connection names are sorted in a separate file and are used in the program to define end points of sections. A connector name will be added to a node if it is the closest also point to it (based on the link to that node).

The filtered post script is broken into two files – the first contains only the point to point information that was contained in the original file, the second contains the filtered connector names that can out of the CessnaConnectorFilter project. The output of the project is two files – BS6.txt and FormatedGraph.ps. BS6.txt is the listing of all of the bundle sections that can be found in the given bundle assembly (this file needs to be changed slightly after completion of the program (change the Link names to reflect the assembly Link00088 -> CE-Link00088).

Project Name: CessnaConnectorFilter
Details: This project takes in the bottom section of the post script file (which includes the text and locations for everything in the file) that is used as input for the CessnaBundleSec project and only keeps those that are actual connector names as defined by the Cessna nomenclature.

Project name: CessnaPower
Details: This project applies the power characteristics to all of the wires that are defined. There are two inputs to the program – 1: the listings of the wires which must contain, at a minimum, the following info – Wire name & connection information (connector name, pin, type of connection (Plug, jack) 2: the listing of the power/ground devices that are known in the program. After going through a number of the system schematics a number of the type specific rules for the Cessna architecture are employed. The output is a modified version of the wire input listing including which type of power the wire is and if it is a current carrying wire, which Circuit protect device is it running through. Additional modifications have been made such that power characteristics were transferred at relays and switches. Also, certain diodes that conform to a particular prefix are addressed.

Project name: CessnaBundleDataConvert
Details: This project takes in the raw data provided to Lectromec from Cessna's database and reformats the data such that it in importable to the EWIS RAT program. The format of the

information from the Wire3 is such that the system name is at the top of the file, followed by some information which is disregarded and then the pin to pin information.

Project Name; CessnaConnectors
Details: This project takes in the output from CessnaBundleDataConvert and handles the renaming of the connectors. With the Cessna nomenclature, the plug side of a connector and the jack side and designated. The program runs through the file and renames all of those connectors such that it is understandable to the EWIS RAT.

Project Name: CessnaConvert-Cables
Details: This project handles naming the cables to coincide with the nomenclature that was used by Cessna.

APPENDIX G—PROTOTYPE ELECTRICAL WIRING INTERCONNECTION SYSTEM SAFETY ASSESSMENT REPORT

PROTOTYPE EWIS SAFETY ASSESSMENT REPORT

ENGINEERING RELEASE SHEET
ACME AIRCRAFT COMPANY

DOCUMENT NUMBER: YY-B1RD-XXX
DOCUMENT TITLE:

MODEL B1RD ELECTRICAL WIRING INTERCONNECTION SYSTEM SAFETY ASSESSMENT

INTRODUCTION

This SSA is a collection of the assessments and analyses performed in the development and verification phases of the electrical wiring interconnection design process. The purpose of this SSA is to provide a record of how the electrical wiring interconnection system design meets the safety requirements established for it during the safety assessment process and shows compliance with 14 CFR 25.1705 (a) and (b).

1. REFERENCES

1.1 Applicable Documents

14 CFR 25	Airworthiness Standards: Transport Category Airplanes
Draft AC 25.17XX	Certification of Electrical Wiring Interconnection Systems on Transport Category Airplanes

2. SYSTEM DESCRIPTION SUMMARY

This electrical wiring interconnection system of this ACME built B1RD aircraft consists of over 1800 bundle sections, over 500 connectors, and over 6900 wires. The wiring transfers the electrical energy for 44 integrated systems from the two Westinghouse 20kVA Model ZKKY450 generators.

In practice, the user would describe the EWIS system more fully, describing a number of the details that would need to be considered as part of the EWIS certification package

3. ELECTRICAL WIRING INTERCONNECTION SYSTEM SAFETY REQUIREMENTS

The Electrical Wiring Interconnection System has no failure conditions passed to this document from AFHA, SFHA or PSSA. However, it failure condition are required to be considered in the SSAs of all of the other systems on the aircraft. Further, a common cause analysis is required that examines the effect of the loss of any particular bundle and the possible effects of failure and shorting of each power carrying wire.

4. SAFETY REQUIREMENT VERIFICATION

5.1 Effect of EWIS failure on the safety aircraft systems certified to § 25.1309

During the construction of the fault trees for all other aircraft systems as required to demonstrate compliance to § 25.1309, EWIS failures that could cause system malfunction or degradations were identified. These failures were inserted into the system fault trees using EWIS Failure Modes and Effects Summary (FMES) Events. Appendix A shows a listing of the EWIS FMES with the associated Wire ID and failure mode. The probability of the EWIS FMES occurring was calculated using the EWIS Risk Assessment Tool. The EWIS Risk Assessment Tool considerers many factors when arriving at a probability of failure including length of the wire, physical properties of the wire and environmental conditions. Table B.1 in Appendix B list the probability of failure for each EWIS FMES event.

Each of these EWIS FMES events was placed in the various system trees as appropriate. It was determined by fault tree analysis that no catastrophic event had a probability of higher than 10^{-9} even when all EWIS failure probabilities were considered. It was determined by fault tree analysis that no hazardous event had a probability of higher than 10^{-7} even when all EWIS failure probabilities were considered.

5.2 Common Cause Analysis (CCA) of EWIS Failures

COMMON MODE ANALYSIS OF EWIS FAILURES

Common mode analysis was accomplished using an analysis of the catastrophic event cut-sets in combination with routing of wire and connectors. First, the cut-sets were examined for the presents of EWIS FMES events. When all elements of a cut-set were found to be associated with a EWIS FMES events, that cut-set was analyzed further for collocation of the associated wire. A collocation was said to be found if at least one wire associated with each element of the cut-set was found to be collocated in the same bundle section (see note below) or in bundle sections that are within 6 inches of each other.

Appendix C Table C1 shows the result of the EWIS cut-set collocation analysis of all catastrophic events. The results in Table C1 list the cut-sets in which each element was a EWIS FMES event and the result of the collocation analysis. In all cases, there was either no collocation found or, if a collocation was found, the issue was successfully resolved.

Note: A bundle section is defined as that part of a bundle assembly in which no wire enters or breaks out from the bundle. There the exact same wires are present in all location of a bundle section. Further, the bundle section must be in the same environmental conditions (i.e. if the wire harness changes zones, then the segment is broken into two separate bundle sections).

Potential Damage due to EWIS Failures
The potential damage due to EWIS failure is analyzed based on the damage that may be caused by an electrical discharge event. Because the insulation type used on this aircraft is a type that is not known to arc track it is assumed that an electrical discharge will not lead to damage to all or many of the wires in the bundle but instead will lead to damage to adjacent wires only. The amount of potential damage was estimated using the methodology defined in Appendix D. Table E1 of Appendix E reports the bundle sections in which the potential damage was either

- Greater than 32 mm^3 (enough to create a 1/8" hole in a 1/8" thick piece of aluminum,
- Alternatively, if installed lines (hydraulic, oxygen, fuel) are within 6" inches of the bundle section and estimated damage is greater than 1.0 mm^3.

For bundle sections with damage potentials greater than 32 mm^3, the 6" region area surround the bundle section was investigated to insure that no structural elements or pieces of equipment were within that volume that could not continue to perform if such a damage was incurred. In addition, the systems within the bundle section were examined to ensure that loss of multiple systems would not cause a catastrophic event to occur. If the bundle section is within 6" of an installed line then the effects of failure of the line and the systems in the bundle section are evaluated and reported

The result of the analysis shows that in all cases where the potential damage level for a bundle section is above the minimum threshold for investigation that it has been found that there are no failure events that will threaten the continued safety flight of the aircraft.

5.4 Compliance

14CFR 25.1705
Each EWIS must be designed and installed so that:
(a) Each catastrophic failure condition-
    1. Is extremely improbable; and
    2. Does not result from a single failure.
(b) Each hazardous failure condition is extremely remote

5. CONCLUSION

After review of the reports generated by the EWIS Risk Assessment Tool, ACME believes that the electrical wiring interconnection system on the B1RD aircraft is in full compliance with the current FAA regulations and best practice recommendations. The aircraft is also in compliance with ACME standard practice manual 15.12 – EWIS Standard Practices, Design, and Internal Safety Certification.

5 APPENDIX

5.1 *Appendix A: EWIS Basic Event – Wire Failure Mode Spreadsheet*

Table A1: EWIS basic event – Wire Failure Mode Spreadsheet

	Basic Event	Wire ID	Fail Open	Fail GND	Fail High Imp	Fail 28 VDC	Fail 115 AC
1	SSA-Electrical-19877	TPCSN881 - NOSIQB880	X	X			X
2		UPCSN881 - NOSIQB880	X	X			X
3		WPCSN881 - 1CSIQB880	X	X			X
4		XPCSN881 - 2CSIQB880	X	X			X
5		A4PNEW899 - GNOQ898	X				
6		LPCCU867 - TJCSN881	X	X			X
7		KPCCU867 - UJCSN881	X	X			X
8		DJB002 - XJCSN881	X	X			X
9		24PNEW899 - DPBAO898	X	X			X
10		\KJCCU867 - 2DCUK859	X	X			X
11		\LJCCU867 - 2DCMJ860	X	X			X
12		KJCCU867 - \KJCCU867	X	X			X
13		LJCCU867 - \LJCCU867	X	X			X
14	B1RD-SI3111	2HCJC870 - YJCEB869	X	X			X
15		NJAHK885 - DJCAW883	X	X			X
16		RJAHK885 - PJCAW883	X	X			X
17		CJCAW883 - YPCEB869	X	X			X
18		PPCAW883 - A3SISF789	X	X			X
19		*SPTUE841 - NPAHK885	X	X			X
20		KPTUE841 - RPAHK885	X	X			X
21	SSA-Electrical-5451	EUDWM892 - GTDX875	X				
22		BUDWM892 - 1HZWP867	X	X			X
23	SSA-Electrical-70261	*ZPTUE841 - GTJT879	X				
24		DJDVP899 - 63PTQO887	X	X			X
25		DPDVP899 - DUDWM892	X	X			X
26		AAPDVP899 - AUDWM892	X	X			X
27		DDPDVP899 - EUDWM892	X	X			X
28		63JTQO887 - 29JZLH797	X	X			X
29		64JTQO887 - 28JZLH797	X	X			X
30		AAPTUE841 - AAJDVP899	X	X			X
31		DDPTUE841 - DDJDVP899	X	X			X
32		WPTUE841 - 64PTQO887	X	X			X
33		\FFJDVP899 - 62PTQO887	X				

34		FFPDVP899 - EUDWM892	X				
35		62JTQO887 - 58JZLH797	X				
36		FFPTUE841 - \FFJDVP899	X				
	Basic Event	**Wire ID**	**Fail Open**	**Fail GND**	**Fail High Imp**	**Fail 28 VDC**	**Fail 115 AC**
37	SSA-Electrical-90350	\SPAHK885 - WPTQG897	X	X			X
38		\SPAHK885 - *SPTQG897	X	X			X
39		*DPTUE841 - LLPTQG897	X	X			X
40		SJAHK885 - RJCAW883	X	X			X
41		TJAHK885 - SJCAW883	X	X			X
42		RPCAW883 - A2SISF789	X	X			X
43		SPCAW883 - A1SISF789	X	X			X
44		*SJTQG897 - 2HTPD740	X	X			X
45		LLJTQG897 - 1HTPD740	X	X			X
46		*DPTUE841 - *DPTUE841	X	X			X
47		*YPTUE841 - FFPTQG897	X	X			X
48		RPTUE841 - *APTQG897	X	X			X
49		BPTUE841 - *MPTQG897	X	X			X
50		*TPTUE841 - YPTQG897	X	X			X
51		1HTPB789 - 2HZWP867	X	X			X
52		2HTKM780 - *AJTQG897	X	X			X
53		*MJTQG897 - 2HTCF792	X	X			X
54		FFJTQG897 - 2HTPB789	X	X			X
55	B1RD-JZ1103	25JZLH797 - 4PZWK893	X				
56	SSA-Electrical-30557	PPTUE841 - 15PTQO887	X	X			X
57		\1PZWK893 - 11PZWK893		X			X
58		15JTQO887 - \1PZWK893	X	X			X
59		1PZWK893 - \1PZWK893	X	X			X
60	B1RD-KZ5003	WJTPA899 - 4PZGD897		X			
61		WPTPA899 - 33PTQO887		X			
62		33JTQO887 - 29JZKA796		X			
63	B1RD-SI7112	2HFPP869 - UJFPX882	X	X			X
64		AJAFS882 - JJCSN881	X	X			X
65		CJAFS882 - LJCSN881	X	X			X
66		HJCSN881 - UPFPX882	X	X			X
67		HPCSN881 - B2SIYB788	X	X			X
68		JPCSN881 - B2SIYB788	X	X			X
69		LPCSN881 - A3SIYB788	X	X			X
70		*SPTPT842 - APAFS882	X	X			X
71		KPTPT842 - CPAFS882	X	X			X
72	SSA-Electrical-8508	EUEEP898 - GTUP876	X				
73		BUEEP898 - 1HZDQ866	X	X			X
74	SSA-Electrical-00262	*ZPTPT842 - GTKK864	X				

75		BPDVP899 - BPDTU889	X	X			X
76		CPDVP899 - APDTU889	X	X			X
77		DPEAW898 - DUEEP898	X	X			X
78		DJEAW898 - KPTVF896	X	X			X
79		AAPEAW898 - AUEEP898	X	X			X
80		DDPEAW898 - EUEEP898	X	X			X
	Basic Event	**Wire ID**	**Fail Open**	**Fail GND**	**Fail High Imp**	**Fail 28 VDC**	**Fail 115 AC**
81	SSA-Electrical-00262 Continued	KJTVF896 - 29JZPX697	X	X			X
82		LJTVF896 - 28JZPX697	X	X			X
83		AAPTPT842 - AAJEAW898	X	X			X
84		DDPTPT842 - DDJEAW898	X	X			X
85		\FFJEAW898 - HPTVF896	X				
86		FFPEAW898 - EUEEP898	X				
87		HJTVF896 - 58JZPX697	X				
88		FFPTPT842 - \FFJEAW898	X				
89		WPTPT842 - LPTVF896	X	X			X
90		YPTUE841 - BJDVP899	X	X			X
91		XPTUE841 - CJDVP899	X	X			X
92	SSA-Electrical-20355	\DPAFS882 - *SPTVF896	X	X			X
93		\DPAFS882 - WPTVF896	X	X			X
94		*DPTPT842 - LLPTVF896	X	X			X
95		DJAFS882 - PJCSN881	X	X			X
96		EJAFS882 - RJCSN881	X	X			X
97		PPCSN881 - A2SIYB788	X	X			X
98		RPCSN881 - A1SIYB788	X	X			X
99		*SJTVF896 - 2HTRJ640	X	X			X
100		LLJTVF896 - 1HTRJ640	X	X			X
101		*DPTPT842 - *DPTPT842	X	X			X
102		*YPTPT842 - FFPTVF896	X	X			X
103		RPTPT842 - *APTVF896	X	X			X
104		BPTPT842 - *MPTVF896	X	X			X
105		*TPTPT842 - YPTVF896	X	X			X
106		2HTYN691 - *MJTVF896	X	X			X
107		2HTRN689 - FFJTVF896	X	X			X
108		2HZDQ866 - 1HTRN689	X	X			X
109		*AJTVF896 - 2HTAX680	X	X			X
110	B1RD-JZ4203	4PZDT894 - 25JZPX697	X				
111	SSA-Electrical-60335	\1PZDT894 - 15JTSV886	X	X			X
112		11PZDT894 - \1PZDT894		X			X
113		1PZDT894 - \1PZDT894	X	X			X

Note that this is an abbreviated table for the purposes of evaluating the form of the EWIS Safety Reports. It contains all of the EWIS basic events found in only one fault tree for a catastrophic top event (PSSA-Ele-7540). The full table would contain the EWIS basic events for all of the fault trees.

5.2 Appendix B: Probability of failure for EWIS FMES events (EWIS RAT Failure matrix report).

Bundle Failure Matrix Report

Detailed Report

Model Name: OEM- Test Aircraft Compiler Version: 2.06
Make: Aircraft Centralized Mfr. Eng. Model: B1rd Series300 Database Version: SB.1.01
Phase of Flight: Landing 6/27/2006 14:38

Higher Level Fault:	Unspecified Event		
Basic Event:	PSSA-Electrical-41	Probability:	7.03E-07
B1RD-SI3111			7.03E-07
Basic Event:	SSA-Electrical-00455	Probability:	1.28E-06
SSA-Electrical-90350			1.28E-06
Basic Event:	SFHA-Electrical-210	Probability:	3.73E-07
SSA-Electrical-19877			3.73E-07

Basic Event:	PSSA-Electrical-85	Probability:	1.36E-06
B1RD-SI7112			7.88E-07
SSA-Electrical-70261			5.76E-07
Basic Event:	SSA-Electrical-3501	Probability:	1.16E-06
SSA-Electrical-20355			1.16E-06
Basic Event:	PSSA-Electrical-119	Probability:	8.74E-07
SSA-Electrical-00262			8.74E-07
Basic Event:	PSSA-Electrical-918	Probability:	7.56E-08
SSA-Electrical-8508			7.56E-08
Basic Event:	SSA-Electrical-68000	Probability:	1.03E-08
B1RD-KZ5003			1.03E-08
Basic Event:	SSA-Electrical-40333	Probability:	1.3E-07
SSA-Electrical-30557			1.3E-07

Basic Event:	SSA-Electrical-70444	Probability:	4.65E-08
SSA-Electrical-60335			4.65E-08

Basic Event:	PSSA-Electrical-64	Probability:	6.24E-08
SSA-Electrical-5451			6.24E-08

Basic Event:	SSA-Electrical-2053	Probability:	4E-08
B1RD-JZ1103			4E-08

Basic Event:	SSA-Electrical-5054	Probability:	4E-08
B1RD-JZ4203			4E-08

5.3 Appendix C: Cut-set EWIS Collocation Analysis of Catastrophic Events

CutSet Colloc Report- Top event PSSA-Ele-7540

6/21/2006 20:02

Model Name: OEM- Test Aircraft
Make: Aircraft Centralized Mfr. Eng. Model: B1rd Series300
Phase of Flight: Landing

Compiler Version: 2.06
Database Version: SB.1.01

List of cutsets in which all basic events have a EWIS failure mode but no collocation was found.

Line	CutSet			Result
2669	B1RD-SI3111	B1RD-SI7112	SSA-Electrical-19877	No Collocation Found
6185	B1RD-SI3111	B1RD-JZ4203	SSA-Electrical-19877	No Collocation Found
6782	SSA-Electrical-8508	B1RD-SI3111	SSA-Electrical-19877	No Collocation Found
8650	B1RD-SI3111	SSA-Electrical-00262	SSA-Electrical-19877	No Collocation Found
8652	B1RD-SI3111	SSA-Electrical-20355	SSA-Electrical-19877	No Collocation Found
8654	B1RD-SI3111	SSA-Electrical-60335	SSA-Electrical-19877	No Collocation Found
8658	B1RD-SI7112	SSA-Electrical-70261	SSA-Electrical-19877	No Collocation Found
8660	B1RD-SI7112	SSA-Electrical-90350	SSA-Electrical-19877	No Collocation Found
8661	B1RD-SI7112	SSA-Electrical-30557	SSA-Electrical-19877	No Collocation Found

Note that this is an abbreviated table for the purposes of evaluating the form of the EWIS Safety Reports. It contains all of the EWIS basic events found in only one fault tree for a catastrophic top event (PSSA-Ele-7540). The full table would contain the EWIS basic events for all of the fault trees of catastrophic events.

The result of "no collocation found" was the result of the collocation analysis done on the OEM data. The following figure shows an example of the report that would be generated if a collocation was found. For this report a collocation inside bundle sections CEF-Link00088 and CEF-Link00090 was artificially generated. In addition, a 6" region collocation was generated where the wire with the three failure effects were not in the same bundle sections but were in bundle sections that were within 6" of each other. Also shown are examples of rational that may be used to justify allowing the collocation in the certified design. Of course, these rational would have to be deemed acceptable to the ACO.

CutSet Colloc Report- Top event PSSA-Ele-7540

6/21/2006 20:02

Model Name: OEM- Test Aircraft
Make: Aircraft Centralized Mfr. Eng. Model: B1rd Series300
Phase of Flight: Landing

Compiler Version: 2.06
Database Version: SB.1.01

	Cuts set 2669	B1RD-SI3111	B1RD-SI7112	SSA-Electrical-19877
Bundle Section Collocation	**Bundle Section**	**Element**	**Wire(s)**	
1	CEF-Link00088	B1RD-SI3111	NJAHK885 - DJCAW883, RJAHK885 - PJCAW883	
		B1RD-SI7112	AJAFS882 - JJCSN881, CJAFS882 - LJCSN881	
		SSA-Electrical-19877	LPCCU867 - TJCSN881, KPCCU867 - UJCSN881	
2	CEF-Link00090	B1RD-SI3111	NJAHK885 - DJCAW883, RJAHK885 - PJCAW883	
		B1RD-SI7112	AJAFS882 - JJCSN881, CJAFS882 - LJCSN881	
		SSA-Electrical-19877	LPCCU867 - TJCSN881, KPCCU867 - UJCSN881	

	Cuts set 2669	B1RD-SI3111	B1RD-SI7112	SSA-Electrical-19877
6" region Collocation	**Bundle Section**	**Element**	**Wire(s)**	
3	CEF-Link00115	B1RD-SI7112	AJAFS882 - JJCSN881, CJAFS882 - LJCSN881	
		SSA-Electrical-19877	LPCCU867 - TJCSN881, KPCCU867 - UJCSN881	
	CEF-Link00113	B1RD-SI3111	NJAHK885 - DJCAW883, RJAHK885 - PJCAW883	

List of cutsets in which all basic events have a EWIS failure mode but no collocation was found.

Line	CutSet			Result
6185	B1RD-SI3111	B1RD-JZ4203	SSA-Electrical-19877	No Collocation Found
6782	SSA-Electrical-8508	B1RD-SI3111	SSA-Electrical-19877	No Collocation Found
8650	B1RD-SI3111	SSA-Electrical-00262	SSA-Electrical-19877	No Collocation Found
8652	B1RD-SI3111	SSA-Electrical-20355	SSA-Electrical-19877	No Collocation Found
8654	B1RD-SI3111	SSA-Electrical-60335	SSA-Electrical-19877	No Collocation Found
8658	B1RD-SI7112	SSA-Electrical-70261	SSA-Electrical-19877	No Collocation Found
8660	B1RD-SI7112	SSA-Electrical-90350	SSA-Electrical-19877	No Collocation Found
8661	B1RD-SI7112	SSA-Electrical-30557	SSA-Electrical-19877	No Collocation Found

Comments of the collocations reported.

Collocations 1 & 2	Bundle Sections CEF-Link00088 and CEF-Link00090 have a combined length of 10 inches. Further, the zone that they are located is not subject to high vibration and the bundle section is protected from external physical damage. There is no feasible routing alternative that would allow separation of these wires.
Collocations 3	The routing bundle sections CEF-Link00113 and CEF-Link00115 was investigated and it was found the bundle sections are separated by at least 2 inches at all points and that proper clamping is used that will maintain that separation.

Appendix D: Model used to calculate potential damage due to arcing in a bundle section.

The method of calculation is detailed in the report **Further Development of the Electrical Wiring Interconnection System (EWIS) Risk Assessment Tool** *(Not yet published).* A brief description of the calculation follows. *Note that the state of understanding of how much damage can be done by an arcing event is limited at this time. However, more work is planned in this area and as new data and calculation methods are developed they will be intergraded into the tool.*

The level of damage to structure is based on the total energy that dissipated in an arcing event. The amount of power that is release in the arc is assumed to be maximum possible power, based on the source voltage, the impedance of the source, the resistance of the wire between the source and the discharge. The time the arc continued is based on the current in the arc and the trip curve of the circuit protection.

It has been found that heat dissipation plays an important role in limiting the damage done by arcing. Also some energy is used to damage the arcing wire as well as the object that is arced to. This effects are taken into account using the factors α and γ respectfully which based on empirical fit to experimental data are taken as α =3 and γ = 0.5.
The energy that melts structure is calculated using

$$E' = \left(\frac{\gamma P_{arc}}{\alpha}\right)\left(1 - e^{(-\alpha\tau)}\right)$$

where

P_{arc} is the power in the arc
t is the time till the circuit breaker trips
α is the factor taking into account thermal dissipation
γ is the factor taking into account energy partition.

This energy used to melt structure based on the formula:

$$VolumeDamage = \frac{E'}{H_f \rho + \Delta T C_p \rho}$$

where

H_f is the heat of fusion
p is the density
ΔT is the change in temperature from room temp to melting
C_p is the heat capacity.

A damage potential level was calculated for each bundle section. The damage potential level was based on the failure of the wires with the highest potential for damage in the bundle. Because the general-purpose wire used on this aircraft does not tend to propagate arcing throughout the bundle section causing multiple wires to fail, the damage potential was based upon the simultaneous failures of two wires that have the highest potential for damage.

Appendix E. Bundle Section Reports filter by damage potential

The table below contains the bundle section report filter by damage potential criteria

- *Greater than 32 mm^3 (enough to create a 1/8" hole in a 1/8" thick piece of aluminum,*
- *or if installed lines (hydraulic, oxygen, fuel) are within 6" inches of the bundle section and estimated damage is greater than 1.0 mm^3.*

Note that because the 3D modeling of the wires harnesses was not used except for connector positions, relative distances of the bundle sections from installed line and other EWIS and Non-EWIS devices are not found in the database. Therefore, these issues are not found in this report. To allow the reader to examine how this data will be used and presented, the reports in the first bundle section (CEF-Link00217) devices and installed lines have been artificially generated to be within 6" of the bundle section. For example, in bundle section CEF-Link00217 the green hydraulic line has been placed in the 6" region of this section and in the comments, systems have been associated with the green hydraulic line. These forced devices appear in italic in the report indicating that they are artificially produced examples.

Bundle Section Report

6/30/2006 11:50

Model Name: OEM- Test Aircraft

Make: Aircraft Centralized Mfr. Eng. Model: B1rd Series300

Phase of Flight: Landing

Database Version: SB.1.01

Compiler Version: 2.06

Bundle Assembly: Cablin Elec. Front

Bundle Section: CEF-Link00217

Sub Zone: Cabin - Front

Length: 7 inches

Wires	Systems	SubSystems	Faults	Description	Zone Environment
KJCAW883 - GCQV878; RPCCU867 - GCQV878; GCQV878 - ACIE895;	Pitot & Static Htrs Power Distribution W Standby Instruments	Pitot & Static Htrs Power Distribution W Standby Instruments			High Traffic Lavatory Fluids Hydraulic Fluids Enclosed Area Oxygen Lines

Comments: There is no reduction of safety margin do to collocation of Pitot & Static Htrs, Power Distribution and Standby Instruments wire in the same bundle section.

Damage Potential	Max Power	Max Damage to Structure	Damage of Other Wires	Min Segregation/ Separation Required	Ignition of Material
There are 3 in this bundle of which 3 are power wires.	GCQV878 - ACIE895 : 380.8 Watts	Aluminum: 1.12mm^3	Possible damage to adjacent wires.		There exists the potential for ignition of other materials.
There are 0 AC power wires.	KJCAW883 - GCQV878 : 380.8 Watts	Copper: 0.61mm^3			
There are 3 DC power wires.		Titanium: 0.61mm^3			

There are 1 circuit protection mechanisms to which wires from this bundle are connected. Largest Circuit Breaker: 5 Amps		Damage approximately the size of a pen tip. Likely to puncture hydraulic/fuel line.			

Bundles in Six Inch Region	Systems in Given Bundle Section	Sub-Systems in Given Bundle Section	Faults in Given Bundle Section	Assorted lines within 6inches of CEF-Link00217
CEF-Link00216	Bleed Air Supply Wir;	Bleed Air Supply Wir;		Hydraulic line (nose wheel steering backup

Electrical Devices in Six Inch Region	Faults Associated with Devices
UF005: Pressure Control PSB	Loss of automated cabin pressure control, Would switch to manual control

Comments:

Loss of Pitot & Static Htrs, Power Distribution, Standby Instruments, in combination with Bleed Air Supply does not result in a decrease in the safety margin.

Loss of Pitot & Static Htrs, Power Distribution, Standby Instruments, in combination with the Hydraulic service (nose wheel steering back up) does not result in a decrease in the safety margin.

It is unlikely that the level of potential damage could effect the operation of the *Pressure Control PCB*. However, Loss of Pitot & Static Htrs, Power Distribution, and Standby Instruments, in combination with Loss of automated cabin pressure control does not result in a decrease in the safety margin.

Type	Safety Questions
No problems detected.	

Bundle Assembly: Engine Electrical

Bundle Section: EE-Link00215 Sub Zone: Engine Length: 27 inches

Wires	Systems	SubSystems	Faults	Description	Zone Environment
FFPDVP899 - EUDWM892; DDPDVP899 - EUDWM892; AAPDVP899 - AUDWM892; DPDVP899 - DUDWM892; CPDVP899 - APDTU889; BPDVP899 - BPDTU889; 72PTXB891 - *FJD011; 56PTXB891 - *HJD011; 55PTXB891 - YJD011; 54PTXB891 - JJD011; 53PTXB891 - *EJD011; 52PTXB891 - AJD011; 51PTXB891 - TJD011; TJDNB893 - RJD011; TJDBE897 - LJD011; BGTCH790 - *AJD011; KGTCH790 - CJD011; JGTCH790 - NJD011; HGTCH790 - WJD011; FGTCH790 - EJD011; EGTCH790 - *CJD011; DGTCH790 - GJD011;	Generators Wiring Di Thrust Reverser Wiri	Generators Wiring Di Thrust Reverser Wiri	PSSA-Electrical-119 PSSA-Electrical-85		High Traffic High Vibration High Temp Pneumatic Lines Fuel Lines
Comments: There is no reduction of safety margin do to collocation of Generator and Trust Reverser wire in the same bundle section. The faults listed do not satisfy all of the conditions for a Catastrophic event.					

Damage Potential	Max Power	Max Damage to Structure	Damage of Other Wires	Min Segregation/ Separation Required	Ignition of Material
There are 22 in this bundle of which 7 are power wires.	KGTCH790 - CJD011: 90.82 Watts	Aluminum: 92.78mm^3	Possible damage to adjacent wires.		There exists the potential for ignition of other materials.
There are 0 AC power wires.	HGTCH790 - WJD011: 90.82 Watts	Copper: 50.27mm^3			
There are 7 DC power wires.		Titanium: 50.73mm^3			
There are 2 circuit protection mechanisms to which wires from this bundle are connected.		Damage between the size of a pen tip and a pencil eraser. Likely to puncture hydraulic/fuel line.			
Largest Circuit Breaker: 5 Amps					

Bundles in Six Inch Region	Systems in Given Bundle Section	Sub-Systems in Given Bundle Section	Faults in Given Bundle Section	Assorted lines within 6inches of EE-Link00215
Electrical Devices in Six Inch Region	Faults Associated with Devices			
Comments: NA				

Type	Safety Questions
Fire Zone	This bundle is routed in a subzone which has been designated as a fire zone. Please Comment: This bundle does not contain safety critical wire.

Bundle Assembly: Engine Electrical

Bundle Section: EE-Link00243

Sub Zone: Engine

Length: 14 inches

Wires	Systems	SubSystems	Faults	Description	Zone Environment
FFPDVP899 - EUDWM892; DDPDVP899 - EUDWM892; AAPDVP899 - AUDWM892; DPDVP899 - DUDWM892; CPDVP899 - APDTU889; BPDVP899 - BPDTU889; 72PTXB891 - *FJD011; 56PTXB891 - *HJD011; 55PTXB891 - YJD011; 54PTXB891 - JJD011; 53PTXB891 - *EJD011; 52PTXB891 - AJD011; 51PTXB891 - TJD011; TJDNB893 - RJD011; TJDBE897 - LJD011; BGTCH790 - *AJD011; KGTCH790 - CJD011; JGTCH790 - NJD011; HGTCH790 - WJD011; FGTCH790 - EJD011; EGTCH790 - *CJD011; DGTCH790 - GJD011;	Generators Wiring Di Thrust Reverser Wiri	Generators Wiring Di Thrust Reverser Wiri	PSSA-Electrical-119 PSSA-Electrical-85		High Traffic High Vibration High Temp Pneumatic Lines Fuel Lines
Comments: There is no reduction of safety margin do to collocation of Generator and Trust Reverser wire in the same bundle section. The faults listed do not satisfy all of the conditions for a Catastrophic event.					

Damage Potential	Max Power	Max Damage to Structure	Damage of Other Wires	Min Segregation/ Separation Required	Ignition of Material
There are 22 in this bundle of which 7 are power wires.	KGTCH790 - CJD011: 92.31 Watts	Aluminum: 94.31mm^3	Possible damage to adjacent wires.		There exists the potential for ignition of other materials.
There are 0 AC power wires.	HGTCH790 - WJD011: 92.31 Watts	Copper: 51.1mm^3			
There are 7 DC power wires.		Titanium: 51.57mm^3			
There are 2 circuit protection mechanisms to which wires from this bundle are connected.		Damage between the size of a pen tip and a pencil eraser. Likely to puncture hydraulic/fuel line.			
Largest Circuit Breaker: 5 Amps					

Bundles in Six Inch Region	Systems in Given Bundle Section	Sub-Systems in Given Bundle Section	Faults in Given Bundle Section	Assorted lines within 6inches of EE-Link00243
Electrical Devices in Six Inch Region	Faults Associated with Devices			
Comments: NA				

Type	Safety Questions
Fire Zone	This bundle is routed in a subzone which has been designated as a fire zone. Please Comment: This bundle does not contain safety critical wire.

Bundle Assembly: Engine Electrical

Bundle Section: EE-Link00340

Sub Zone: Engine

Length: 6.02 inches

Wires	Systems	SubSystems	Faults	Description	Zone Environment
FFPDVP899 - EUDWM892; DDPDVP899 - EUDWM892; AAPDVP899 - AUDWM892; DPDVP899 - DUDWM892; CPDVP899 - APDTU889; BPDVP899 - BPDTU889; 72PTXB891 - *FJD011; 56PTXB891 - *HJD011; 55PTXB891 - YJD011; 54PTXB891 - JJD011; 53PTXB891 - *EJD011; 52PTXB891 - AJD011; 51PTXB891 - TJD011; TJDNB893 - RJD011; TJDBE897 - LJD011; BGTCH790 - *AJD011; KGTCH790 - CJD011; JGTCH790 - NJD011; HGTCH790 - WJD011; FGTCH790 - EJD011; EGTCH790 - *CJD011; DGTCH790 - GJD011; GDPJ897 - BPDYD874; *XPDVP899 - APDSE894; CPDCY881 - WPDVP899; APDCY881 - XPDVP899; HHPDVP899 - ADMG898; GGPDVP899 - ADAB899;	Bleed Air Supply Wir Engine Monitoring Engine/Wing Anti-Ice Generators Wiring Di Temp Sensing Anti-Ic Thrust Reverser Wiri	Bleed Air Supply Wir Engine Monitoring Engine/Wing Anti-Ice Generators Wiring Di Temp Sensing Anti-Ic Thrust Reverser Wiri	PSSA-Electrical-119 PSSA-Electrical-85		High Traffic High Vibration High Temp Pneumatic Lines Fuel Lines

Comments: There are no safety issues with loss of the systems listed above. The faults listed do not satisfy all of the conditions for a Catastrophic event.

Damage Potential	Max Power	Max Damage to Structure	Damage of Other Wires	Min Segregation/ Separation Required	Ignition of Material
There are 28 in this bundle of which 7 are power wires.	KGTCH790 - CJD011: 96.29 Watts	Aluminum: 98.36mm^3	Possible damage to adjacent wires.		There exists the potential for ignition of other materials.
There are 0 AC power wires.	HGTCH790 - WJD011: 96.29 Watts	Copper: 53.3mm^3			
There are 7 DC power wires.		Titanium: 53.79mm^3			
There are 2 circuit protection mechanisms to which wires from this bundle are connected.		Damage between the size of a pen tip and a pencil eraser. Likely to puncture hydraulic/fuel line.			
Largest Circuit Breaker: 5 Amps					

Bundles in Six Inch Region	Systems in Given Bundle Section	Sub-Systems in Given Bundle Section	Faults in Given Bundle Section	Assorted lines within 6inches of EE-Link00340
Electrical Devices in Six Inch Region	Faults Associated with Devices			
Comments: There are no safety concerns for damage, to the extent reported above, to EWIS or non-EWIS components within 6 inches of this bundle section.				

Type	Safety Questions
Fire Zone	This bundle is routed in a subzone which has been designated as a fire zone. Please Comment: This bundle does not contain safety critical wire.

Bundle Assembly: Engine Electrical

Bundle Section: EE-Link00930

Sub Zone: Engine

Length: 18 inches

Wires	Systems	SubSystems	Faults	Description	Zone Environment
FFPDVP899 - EUDWM892; DDPDVP899 - EUDWM892; AAPDVP899 - AUDWM892; DPDVP899 - DUDWM892; CPDVP899 - APDTU889; BPDVP899 - BPDTU889; 72PTXB891 - *FJD011; 56PTXB891 - *HJD011; 55PTXB891 - YJD011; 54PTXB891 - JJD011; 53PTXB891 - *EJD011; 52PTXB891 - AJD011; 51PTXB891 - TJD011; TJDNB893 - RJD011; TJDBE897 - LJD011; BGTCH790 - *AJD011; KGTCH790 - CJD011; JGTCH790 - NJD011; HGTCH790 - WJD011; FGTCH790 - EJD011; EGTCH790 - *CJD011; DGTCH790 - GJD011; HHPDVP899 - ADMG898; GGPDVP899 - ADAB899;	Generators Wiring Di Temp Sensing Anti-Ic Thrust Reverser Wiri	Generators Wiring Di Temp Sensing Anti-Ic Thrust Reverser Wiri	PSSA-Electrical-119 PSSA-Electrical-85		High Traffic High Vibration High Temp Pneumatic Lines Fuel Lines
Comments: There are no safety issues with loss of the systems listed above. The faults listed do not satisfy all of the conditions for a Catastrophic event.					

Damage Potential	Max Power	Max Damage to Structure	Damage of Other Wires	Min Segregation/ Separation Required	Ignition of Material
There are 24 in this bundle of which 7 are power wires.	KGTCH790 - CJD011: 94.31 Watts	Aluminum: 96.35mm^3	Possible damage to adjacent wires.		There exists the potential for ignition of other materials.
There are 0 AC power wires.	HGTCH790 - WJD011: 94.31 Watts	Copper: 52.2mm^3			
There are 7 DC power wires.		Titanium: 52.69mm^3			
There are 2 circuit protection mechanisms to which wires from this bundle are connected.		Damage between the size of a pen tip and a pencil eraser. Likely to puncture hydraulic/fuel line.			
Largest Circuit Breaker: 5 Amps					

Bundles in Six Inch Region	Systems in Given Bundle Section	Sub-Systems in Given Bundle Section	Faults in Given Bundle Section	Assorted lines within 6inches of EE-Link00930
Electrical Devices in Six Inch Region	Faults Associated with Devices			
Comments: There are no safety concerns for damage, to the extent reported above, to EWIS or non-EWIS components within 6 inches of this bundle section.				

Type	Safety Questions
Fire Zone	This bundle is routed in a subzone which has been designated as a fire zone. Please Comment:

Bundle Assembly: Engine Electrical

Bundle Section: EE-Link00945

Sub Zone: Engine

Length: 2.01 inches

Wires	Systems	SubSystems	Faults	Description	Zone Environment
FFPDVP899 - EUDWM892; DDPDVP899 - EUDWM892; AAPDVP899 - AUDWM892; DPDVP899 - DUDWM892; CPDVP899 - APDTU889; BPDVP899 - BPDTU889; 72PTXB891 - *FJD011; 56PTXB891 - *HJD011; 55PTXB891 - YJD011; 54PTXB891 - JJD011; 53PTXB891 - *EJD011; 52PTXB891 - AJD011; 51PTXB891 - TJD011; TJDNB893 - RJD011; TJDBE897 - LJD011; BGTCH790 - *AJD011; KGTCH790 - CJD011; JGTCH790 - NJD011; HGTCH790 - WJD011; FGTCH790 - EJD011; EGTCH790 - *CJD011; DGTCH790 - GJD011; GDPJ897 - BPDYD874; *XPDVP899 - APDSE894; CPDCY881 - WPDVP899; APDCY881 - XPDVP899; HHPDVP899 - ADMG898; GGPDVP899 - ADAB899;	Bleed Air Supply Wir Engine Monitoring Engine/Wing Anti-Ice Generators Wiring Di Temp Sensing Anti-Ic Thrust Reverser Wiri	Bleed Air Supply Wir Engine Monitoring Engine/Wing Anti-Ice Generators Wiring Di Temp Sensing Anti-Ic Thrust Reverser Wiri	PSSA-Electrical-119 PSSA-Electrical-85		High Traffic High Vibration High Temp Pneumatic Lines Fuel Lines

Comments: There are no safety issues with loss of the systems listed above. The faults listed do not satisfy all of the conditions for a Catastrophic event.

Damage Potential	Max Power	Max Damage to Structure	Damage of Other Wires	Min Segregation/ Separation Required	Ignition of Material
There are 28 in this bundle of which 7 are power wires. There are 0 AC power wires. There are 7 DC power wires. There are 2 circuit protection mechanisms to which wires from this bundle are connected. Largest Circuit Breaker: 5 Amps	KGTCH790 - CJD011: 95.58 Watts HGTCH790 - WJD011: 95.58 Watts	Aluminum: 97.64mm^3 Copper: 52.9mm^3 Titanium: 53.39mm^3 Damage between the size of a pen tip and a pencil eraser. Likely to puncture hydraulic/fuel line.	Possible damage to adjacent wires.		There exists the potential for ignition of other materials.

Bundles in Six Inch Region	Systems in Given Bundle Section	Sub-Systems in Given Bundle Section	Faults in Given Bundle Section	Assorted lines within 6inches of EE-Link00945
Electrical Devices in Six Inch Region	Faults Associated with Devices			
Comments: There are no safety concerns for damage, to the extent reported above, to EWIS or non-EWIS components within 6 inches of this bundle section.				

Type	Safety Questions
Fire Zone	This bundle is routed in a subzone which has been designated as a fire zone. Please Comment: This bundle does not contain safety critical wire.

Bundle Assembly: Engine Electrical

Bundle Section: EE-Link00983

Sub Zone: Engine

Length: 0.39 inches

Wires	Systems	SubSystems	Faults	Description	Zone Environment
CPDVP899 - APDTU889; BPDVP899 - BPDTU889; 72PTXB891 - *FJD011; 56PTXB891 - *HJD011; 55PTXB891 - YJD011; 54PTXB891 - JJD011; 53PTXB891 - *EJD011; 52PTXB891 - AJD011; 51PTXB891 - TJD011; TJDNB893 - RJD011; TJDBE897 - LJD011; BGTCH790 - *AJD011; KGTCH790 - CJD011; JGTCH790 - NJD011; HGTCH790 - WJD011; FGTCH790 - EJD011; EGTCH790 - *CJD011; DGTCH790 - GJD011;	Generators Wiring Di Thrust Reverser Wiri	Generators Wiring Di Thrust Reverser Wiri	PSSA-Electrical-119		High Traffic High Vibration High Temp Pneumatic Lines Fuel Lines

Comments: There are no safety issues with Generator and Trust Reverser Wire being routed in the same bundle section. The faults listed do not satisfy all of the conditions for a Catastrophic event.

Damage Potential	Max Power	Max Damage to Structure	Damage of Other Wires	Min Segregation/ Separation Required	Ignition of Material
There are 18 in this bundle of which 7 are power wires.	KGTCH790 - CJD011: 88.06 Watts	Aluminum: 89.96mm^3	Possible damage to adjacent wires.		There exists the potential for ignition of other materials.
There are 0 AC power wires.	HGTCH790 - WJD011: 88.06 Watts	Copper: 48.74mm^3			
There are 7 DC power wires.		Titanium: 49.2mm^3			
There are 2 circuit protection mechanisms to which wires from this bundle are connected.		Damage between the size of a pen tip and a pencil eraser. Likely to puncture hydraulic/fuel line.			
Largest Circuit Breaker: 5 Amps					

Bundles in Six Inch Region	Systems in Given Bundle Section	Sub-Systems in Given Bundle Section	Faults in Given Bundle Section	Assorted lines within 6inches of EE-Link00983
Electrical Devices in Six Inch Region	**Faults Associated with Devices**			
Comments: There are no safety concerns for damage, to the extent reported above, to EWIS or non-EWIS components within 6 inches of this bundle section.				

Type	Safety Questions
Fire Zone	This bundle is routed in a subzone which has been designated as a fire zone. Please Comment: This bundle does not contain safety critical wire.

Bundle Assembly: Tail Cone Electrical

Bundle Section: TCE-Link02117 Sub Zone: Tail Cone Length: 20.59 inches

Wires	Systems	SubSystems	Faults	Description	Zone Environment
6PTER876 - RGTFK786; TPTSY829 - AGTFK786; EGTFK786 - AJVSM899; DGTFK786 - 2JVHN897; \SPTSY829 - BGTFK786; \BPTSY829 - CGTFK786; FGTFK786 - *GJVKQ898; BJVKR896 - HGTFK786; 2PTAR792 - MGTFK786; *PPASO894 - L1UTCM872; *YPASO894 - R1UTCM872; GTSX890 - BPTEG868; GTSX890 - CPTEG868; \5PTMH-14 - APTEG868;	Auxiliary Power Unit B/A Lk Det Wiring Di Engine Fire Extingui Exterior Lighting Wi Horizontal Stab Trim Standby Instruments	Auxiliary Power Unit B/A Lk Det Wiring Di Engine Fire Extingui Exterior Lighting Wi Horizontal Stab Trim Standby Instruments			SWAMP Fuel Lines Ducts Enclosed Area
Comments: There are no safety issues with loss of the systems listed above. The faults listed do not satisfy all of the conditions for a Catastrophic event.					

Damage Potential	Max Power	Max Damage to Structure	Damage of Other Wires	Min Segregation/ Separation Required	Ignition of Material
There are 14 in this bundle of which 11 are power wires. There are 0 AC power wires. There are 11 DC power wires. There are 3 circuit protection mechanisms to which wires from this bundle are connected. Largest Circuit Breaker: 7.5 Amps	2PTAR792 - MGTFK786: 298.71 Watts DGTFK786 - 2JVHN897: 109.87 Watts	Aluminum: 39.88mm^3 Copper: 21.61mm^3 Titanium: 21.81mm^3 Damage between the size of a pen tip and a pencil eraser. Likely to puncture hydraulic/fuel line.	Possible damage to adjacent wires.		There exists the potential for ignition of other materials.

Bundles in Six Inch Region	Systems in Given Bundle Section	Sub-Systems in Given Bundle Section	Faults in Given Bundle Section	Assorted lines within 6inches of TCE-Link02117
Electrical Devices in Six Inch Region	**Faults Associated with Devices**			
Comments: There are no safety concerns for damage, to the extent reported above, to EWIS or non-EWIS components within 6 inches of this bundle section.				

Type	Safety Questions
Generator Overlap	This bundle contains power wires from different generators. Please Comment: These wires are protected with adequate circuit protection so that loss of the bundle could not cause loss of function of both generators.

Bundle Assembly: Tail Cone Electrical

Bundle Section: TCE-Link02805 Sub Zone: Tail Cone Length: 6.55 inches

Wires	Systems	SubSystems	Faults	Description	Zone Environment
6PTER876 - RGTFK786; TPTSY829 - AGTFK786; EGTFK786 - AJVSM899; DGTFK786 - 2JVHN897; \SPTSY829 - BGTFK786; \BPTSY829 - CGTFK786; FGTFK786 - *GJVKQ898; BJVKR896 - HGTFK786; 2PTAR792 - MGTFK786;	Auxiliary Power Unit B/A Lk Det Wiring Di Exterior Lighting Wi Horizontal Stab Trim Standby Instruments	Auxiliary Power Unit B/A Lk Det Wiring Di Exterior Lighting Wi Horizontal Stab Trim Standby Instruments			SWAMP Fuel Lines Ducts Enclosed Area
Comments: There are no safety issues with loss of the systems listed above. The faults listed do not satisfy all of the conditions for a Catastrophic event.					

Damage Potential	Max Power	Max Damage to Structure	Damage of Other Wires	Min Segregation/ Separation Required	Ignition of Material
There are 9 in this bundle of which 9 are power wires. There are 0 AC power wires. There are 9 DC power wires. There are 1 circuit protection mechanisms to which wires from this bundle are connected. Largest Circuit Breaker: 7.5 Amps	2PTAR792 - MGTFK786 : 298.71 Watts DGTFK786 - 2JVHN897 : 111.49 Watts	Aluminum: 39.88mm^3 Copper: 21.61mm^3 Titanium: 21.81mm^3 Damage between the size of a pen tip and a pencil eraser. Likely to puncture hydraulic/fuel line.	Possible damage to adjacent wires.		There exists the potential for ignition of other materials.

Bundles in Six Inch Region	Systems in Given Bundle Section	Sub-Systems in Given Bundle Section	Faults in Given Bundle Section	Assorted lines within 6inches of TCE-Link02805
TCE-Link00462	Temp Sensing Anti-Ic; Horizontal Stab Trim; Crew Warning System;	Temp Sensing Anti-Ic; Horizontal Stab Trim; Crew Warning System;		
TCE-Link02809	Temp Sensing Anti-Ic; Rudder/Aileron Trim; Mach Trim Wiring Dia; Gust Lock Wiring Dia; Exterior Lighting Wi;	Temp Sensing Anti-Ic; Rudder/Aileron Trim; Mach Trim Wiring Dia; Gust Lock Wiring Dia; Exterior Lighting Wi;		
TCE-Link03172	Standby Instruments; Horizontal Stab Trim; Exterior Lighting Wi; B/A Lk Det Wiring Di; Auxiliary Power Unit;	Standby Instruments; Horizontal Stab Trim; Exterior Lighting Wi; B/A Lk Det Wiring Di; Auxiliary Power Unit;		

Electrical Devices in Six Inch Region	Faults Associated with Devices

Comments: There are no safety concerns for damage, to the extent reported above, to EWIS or non-EWIS components within 6 inches of this bundle section.

Type	Safety Questions
No problems detected.	

Bundle Assembly: Tail Cone Electrical

Bundle Section: TCE-Link02987 Sub Zone: Tail Cone Length: 15.91 inches

Wires	Systems	SubSystems	Faults	Description	Zone Environment
6PTER876 - RGTFK786; TPTSY829 - AGTFK786; EGTFK786 - AJVSM899; DGTFK786 - 2JVHN897; \SPTSY829 - BGTFK786; \BPTSY829 - CGTFK786; 49PPTSQ-6 - SJVKR896; 50PPTSQ-6 - RJVKR896; 48PPTSQ-6 - PJVKR896; 52PPTSQ-6 - NJVKR896; 51PPTSQ-6 - MJVKR896; GPAFS882 - LJVKR896; FPAFS882 - KJVKR896; FGTFK786 - *GJVKQ898; AJVKR896 - PPPTFB893; 2PTAR792 - MGTFK786; DJVKR896 - 16PTSA-15; 5PALA890 - CJVKR896; 11PABP886 - *AJVKR896; 10PABP886 - ZJVKR896; 9PABP886 - YJVKR896; 8PABP886 - XJVKR896; 7PABP886 - *KJVKR896; *PPASO894 - L1UTCM872; *YPASO894 - R1UTCM872; GTSX890 - BPTEG868; GTSX890 - CPTEG868; \5PTMH-14 - APTEG868; 49PTSW890 - *GJVKR896; 48PTSW890 - *FJVKR896;	Auxiliary Power Unit B/A Lk Det Wiring Di Engine Fire Extingui Exterior Lighting Wi Gust Lock Wiring Dia Horizontal Stab Trim Mach Trim Wiring Dia Rudder/Aileron Trim Standby Instruments Temp Sensing Anti-Ic	Auxiliary Power Unit B/A Lk Det Wiring Di Engine Fire Extingui Exterior Lighting Wi Gust Lock Wiring Dia Horizontal Stab Trim Mach Trim Wiring Dia Rudder/Aileron Trim Standby Instruments Temp Sensing Anti-Ic			SWAMP Fuel Lines Ducts Enclosed Area

47PTSW890 - *EJVKR896; 46PTSW890 - *DJVKR896; 45PTSW890 - *CJVKR896; 44PTSW890 - *BJVKR896;					
Comments: There are no safety issues with loss of the systems listed above. The faults listed do not satisfy all of the conditions for a Catastrophic event.					

Damage Potential	Max Power	Max Damage to Structure	Damage of Other Wires	Min Segregation/ Separation Required	Ignition of Material
There are 34 in this bundle of which 11 are power wires. There are 0 AC power wires. There are 11 DC power wires. There are 4 circuit protection mechanisms to which wires from this bundle are connected.	2PTAR792 - MGTFK786 : 298.71 Watts DGTFK786 - 2JVHN897 : 105.06 Watts	Aluminum: 39.88mm^3 Copper: 21.61mm^3 Titanium: 21.81mm^3 Damage between the size of a pen tip and a pencil eraser. Likely to puncture hydraulic/fuel line.	Possible damage to adjacent wires.		There exists the potential for ignition of other materials.

Largest Circuit Breaker: 7.5 Amps					

Bundles in Six Inch Region	Systems in Given Bundle Section	Sub-Systems in Given Bundle Section	Faults in Given Bundle Section	Assorted lines within 6inches of TCE-Link02987
Electrical Devices in Six Inch Region	Faults Associated with Devices			
Comments: There are no safety concerns for damage, to the extent reported above, to EWIS or non-EWIS components within 6 inches of this bundle section.				

Type	Safety Questions
Generator Overlap	This bundle contains power wires from different generators. Please Comment: These wires are protected with adequate circuit protection so that loss of the bundle could not cause loss of function of both generators.

Bundle Assembly: Tail Cone Electrical

Bundle Section: TCE-Link03006 Sub Zone: Tail Cone Length: 6.55 inches

Wires	Systems	SubSystems	Faults	Description	Zone Environment
5PTER876 - *NPTWH888; 4PTER876 - *MPTWH888; TPTSY829 - AGTFK786; EGTFK786 - AJVSM899; DGTFK786 - 2JVHN897; \SPTSY829 - BGTFK786; \BPTSY829 - CGTFK786; 49PPTSQ-6 - SJVKR896;	Auxiliary Power Unit B/A Lk Det Wiring Di Engine Fire Extingui Exterior Lighting Wi Gust Lock Wiring Dia	Auxiliary Power Unit B/A Lk Det Wiring Di Engine Fire Extingui Exterior Lighting Wi Gust Lock Wiring Dia			SWAMP Fuel Lines Ducts Enclosed Area

50PPTSQ-6 - RJVKR896; 48PPTSQ-6 - PJVKR896; 52PPTSQ-6 - NJVKR896; 51PPTSQ-6 - MJVKR896; GPAFS882 - LJVKR896; FPAFS882 - KJVKR896; FGTFK786 - *GJVKQ898; AJVKR896 - PPPTFB893; 2PTAR792 - MGTFK786; DJVKR896 - 16PTSA-15; 5PALA890 - CJVKR896; 11PABP886 - *AJVKR896; 10PABP886 - ZJVKR896; 9PABP886 - YJVKR896; 8PABP886 - XJVKR896; 7PABP886 - *KJVKR896; *PPASO894 - L1UTCM872; *YPASO894 - R1UTCM872; GTSX890 - BPTEG868; GTSX890 - CPTEG868; \5PTMH-14 - APTEG868; 49PTSW890 - *GJVKR896; 48PTSW890 - *FJVKR896; 47PTSW890 - *EJVKR896; 46PTSW890 - *DJVKR896; 45PTSW890 - *CJVKR896; 44PTSW890 - *BJVKR896;	Horizontal Stab Trim Mach Trim Wiring Dia Rudder/Aileron Trim Standby Instruments Temp Sensing Anti-Ic	Horizontal Stab Trim Mach Trim Wiring Dia Rudder/Aileron Trim Standby Instruments Temp Sensing Anti-Ic			
Comments: There are no safety issues with loss of the systems listed above. The faults listed do not satisfy all of the conditions for a Catastrophic event.					

Damage Potential	Max Power	Max Damage to Structure	Damage of Other Wires	Min Segregation/ Separation Required	Ignition of Material
There are 35 in this bundle of which 10 are power wires.	2PTAR792 - MGTFK786 : 298.71 Watts	Aluminum: 39.88mm^3	Possible damage to adjacent wires.		There exists the potential for ignition of other materials.
There are 0 AC power wires.	DGTFK786 - 2JVHN897 : 96.25 Watts	Copper: 21.61mm^3			
There are 10 DC power wires.		Titanium: 21.81mm^3			
There are 4 circuit protection mechanisms to which wires from this bundle are connected.		Damage between the size of a pen tip and a pencil eraser. Likely to puncture hydraulic/fuel line.			
Largest Circuit Breaker: 7.5 Amps					

Bundles in Six Inch Region	Systems in Given Bundle Section	Sub-Systems in Given Bundle Section	Faults in Given Bundle Section	Assorted lines within 6inches of TCE-Link03006
Electrical Devices in Six Inch Region	Faults Associated with Devices			
Comments: There are no safety concerns for damage, to the extent reported above, to EWIS or non-EWIS components within 6 inches of this bundle section.				

Type	Safety Questions
Generator Overlap	This bundle contains power wires from different generators. Please Comment: These wires are protected with adequate circuit protection so that loss of the bundle could not cause loss of function of both generators.

APPENDIX H—PARAMETERIZATION OF CIRCUIT PROTECTION

For the circuit protection to be properly modeled in the Electrical Wiring Interconnection Systems (EWIS) Risk Assessment Tool (RAT), the duration of the over-current event has to be properly represented. To handle this for the general cases, a format was developed to match the trip curves that are available for all circuit protection devices. Figure H-1 shows the standard trip curve for thermal breakers considering different initial thermal conditions for the breaker.

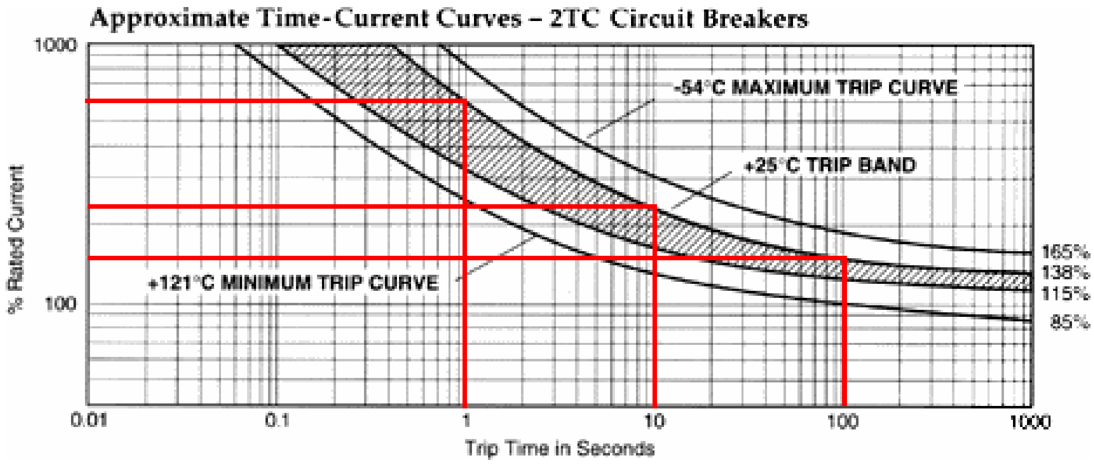

Figure H-1. Trip Bands for a Particular Thermal Circuit Breaker (The red lines show the percentage over a rated current that a breaker meeting this specification can operate before it should open the circuit.)

For this effort, the upper limit of the +25°C trip band was used for all devices that were evaluated. Similarly, the same recommendations are within the EWIS RAT instruction manual. To represent this in the EWIS RAT, a general equation that was used for this curve:

$$f(x) = \exp\left\{C \exp^{(-\alpha-\beta\ln(t))}\right\} + Offset \tag{H-1}$$

where C, α, β, and *Offset* are fit variables for the particular time, and t is the duration of the over current. With this equation, for a given over-current rating, the time at which the circuit protection would activate could be estimated (as shown in equation H-2).

$$
\begin{aligned}
&f(x) = \exp\left\{C\exp^{(-\alpha-\beta\, ln(t))}\right\} + D \\
&Y = \exp\left\{C\exp(-\alpha-\beta ln(t))\right\} + D \\
&ln\left(\frac{ln(Y-D)}{C} -> A\right) \\
&A = -\alpha - \beta\; ln(t) \\
&\frac{A+\alpha}{-\beta} = ln(t) \\
&t = \exp\left(\frac{A+\alpha}{-\beta}\right)
\end{aligned}
\qquad \text{(H-2)}
$$

To determine the optimal values for the fit variables, a multivariable minimization method was employed. From this, the fit variables would converge to values, which would result in a function closely resembling that of the thermal circuit protection trip curve. An example of the result of the multivariable minimization method is shown in figure H-2.

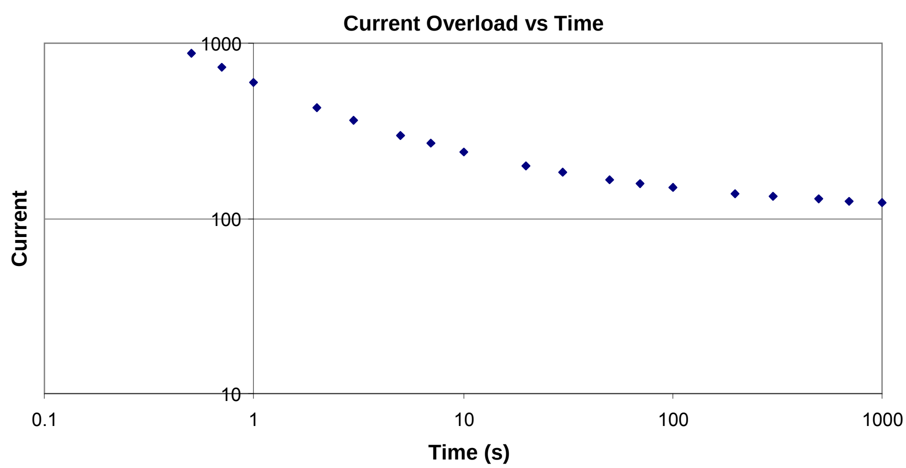

Figure H-2. Data Points Taken From the Multivariable Minimization Method Applied to the Thermal Trip Curve Shown in Figure H-1

The shape and values of the fit function closely match that of the trip curve. For this particular graph, the values of the fit variables are as follows:

- Alpha 1.012354127
- Beta 0.106521564
- Constant 17.03626143
- Offset 112.566701

To determine the accuracy of the minimization method, a goodness of fit parameter was used. This was a useful metric for determining how well the EWIS RAT has fit the parameters for the trip curve. Each level in table H-1 corresponds to an increase in the likelihood that the approximated curve does not match the provided data. A near perfect fit means that the approximated curve was within 2% of all of the data points provided, very good rating within 10%, fair within 20%, and the last category provides no guarantee on the quality of the data.

Table H-1. Goodness of Fit Evaluation for Circuit Breaker Trip Curve

Goodness of Fit	Validity of Equation
<10	Near perfect fit
10-100	Very Good
100-1000	Fair
>1000	No Guarantee on data

The value goodness of fit for the above minimization was approximately 1.45. Other trip curves that were evaluated had larger goodness of fit values, but all minimized to a very good rating or better. Note: the specifications will typically be applicable to an entire family of circuit breakers (various current ratings), but will have to be individually identified for fuses with different current ratings. The same algorithms and methodologies were applicable to fuses.