ELECTRIC SHOCK RISKS IN AN ELECTRIC VEHICLE

by

CAMILLA M. DENISON

Bachelor of Science in Electrical Engineering
GMI Engineering and Management Institute (1987)

Submitted to the Department of Electrical Engineering and Computer Science and the Sloan School of Management in partial fulfillment of the requirements for the degrees of

Master of Science in Electrical Engineering
and
Master of Science in Management

in conjunction with the
LEADERS FOR MANUFACTURING PROGRAM

at the
Massachusetts Institute of Technology
May, 1992

Signature of Author____
Department of Electrical Engineering
Department of Management Science
April 27, 1992

Certified By____
Alvin W. Drake
Professor of Electrical Engineering
Thesis Supervisor

Certified By____
Stephen C. Graves
Professor of Management
Thesis Supervisor

Certified By____
Norman C. Rasmussen
Professor of Nuclear Engineering
Thesis Supervisor

Accepted By____
~~Frederic Morgenthaler, Chairman~~
Electrical Engineering Department
Campbell L. Searle, Chair
Department Committee on Graduate Students

Accepted By____
Jeffrey Barks, Associate Dean,
Sloan School of Management

ELECTRIC SHOCK RISKS IN AN ELECTRIC VEHICLE

by
CAMILLA M. DENISON

submitted to the departments of
Electrical Engineering and **Management**
in partial fulfillment of the requirements
for the degrees of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING
and
MASTER OF SCIENCE IN MANAGEMENT

Abstract

An assessment has been conducted of the health risks associated with the voltage required for propulsion of an electric vehicle. The risk was assessed for the installation, service and use of "high voltage" direct current components, as well as in the event of a vehicle accident. The analysis accounts for the dominant additional risk of serious personal injury from electric shock as a result of the propulsion system being electric.

Fault tree methodology was employed to estimate the probabilities of possible system failures that could lead to injurious electric shock. The possible safety and product liability ramifications are discussed as well as the marketing and business concerns associated with the high voltage. Modifications that could reduce the risk of electric shock on the electric vehicle are proposed. This analysis was done on GM's Impact design as of September 1991, and several design changes have been implemented as a result of this.

This topic is timely due to the large number of automobile manufacturers who have recently announced their intention to produce electric vehicles for public sale. There is also limited knowledge available on this topic.

The assessment results have shown that the risk associated with the high voltage propulsion system in the electric vehicle design studied, GM's Impact, is smaller than the risks associated with conventional gasoline internal combustion engined vehicles. In either system this is a small part of the total risk. Road and traffic hazards dominate the overall risk for both types of vehicles. The results have also demonstrated that nearly all of the electric vehicle risk can be attributed to a very small number of events.

Advisors: Jon Bereisa, Chief Engineer, Propulsion Systems, GM Electric Vehicle
Tom Donnan, Department Head, Production Systems, GM Electric Vehicle
Alvin Drake, Professor, Electrical Engineering, MIT
Stephen Graves, Professor, Management, MIT
Norman Rasmussen, Professor, Nuclear Engineering, MIT

Disclaimer

This thesis is being submitted as partial fulfillment of the requirements of MIT needed to obtain a Master of Science in Electrical Engineering and a Master of Science in Management.

The conclusions and opinions expressed in this thesis are those of the author and do not necessarily represent the position of MIT or General Motors, or any of its directors, officers, agents, or employes with respect to the matters discussed.

Acknowledgements

I gratefully acknowledge the support and resources made available to me through General Motors Corporation and the Leaders for Manufacturing Program, a partnership between MIT and major U.S. manufacturing companies.

I also wish to acknowledge Flint Automotive Division, and in particular John Wiley, for allowing me to do this research on the electric vehicle.

A special thanks to my advisors on this project: Al Drake who doesn't understand why I don't run General Motors; Steve Graves whose quiet support and gentle nudging was very much appreciated; Norm Rasmussen whose intelligence I can't begin to describe; Tom Donnan who was always encouraging; and Jon Bereisa, "Mr. Lithuanian idea man" who never let me rest because **HE** doesn't know how to. Thank you.

Thank you to all the engineers, technicians, managers, scientists, etc., who took the time to answer my never-ending and probing questions without losing patience.

I would like to thank my father, Roger Sr., and my brothers, Roger Jr. and Buford who still believe there isn't anything I can't do. I hope I never disappoint them.

I would like to thank my mother, Emily Shumaker, for being my safety net. If all else failed, she would be there.

Finally, and most importantly, I would also like to acknowledge my husband, Bruce Robert Denison, and my three sons to whom this thesis is dedicated; Shalako Lee, Chesleigh Robert, and Ashland Nathaniel, for their patience when I was impatient, their tolerance when I was intolerable, and their never-ending support and "I love you, mommy's" just when I needed it most. Thank you.

Table of Contents

List of Figures

Great as have been the engineering advances since 1920, we have today basically the same kind of machine that was created in the first twenty years of the industry.
--Alfred P. Sloan, Jr.
My Years with General Motors, 1963

1 Introduction

General Motors is on the brink of revolutionizing the automobile by building the "Impact", the first mass produced electric vehicle. While new technology is always exciting, it also presents many challenges. Engineering solutions involve new types of risk that may not be easily predictable or quantifiable. This study is an analysis of one new area of vehicular risk--the risk of electric shock. General Motors showed both the vision and the courage to conduct this study to assess the probable risk associated with their product (and take action to reduce that risk) because of a committment of excellence to the product and the customer.

Statement of the Problem

When a company sells a product for consumer use, it will always have some associated risk. In the early phases of product development, these risks are not known with complete certainty. However, there are useful ways to estimate them. The estimates are more accurate if the new product is similar to an existing product with existing data, and obviously less accurate, but still very useful, for a completely new product.

General Motors' electric vehicle, in total, is very similar to existing automobiles. However, the propulsion system is unique. In order to make correct decisions, GM must have the best possible estimate of the risks associated with this new propulsion system. In addition, GM needs to be aware of the marketing implications if an electrical accident should occur. Finally, GM must also consider the potential safety and product liability ramifications of such an accident.

As a new product, the electric vehicle will have new or different risks. In order to understand these risks, GM needs to answer the following questions: What are the risks? How significant are they? How do they compare to the product being replaced (internal combustion engined vehicles)? What is the most effective allocation of resources to reduce the risk? How do we stimulate designers and engineers to think in terms of further reducing risk? These issues surrounding electric shock need to be systematically analyzed and addressed.

Objective of the Investigation

The purpose of this investigation was to determine the dominant factors that contribute to the risk of unintentional electric shock on the electric vehicle. Aspects of this include estimating the risk of each individual factor, combining the individual risks to quantify the overall risk of the conditions analyzed, and establishing a baseline of comparison with conventional vehicles. The further objective was to suggest and help implement improvements to the electric propulsion system that would reduce product risk.

The strategy behind this investigation was to conduct the study in "real-time" with the Impact propulsion system design. By approaching the problem in this manner, the design could be analyzed and changed during the design cycle. This will lead to a safer product with respect to customers, vehicle assemblers, service technicians, and rescue personnel.

Scope and Limitations of the Investigation

The primary focus of this thesis is electric shock to humans due to the new hazard of "high voltage" on the electric vehicle. The thesis is not meant to be a completely exhaustive study of the risk associated with electric vehicles. Specifically, I address the potential danger of electric shock to (1.) the driver and occupant of the vehicle, during regular driving conditions and in the event of an accident; (2.) authorized service technicians, unauthorized mechanics and assembly plant workers and; (3.) rescuers or assisting personnel at the scene of an accident.

Manufacture of components (including the battery pack), shipment of components or vehicles, charging of the vehicle, recycling the vehicle, and deliberate or intentional abuse are outside the realm of this investigation. Additional risks I specifically will not address include: the possible accumulation and ignition of hydrogen gas, electrolyte leakage, electromagnetic fields, extra low frequency magnetic fields, and the mass effects of the battery pack in a collision. However, these issues are being addressed vigorously within General Motors.

During the design period, the electric vehicle is in a continual state of change. I therefore took a "snapshot in time" of the design and based this analysis on that configuration. I want to make clear, however, that this is <u>NOT</u> the final design. I took this "snapshot" in mid-September, 1991. Since then, there have been many design modifications to the vehicle and there will continue to be design changes up until the time when the vehicle is produced for sale to the public. The methodology and models developed during this analysis remain in use by GM to assess the effects of design changes.

A secondary focus was a vehicle accident investigation. This was limited to collisions that are of common types--front end, rear end, side impact, roll over and contact with a stationary object in one of the above ways. This accounts for nearly every imaginable vehicle accident, but there is always the possibility of one that has not been accounted for.

The total scope of the project, in diagram form, is summarized in figure 1. System level and component level hardware and interactions are simply illustrated. Corresponding hazards and the conditions under which they apply are shown as subsets. The areas outlined in bold were the primary subjects of this work. While the other areas were not of primary significance for this research, it was very important to have a complete understanding of the entire system to make effective recommendations.

Historical Background

The oil embargo and Gulf War[1] underline the fact that the United States needs to be less dependent on foreign oil. It has become clear that we cannot continue to consume fuel at our current level. There is, consequently, increasing pressure to find alternate forms of energy. Transportation accounts for nearly one third of our total annual energy consumption.[2] Therefore, one of the obvious, although difficult, potential solutions is to use alternate forms of energy to propel our personal transportation. Electric vehicles may be a partial solution to the energy consumption problem. Figure 2 compares the energy necessary to propel a typical internal combustion engined vehicle 1 mile and GM's electric vehicle prototype, the Impact, 1 mile.

[1]This refers to Operation Desert Storm, which was a military action to liberate Kuwait following the invasion and occupation by Iraq. This began in January 1991 and ended 100 days later.

[2]W.J.Ramsey, U.S. Energy Flow in 1976, Lawrence Livermore Laboratory, Rept. UCID--17443 (1977).

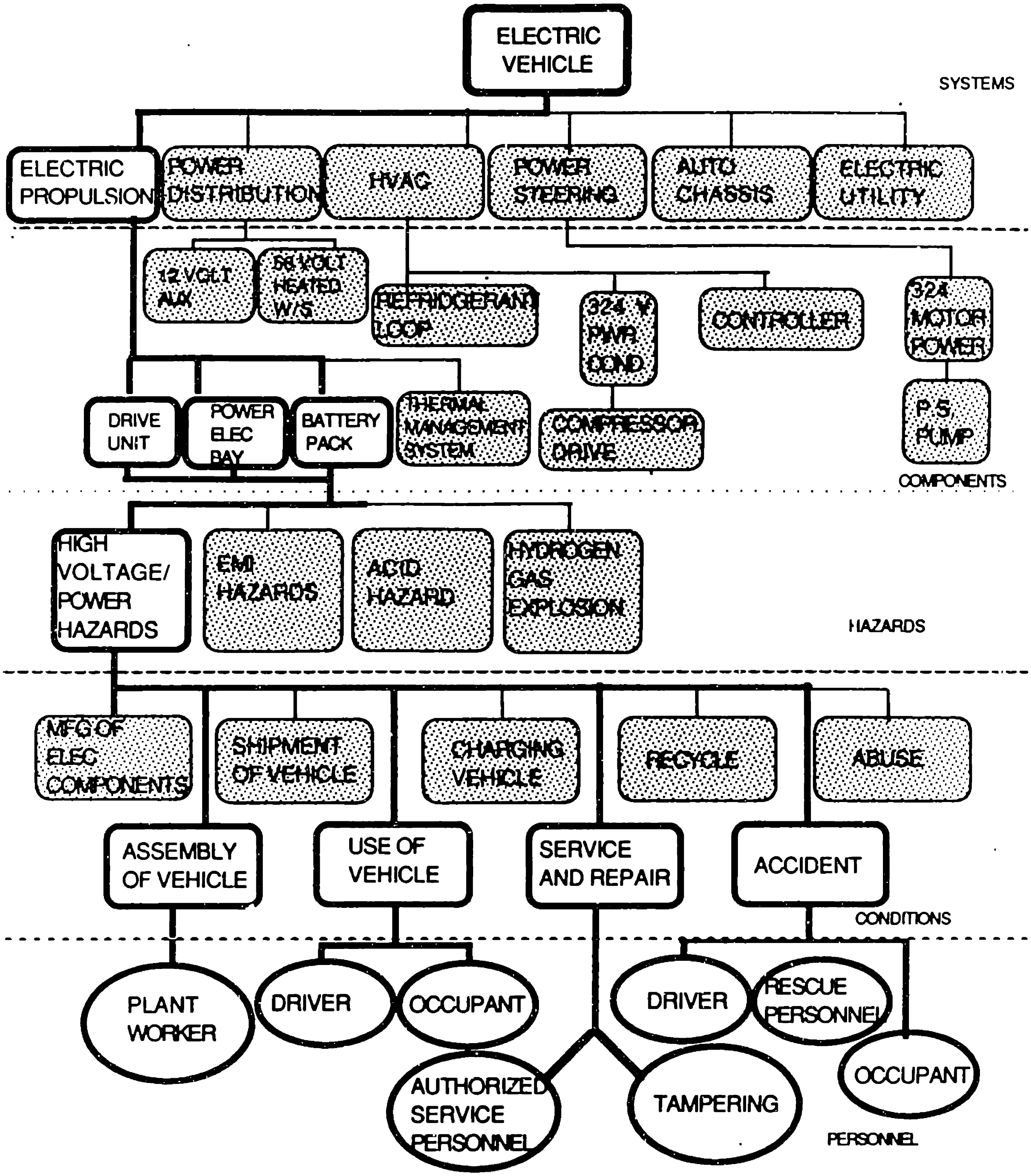


figure 1
Scope of the Project

Vehicle	Fuel Consumed for one mile	Heat (BTU) incl refining energy	HC* (g)	CO (g)	NOx (g)
Gasoline-typical 2850 lb, 27.5 mpg	0.036 gal	4600	0.1 to 0.3 typ.	3	0.35
Gasoline-super efficient 1700 lb, 65 mpg	0.015 gal	1940	0.1 to 0.3 typ	2	0.35
Impact EV/ nat. gas# 2300 lb, '77 mpg'**	not calculated	N/A	0.004	0.03	0.35 to 0.15
Impact EV/coal# 2300 lb, '77 mpg**	0.15 kWh (0.13 lb coal)	N/A	0.0015	0.017	0.53 to 0.15

** Fuel economy based on equivalent BTU content of gasoline

* Data shown does not include evaporative, refueling, and off-cycle emissions which would triple the data shown if not managed properly

This means that the fuel used at a power plant to generate the electricity would be either natural gas, or coal

figure 2

Environmental Impact of One Mile Travelled[3]

A second driver for electric vehicle development comes from environmental issues. Air quality, global warming and acid rain have become topics of increasing concern. Internal combustion engines have been blamed as contributors to the first two by increasing hydrocarbon, carbon monoxide and nitrogen oxide emissions. Figure 2 demonstrates the differences in regulated emissions between typical and super-efficient gasoline engines and the Impact, assuming the original energy source for electricity is from natural gas or coal.

---

[3] GM internal study on Electric Vehicles

The third major driver for development of an electric vehicle has been legislation. The State of California has mandated that 2% of all vehicles sold in that state will have zero emissions by the year 1998 and 10% by 2003. This essentially mandates electric vehicles as it is not possible with our present state of the art technology to meet the zero emissions criteria any other way. Other states including New York, the New England states and other states are considering similar legislation.

In response to these issues, most major automobile manufacturers, domestic and foreign, have announced their intent to manufacture an electric powered vehicle.[4]

Electric Vehicle Background

Electric vehicles were already commonplace when General Motors first began working on them in 1916 when electric motors, steam engines and internal combustion engines were all potential propulsion systems for automobiles. At first it appeared as though the electric vehicles would become dominant. In fact in the first American motor vehicle track races at Narragansett Park, R.I., in 1896, there were two electric vehicles entered and they claimed both first and second place.[5]

But by 1911, GM's C.F. "Boss" Kettering had developed the electric starter and internal combustion engines became commonplace. Interestingly, by 1916 most delivery trucks were electrics but by 1924, there was no longer an electric vehicle in the National Auto Show, and by 1938, electric vehicles were no longer produced once the Detroit Electric Company ceased production.[6] The electric echnology could not keep up.

---

[4]Washington Times February 14, 1992

[5]GM publicity literature

[6]Ibid.

Electric car research reappeared at GM in the 1960s with the Electrovaire I and II (see fig.3). These vehicles were based on the Chevrolet Corvair and used silver-zinc batteries (similar technology that powered U.S. intercontinental balistic missile system). However, the internal combustion engine was by then far more efficient and the performance, range and cost of these electrics was deemed unacceptable to consumers.

Electric Car Program	Year	Energy/Power System	Motor Technology	Vehicle Configuration	Motor Placement/ Drive Wheels	Conversion of Prod. Car?	0 to 30 Accel MPH	Range (miles)
Electrovan	1965	LOx/Hydrogen Fuel Cell	AC	3-Dr, 2-Place Van	Rear/Rear	Yes	15.0 sec.	125
Electrovair	1966	Silver-Zinc Batteries	AC	4-Dr, 5-Place Hardtop	Rear/Rear	Yes	8.10 sec.	50
AES 512 Electric Commuter	1969	Lead Acid Batteries	DC	2-Dr, 2-Place Commuter	Front/Rear	No	12.0 sec.	30
ElectroVette	1977	Nickel-Zinc Batteries	DC	2-Dr, 2-Place Hatchback	Front/Rear	Yes	7.8 sec.	60
GM Electric Car Project	1980	Nickel-Zinc Batteries	DC	2-Dr, 2-Place Hatchback	Front/Front	No	6.0 sec.	74
T-Car Test Mules	1980	Nickel-Zinc Batteries	DC	2-Dr, 2-Place Hatchback	Front/Rear	Yes	3.5 sec.	120
Impact	1989	Lead Acid Batteries	AC	2-Dr, 2-Place Coupe	Front/Front	No	3.5 sec.	120

figure 3
Brief History of Electric Vehicles at GM[7]

Also in the mid-sixties, GM along with Union Carbide developed the Electrovan, which used a modified hydrogen-oxygen fuel cell system. In this case, the size and cost proved impractical. Electric car development was also continued with the AES 512 electric commuter vehicles which were 2-seater micro-cars in three different versions:

---

[7]GM internal study on Electric Vehicles

one powered by lead-acid batteries, one was gasoline powered, and the third was an electric-gasoline hybrid. At that time, the American market was not ready for vehicles this small and therefore these cars were used only for engineering studies.

In the late 70s and early 80's as the repeated energy crises hit, it appeared as though an electric vehicle would finally make it to market. GM's Chevrolet division developed an electric vehicle based on the Chevette called the Electrovette. This led to a full scale development program at GM to produce an electric car by 1984. These were powered by longer life nickel-zinc batteries. These batteries were expensive. Also, there was insufficient free world reserves of battery grade nickel for volume production. So when the feared $2 or more/gallon gasoline prices did not materialize, the project was dropped for economic reasons.[8]

In 1979 AT&T was given the use of 35 lead-acid battery powered vans to test in the field. Then in 1983, GM again began producing electric vehicles with the Bedford CF Van. These vans were supplied to Vauxhall Motors Limited in the United Kingdom and then converted to electrics. This venture met with limited success.

Over the last 30 years, significant advancements have been made in power semiconductors, microcomputers, electric motors, and batteries as well as vehicle aerodynamics. As a result the performance and cost potential of electric vehicles drastically improved. In 1987 GM realized several technological breakthroughs with the solar electric powered Sunraycer[9] (see fig.4). The culmination of all of these studies

---

[8]GM publicity briefs

[9]The Sunraycer is a solar powered vehicle which was designed by GM to race in Australia. The vehicle finished in first place, more than two days ahead of the second place finisher while running on the power

became the Impact show car for 1990 (see fig.5). The Impact is the basis for GM's production intent vehicle.

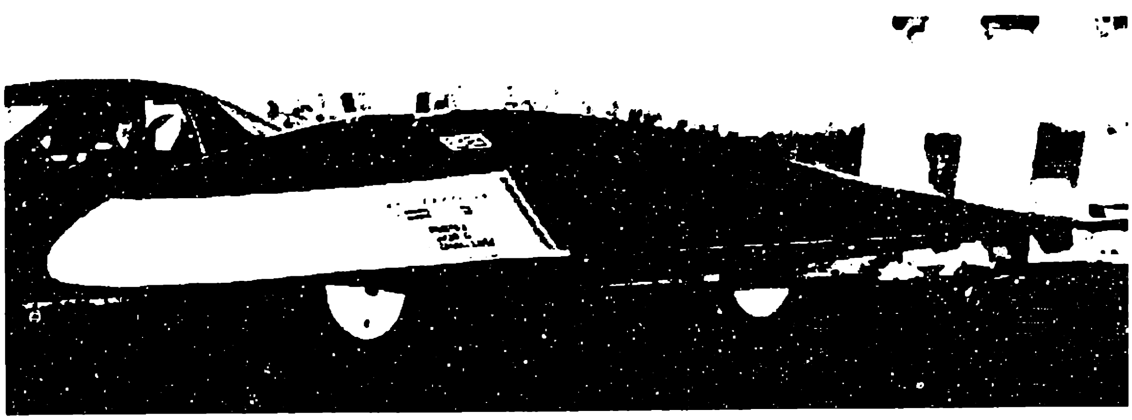


fig.4
Sunraycer

of a typical hair dryer of today. There were several new concepts and ideas that were tested on this vehicle.

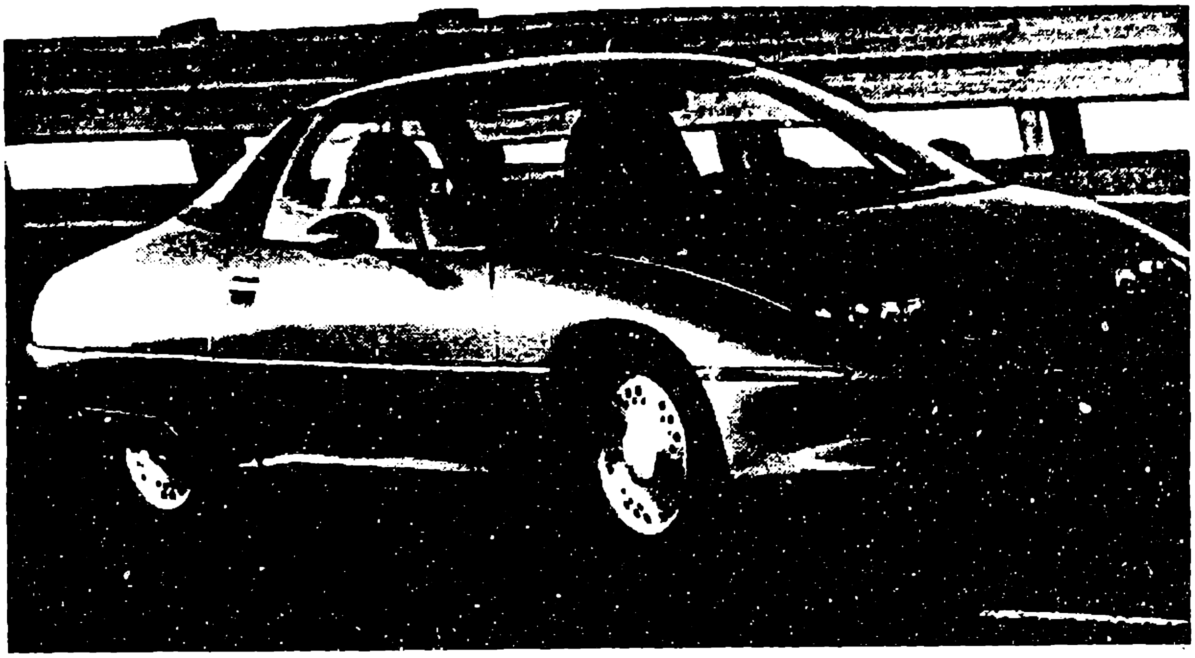


fig. 5
The Impact

Methods and Materials Used for the Investigation

Collection of Information

My investigation began with a series of literature searches. I collected information on batteries, electric vehicles, safety measures and standards, automobile accident statistics, electrical hazards, automotive testing techniques, marketing theory, medical treatment for electric shock, employe safety training, legal issues in automobile design, and risk analysis techniques.

Next, it was critical to completely familiarize myself with GM's new electric propulsion technology. I arranged discussions with managers, engineers, technicians, and assembly workers, and spent time as an understudy for key individuals. As my understanding developed, I participated in design reviews, problem solving, brainstorming sessions, and became an integral part of the day to day engineering operation.

With a firm understanding of the propulsion system, I began constructing the fault trees. I analyzed component relationships to deterimine how an incident of electric shock could occur. Next, the fault tree was analyzed quantitatively. Interviews were carefully planned and conducted to determine event failure probabilities. Once the fault tree results were determined, they served as a baseline for comparison against existing internal combustion engined vehicles.

Finally, it was necessary to complete my investigation not just with the probability of system failure, but with the implications of an occurance of electric shock. I concluded my research by interviewing experts and investigating existing pertinent data in the fields of marketing and product liability. I present an overview of these topics in the final chapter of the thesis.

Fault Tree Analysis

I utilized fault tree analysis as the engineering tool to determine the risk of defined system failure from the failure estimates of the system components. Fault tree analysis is recognized as a valid predictive tool in determining system risks for new applications with very low expected failure probabilities.

The Nuclear Regulatory Commision makes extensive use of fault trees to determine the safety of nuclear reactors. In my investigation I made use of both the fault tree handbook[10] and the software package[11] developed by this agency. This technique is also used by many organizations outside the nuclear energy area, including: the aerospace industry, national laboratories, contractors, utilities, architectural engineering firms, consultants, universities, and many government agencies[12]. In addition, fault tree analysis is used in various locations throughout General Motors. The inflatable restraint systems and new anti-lock brake systems are two recent examples.

---

[10] H.R.Roberts, W.E.Vesley, D.F.Haast, and F.F.Goldberg, Fault Tree Handbook, U.S.Nuclear Regulatory Commission, NUREG-0492, 1981.

[11] The software package used was Integrated Reliability and Risk Analysis System (IRRAS) Version 2.5, NUREG/CR-5300, Vol.1, March 1991..

[12] IRRAS users Group Bulletin

2 Executive Summary

This section is an overview of the study, methodology, and tools, results of analysis, conclusions, and recommendations based on those conclusions. The following pertain to the GM Impact electric vehicle design as of September 1991.

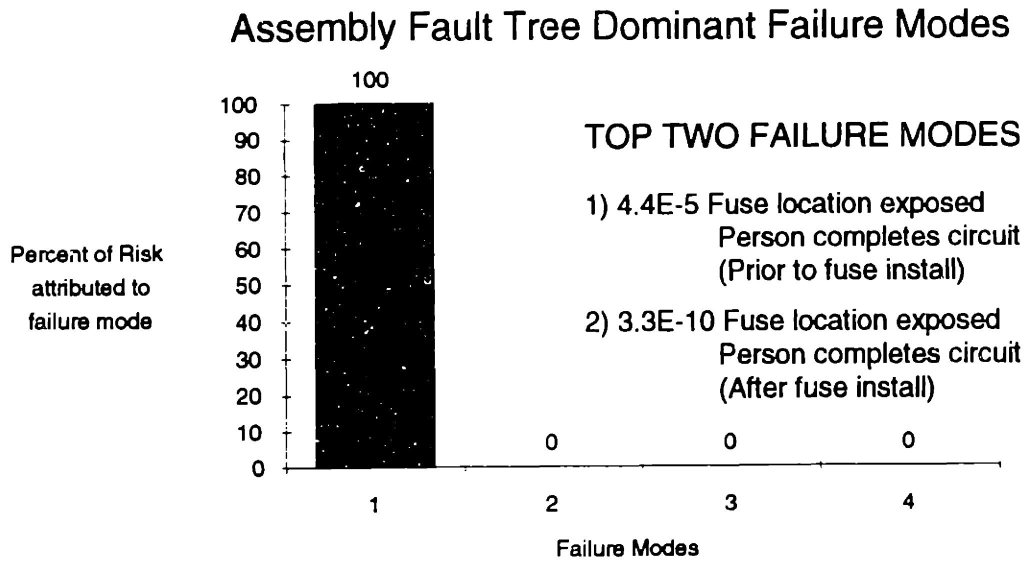
Analysis

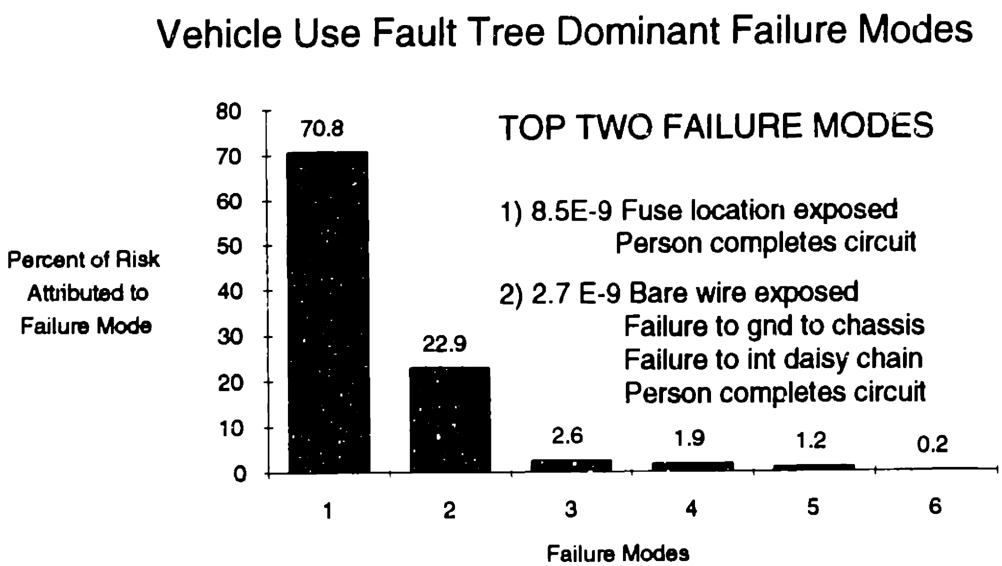
Fault trees were developed and analyzed quantitatively to determine the risk of electric shock due to "high voltage" on GM's electric vehicle. The analysis was done during the design phase and interaction with design engineers, technicians, and managers was on a daily basis and spanned a period of 6 months. The results presented are based on the September 1991 design. These results do not necessarily reflect the final electric vehicle that will be sold to consumers. The Nuclear Regulatory Commission Fault Tree Handbook and software developed by the U.S. government, called IRRAS was used for analysis.

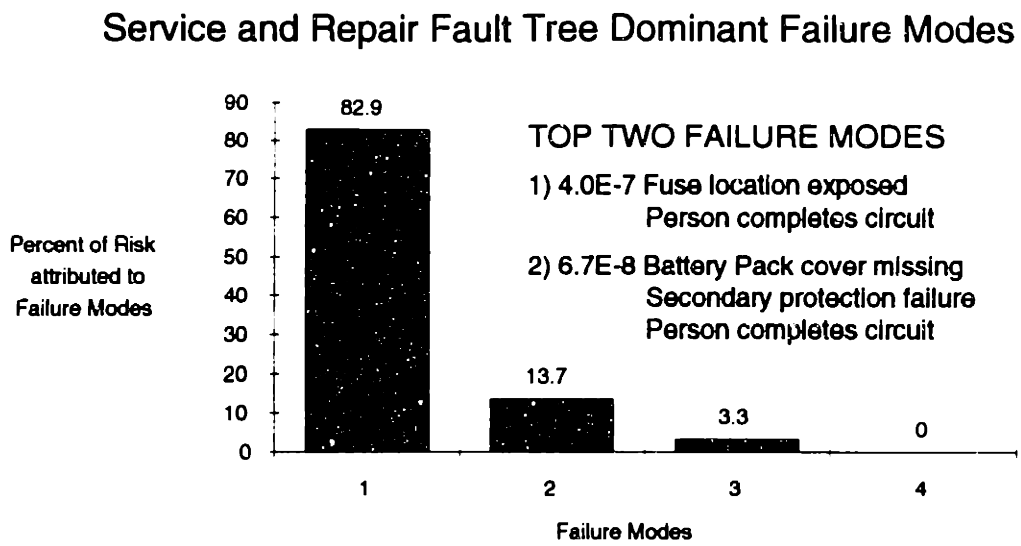
Four fault trees were developed: during vehicle assembly, during service and repair, while in use, and in the event of an accident. Any occurrence of electric shock, regardless of severity, was defined as an undesired event to be minimized. Potential liability and marketing ramifications were also researched and analyzed.

Results

Figure 6 shows the results of the four fault trees analyzed. For instance, as can be seen from the bar chart entitled "During Assembly", the dominant failure mode during the assembly of the vehicle is that the fuse location becomes exposed, for example, when the fuse is removed, and someone completes the circuit prior to the installation of the fuse system. This has an associated probability of 4.4×10^{-5} per vehicle for the life of the vehicle, which accounts for nearly all of the risk in this situation, as the next failure mode is several orders of magnitude less likely to occur. Note that this same failure mode is also the dominant failure mode for all of the other fault trees.







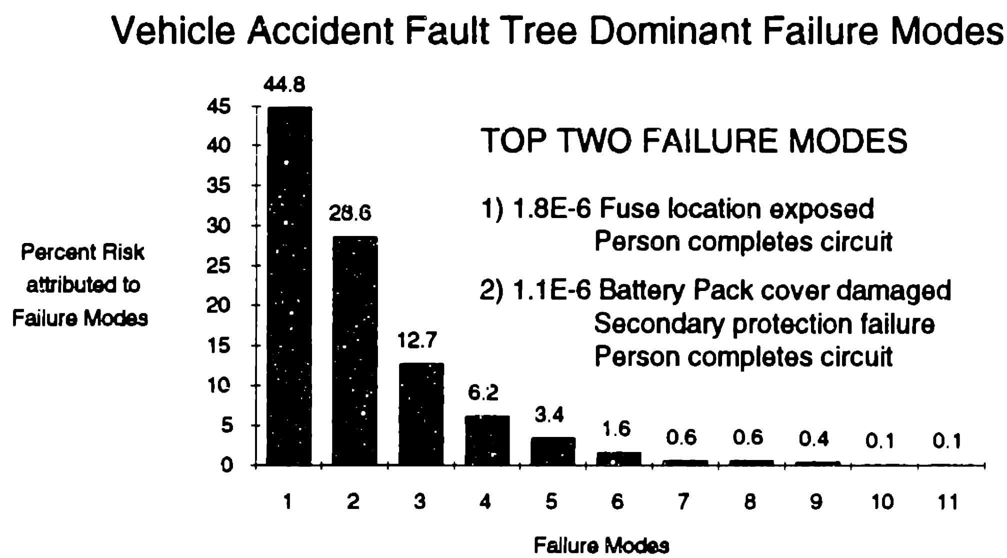


figure 6

Major Failure Modes of Four Fault Trees

Several additional results were obtained during the course of this study.

1. The numerical results of the fault trees show that:

   a. Human error is the single largest contributor to risk in all cases (see Appendix C).

   b. The fuse location is the most likely point for a person to contact high voltage in all four fault trees.

   c. A very small number of failure events dominate the risk. (In all four fault trees, less than four failure modes account for more than 90% of the risk).

   d. The risk of electric shock due to the existence of an electric propulsion system is very small for the situations analyzed. For example, the risk of any electric shock (mild tingle or fatal jolt) occuring in the event of a vehicle accident is expected to be approximately 10,000 times less likely than death due to fire in a fatal internal combustion engined vehicle accident.

2. The fault tree analysis identified:

   a. Where we should focus attention to significantly reduce the risk of electric shock--the design of the fuse and location.

   b. Areas that we do not need to expend resources to improve as they would not significantly effect the risk of electric shock even if it were possible to make them perfect.

3. The risk due to the propulsion system, whether electric or conventional, is a very small fraction of the total vehicle risk. Total risk includes the risk of driving the vehicle in traffic (risk of vehicle accidents).

Conclusions

1. Safety and low cost are not necessarily mutually exclusive and can be achieved simultaneously through rigorous and good design.

2. Fault tree analysis is very effective when used:

a. On systems (as opposed to components) and particularly new systems (as opposed to existing systems with frozen designs and existing data) where there is no available reliability data.

b. During the design phase as it will have the largest and earliest beneficial effect.

3. Perceptions of risk, marketing strategies and product liability issues all need to be considered in addition to the pure numeric results of the fault tree analysis to determine what combined level of numeric and perceived risk is "acceptable".
4. Most people do not view batteries as potentially dangerous, regardless of the voltage. Typically they are viewed in the context of other familiar batteries (12 volt storage batteries, flashlight batteries, etc.). But in the case of electric vehicles, lethal voltages may possibly be encountered and design precautions are therefore particularly necessary.
5. Both manual and automatic disconnect systems are necessary. The need for an automatic disconnect is driven by human error and the need to disconnect in the event of an accident.

Recommendations

These recommendations suggest additional ways to possibly reduce the affect of human error on the risk of electric shock. Some of these recommendations are currently being implemented by GM, others are under investigation. This list is not meant to be exhaustive. The final implementation decisions should be made by incorporating the results of several different analyses.

These recommendations are made with regard to the electrical safety only and are based on the above conclusions:

1. Vehicle assembly operations within the motor compartment, or pertaining to the propulsion system, should be done prior to the fuse/manual disconnect installation in the vehicle.
2. After the fuse/manual disconnect is installed, operations in the motor compartment or pertaining to the propulsion system should be one handed where practical. Considering that this is not very practical much of the time, the design should be safe even when two hands are used.
3. Train assembly operators, service personnel and rescue workers to increase awareness of the risk of electric shock.
4. Run publicity campaign to increase public awareness of the danger in tampering with electric vehicles.
5. Isolate and control access to the area within the production facility where the battery pack itself will be assembled or repaired.
6. Improve the design of the fuse/manual disconnect location to further protect against inadvertent access to high voltage.
7. Color code or otherwise identify all components carrying 324 volts.
8. Appropriate labels and warnings should be added to all 324 volt components.
9. Design automatic safety mechanisms such that it is very difficult to short cut or by-pass procedures without deliberate alteration.
10. Incorporate into crash tests a validation of safety specific components and systems with more than normal emphasis on the fuse location.
11. Use fault tree analysis to assess risks of other critical systems such as the regenerative braking system or the assembly and service of the battery pack as an individual component.

12. Review procedures to assure that recommended actions given by the Consumer Products Safety Commission, listed in chapter 7, have been followed to reduce the likelihood of product liability litigation.
13. Update the fault tree analysis as product field experience provides further information to more accurately assess probabilities of event failures.

Thesis Organization

This thesis is comprised of seven chapters. The first chapter is an introduction of the work. The second is an executive summary of the results, conclusions, recommendations, and organization of the thesis.

Chapter three describes certain important aspects of the design of the electric vehicle propulsion system at the time of this analysis. The discussion is limited to the unique or new features of the propulsion system that were relevant to the risk analysis. Specifically, it includes the fuse/manual disconnect, wiring daisy chain, and ground fault detection systems and the protection they afford, as well as a brief description of the propulsion system and major components.

Chapter four is a general discussion of risk analysis techniques. Electric shock and factors that effect its consequences are explained. Chapter five describes the fault tree analysis technique. This section explains step by step how a fault tree is constructed and evaluated, how the probabilities are assessed, what applications are most appropriate for fault tree analysis.

Chapter six contains the actual fault trees that were constructed, the results of the analysis, and the conclusions and recommendations that can be drawn directly from the fault trees.

Chapter seven is a discussion of how to determine an "acceptable" level of risk. Some of the risks associated with internal combustion engine vehicles are presented as a frame of reference to compare against the results of the fault trees. The level of risk due to the electric propulsion system is put into the context of total vehicle risk. The argument is developed that the electric vehicle needs to be safer than existing vehicles due to perceptions of risk and the negative marketing effect that an incident of electric shock could have on vehicle sales. Finally, a general discussion of product liability issues, which includes a list of recommendations from the Consumer Products Safety Commission to avoid product liability litigation, is included.

"An automobile is a machine with four wheels, a motor, and not quite enough seats, which enables people to get about with great rapidity and ease to places they never bothered going before and where they'd just as soon not be now, because now that they're there, there is no place to park."

Elinor Goulding Smith

3 Electric Vehicle System

This chapter includes a description of certain unique characteristics of the electric vehicle propulsion system. Particular attention is given to the fuse system and protective circuitry, the battery pack, and the drive motors.

The electric vehicle design was analyzed as of mid-September, 1991. This document does not include changes since that time. Again, I want to emphasize that this is NOT the final design. Also, I would like to stress that this analysis was interactive and not isolated from the design process. Design changes have been made to improve the safety of the vehicle, at least in part because of the findings of this study. It would be desirable to update the analysis throughout the design process. General Motors has committed to do that for the remainder of the electric vehicle design process.

Current Design

The September 92 design has 27 12-volt batteries connected in series to produce a total potential of 324 volts. After the series connection is made, each individual battery terminal is covered with a wax coating to isolate the potential from touch and water. The batteries are placed in a battery tray and then enclosed on three sides by a plastic cover fastened to the tray. The entire pack consisting of the batteries, tray, cover, and cooling mechanism is contained within a tunnel structure in the car. Figure 7 shows a battery pack being lifted into place in the Impact. The battery pack is by far the largest component of the vehicle both by volume and weight (the pack weighs over 800 pounds).

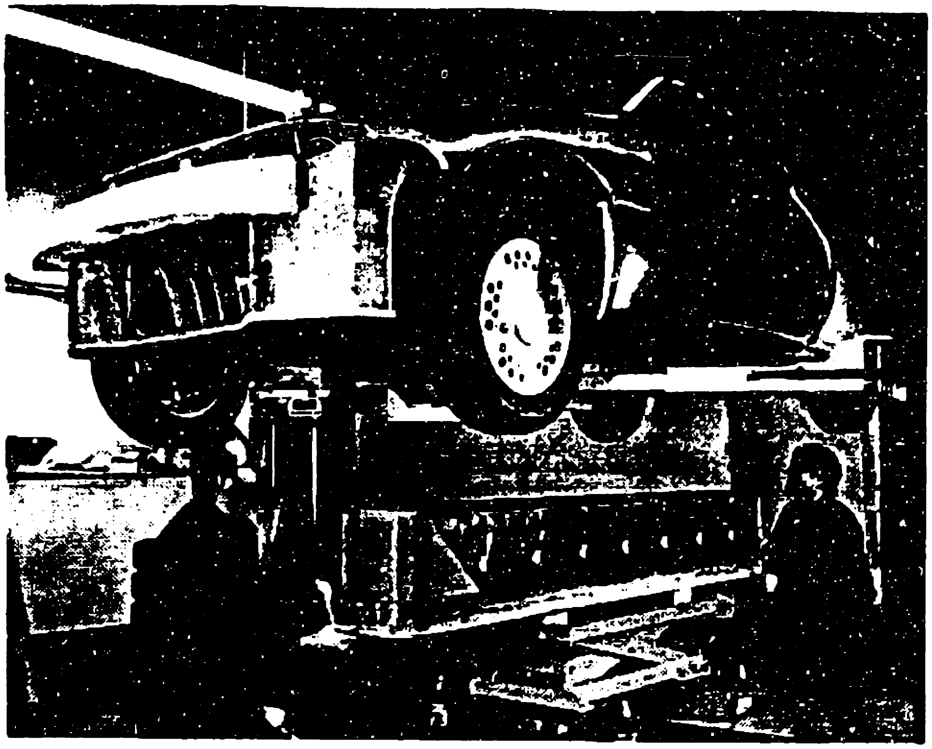


figure 7
Installation of the Battery Pack

The 324 volt output terminal connects to a fuse system which is an integral part of the battery pack. From there, the battery cables, which are inert until the fuse is installed, are connected to the power electronics bay (PEB). Most of the electronics for the drive unit and propulsion system are contained within the PEB. The DC voltage from the battery pack is converted to AC to power the drive motors. Also, recharging of the batteries is done through the PEB. During charging, current flows from the charge port to the charge interface unit (CIU) and into the PEB and finally back to the batteries. The direct current also exits the battery pack to the HVAC (heating ventilation and air conditioning) controller and power steering (see fig. 8). At the time of this analysis, there were no other areas on the car where 324 volts was used. Every other electronic

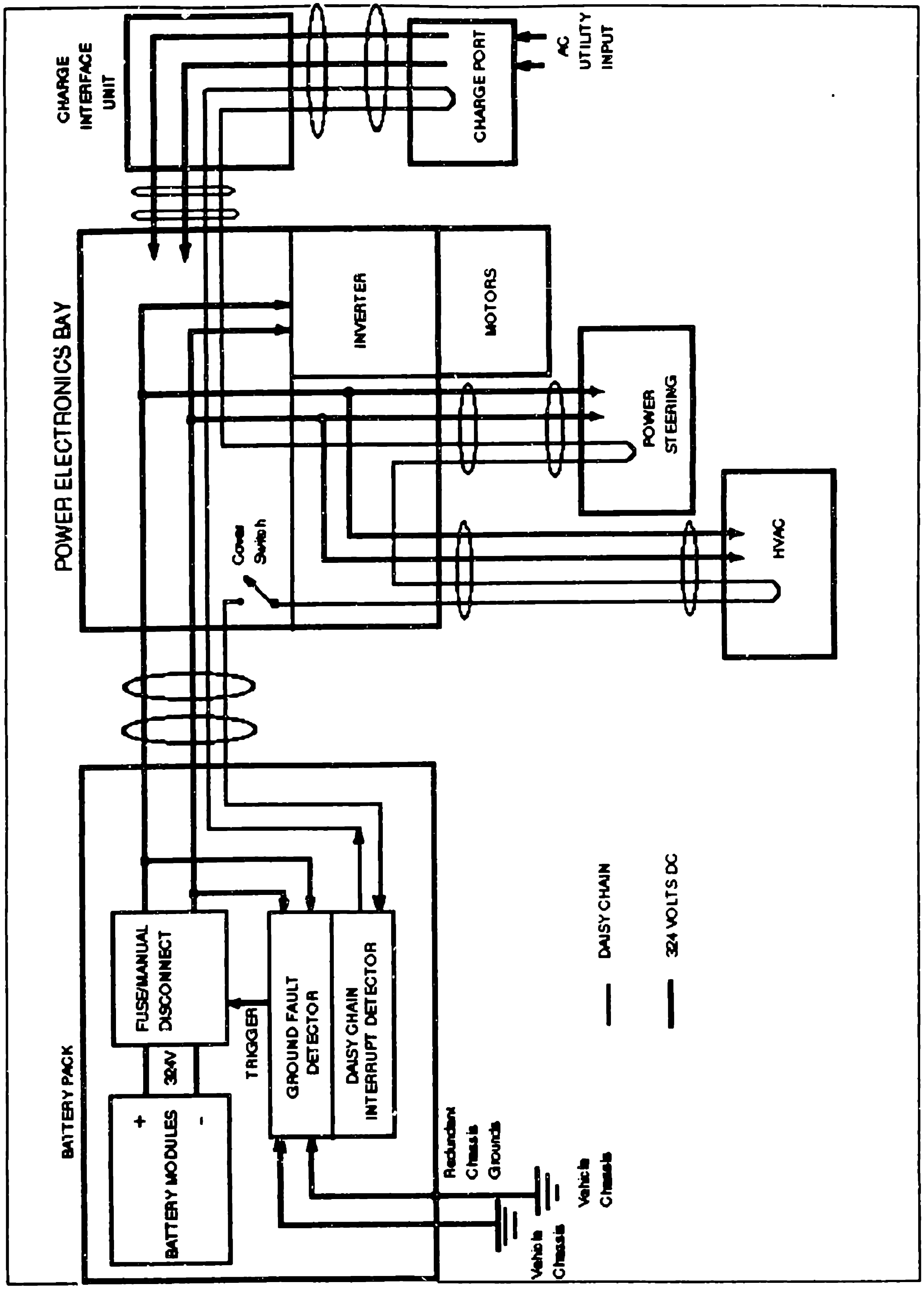


figure 8
324 Volt Availability

device uses 12 volts with the exception of the heated windshielu which uses a potential of 74 volts. For safety reasons, the entire 324 volt system is isolated from ground. This means that you can touch the 324 volt circuit at any one point and any ground safely.

Fuse System

The fuse system and protective circuitry are similar to the ground fault interrupter circuit breaker in many homes. It is a "crowbar" fuse directly across the terminals of the battery pack. There are two conditions which will trigger the fuse to clear: loss of isolation from chassis, and interruption of a "daisy chain" loop. When the fuse is triggered, the system will intentionally short (C_p) and the fuses will blow (see fig. 9). The intentional short causes the voltage available at the battery connector, V_{bp}, to reduce to practically zero in approximately 10 microseconds. The fuse then can take longer to actually clear without the continued risk of electric shock. This is important because the normal operating current can be as high as 450 amps and the maximum short circuit current is only 1000 amps. This approximately 2:1 ratio of short circuit current to operating current necessitates the intentional short. The longer the fuse will take to clear[13].

Loss of Isolation to Chassis

The fuse will be blown any time the system detects loss of isolation to chassis from either side of the battery pack (the threshold resistance value for detection is currently set at 5 megaohms). For example, if for some reason, the insulation is removed from one of the wires and that bare wire touches any metal connected to chassis, the fuse will be triggered.

[13]It is possible with dc circuits of this type to get a sustainable arc, even after a fuse is blown. Therefore, in order to interrupt the circuit, or "clear" the fuse, a mechanism will need to be included within the fuse system to eliminate any potential arcing..

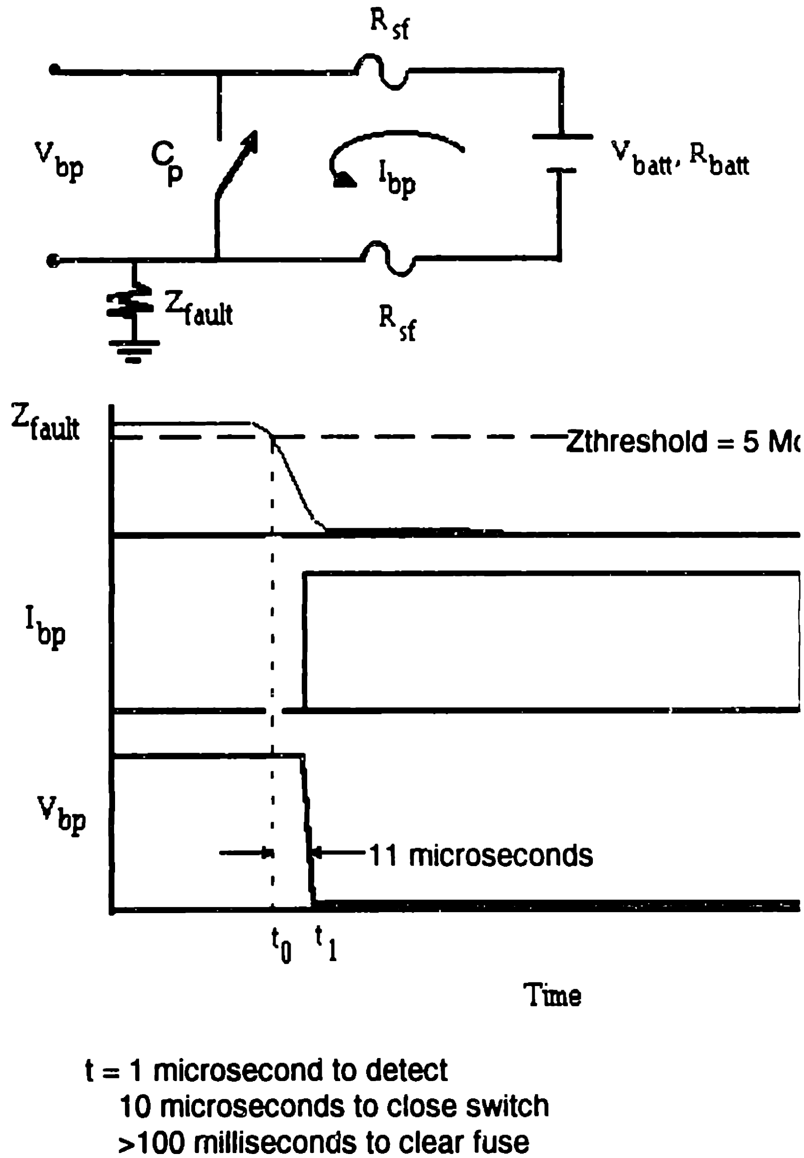


figure 9
Fuse System and Response Times

Daisy Chain

In addition to the loss of isolation detection, the fuse will be triggered if the integrity of the wiring or any of the connections is disrupted. There is a closed loop from the battery pack to each 324 volt component and back to the battery pack. If for any reason this circuit becomes discontinuous (for example, a wire is cut) while the fuse system is in place, the fuse will be cleared. To maintain this safety feature, for the case of removeable "box covers", each such cover has a switch built in series with the daisy chain wiring. If the covers are removed while the fuse is installed, the daisy chain will be interrupted which will signal the fuse to blow.

The daisy chain wires run within wiring harness bundles that contain the 324 volt wires to increase the chance that if a 324 volt wire gets damaged or severed, the "daisy chain" will also be severed, causing interruption of the circuit and clearing of the fuse. The main purpose for this safety mechanism is to protect users and service personnel. In the event that someone tries to service a 324 volt component without first pulling the fuse, this system will "pull the fuse" for them. An additional advantage is in the case of an accident which severs or pulls apart those harnesses, the fuse system will clear.

Batteries

General Motor's electric vehicle propulsion system is based on lead acid battery electro-chemistry technology. However, the design of this battery is not the type battery that is typically found in conventional internal combustion engined vehicles. While several "advanced technology" batteries show a great deal of promise for the future of electric vehicles, the only technology that appears feasible in the short-term is lead-acid. The cost advantage and experience base make this battery technology the logical choice for start up.

A battery stores chemical energy, then when called upon, converts that chemical energy into electrical energy. A single battery is made up of several cells connected in series. Each cell accounts for approximately 2 volts. The more cells in a battery, the higher the voltage if connected in series.

The active ingredients in each cell include positive and negative electrodes immersed in an electrolyte of sulfuric acid. Current is produced when the active materials of the plates--lead dioxide (PbO_2) in the positive plate and lead (Pb) in the negative plate--chemically react with the sulfuric acid in the electrolyte to produce lead sulfate and water. Because the lead, lead sulfate, and lead dioxide are relatively insoluble in sulfuric acid and therefore remain solid, the reaction can be reversed and the battery recharged to its initial state.

There are two problems with the lead-acid battery technology. First, it is difficult to attain the range necessary for a commercially viable electric vehicle with lead acid batteries. It takes several batteries to come close to the desired range. This becomes a "catch 22": it takes more batteries to extend the range, but additional batteries add mass to the car which decreases range. Second, lead-acid batteries are not capable of withstanding thousands of deep-discharge cycles without severe degradation of the plates.

The battery pack consists of 27 12-volt batteries, connected in series, which were developed specifically for the GM electric vehicle. These batteries are valve regulated, recombinant design with no free electrolyte, are completely sealed for life, and never require water. The batteries are stacked two high by two wide and when assembled, the pack weighs over eight hundred pounds. Due to the proprietary nature of GM's electric vehicle battery technology at the time of this writing, it is not possible to disclose the specifics of this particular battery, except to say that the battery performance is exceptional for lead-acid technology.

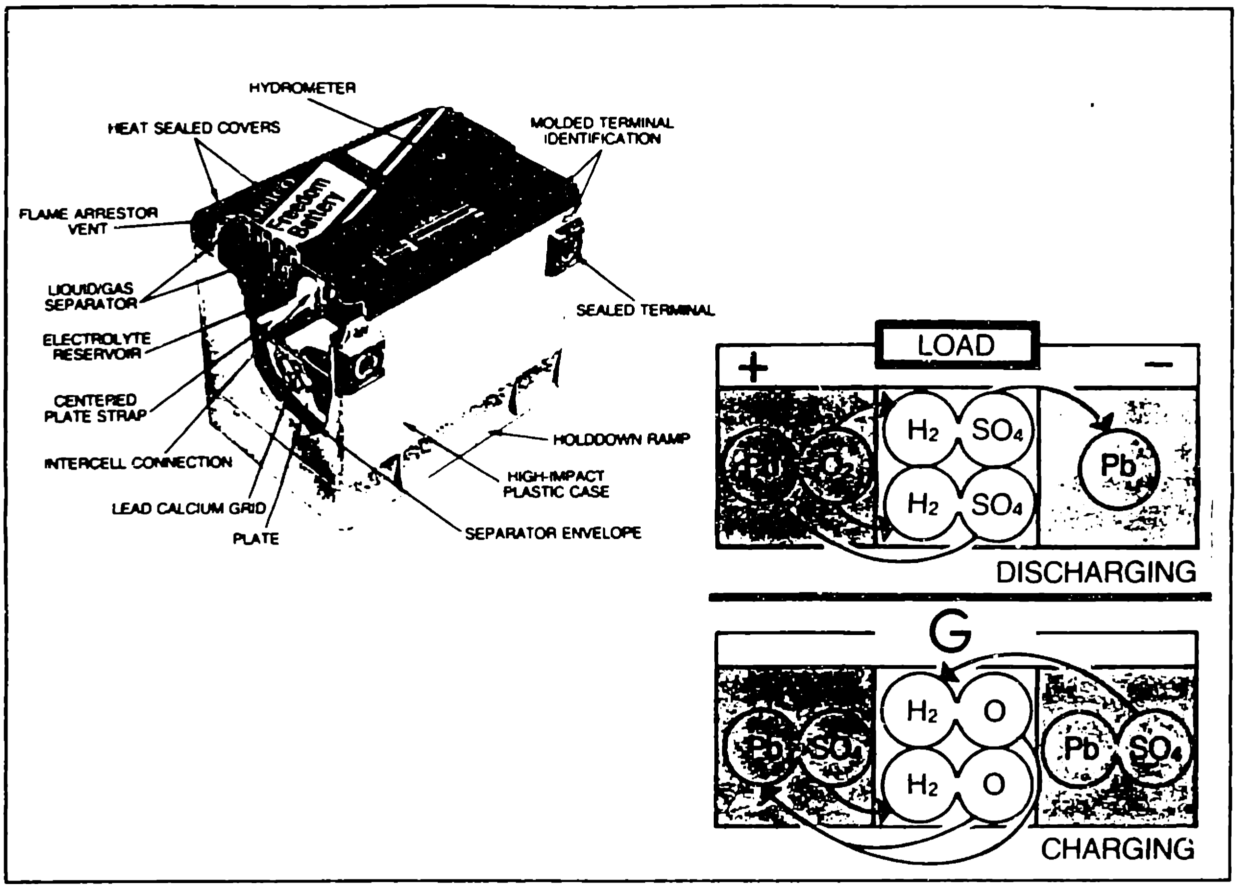


fig. 10

$$Pb + PbO_2 + 2H_2SO_4 = 2PbSO_4 + 2H_2O$$

Battery Chemical Reaction[14]

Drive Motors

The prototype Impact uses two ac induction motors. There is one motor at each front wheel. These motors operate at efficiencies of 90-95% over most operating speeds and torques.[15] The Impact has a governor-limited top speed of 75 miles per hour. At that speed, the motors turn at 11,900 RPM.

---

[14] "Freedom Batteries", Training Chart Manual, section F, Delco Remy, division of General Motors, Anderson Indiana, 4-79, pp.5,6.

[15] GM publicity briefs

This vehicle also takes advantage of regenerative braking. Every time the vehicle slows down, some energy is recaptured and used to recharge the batteries or help supply power to other systems that may be in use, such as the HVAC system.

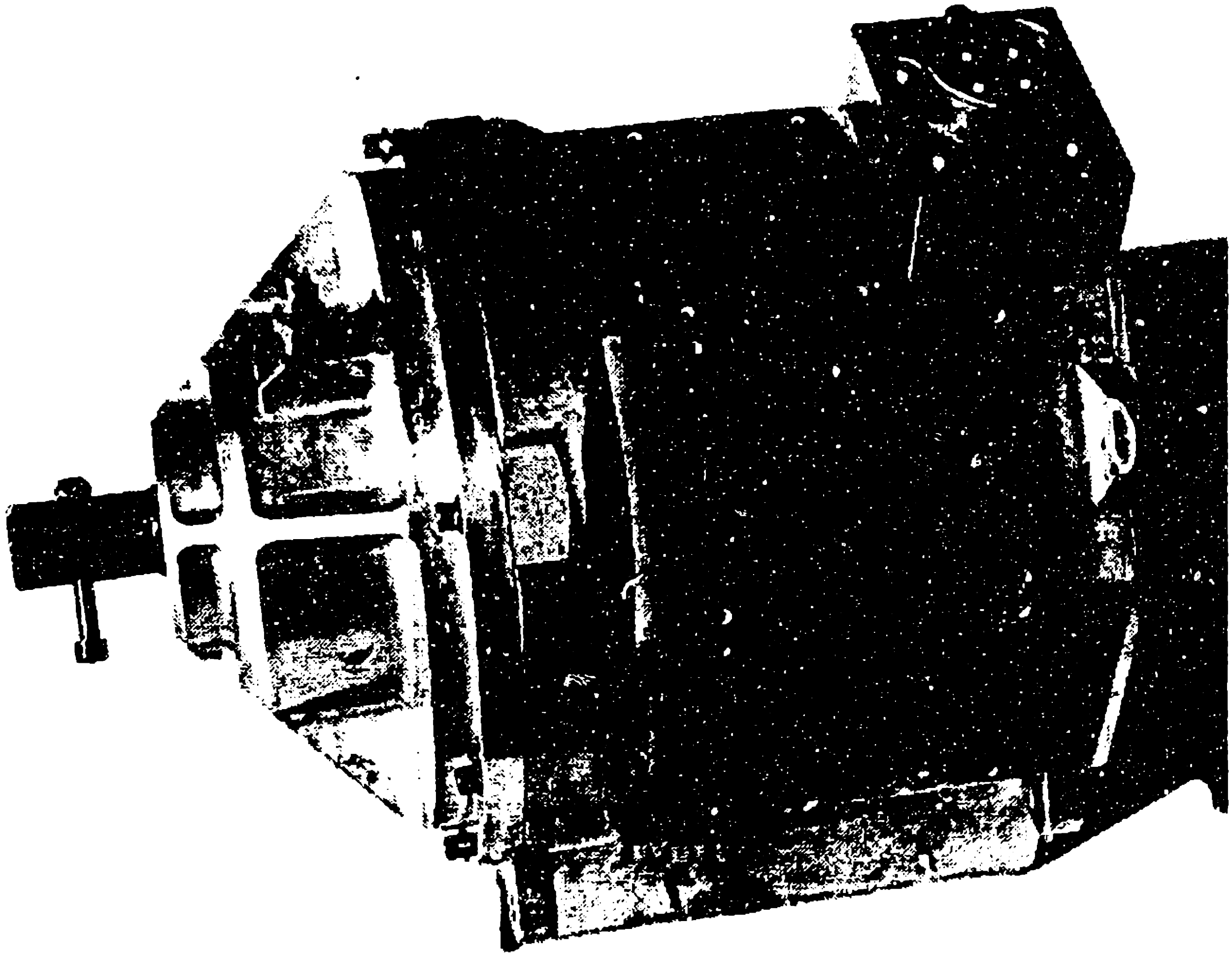


figure 11
Drive Motor

"The desire for a risk-free society is one of the most debilitating influences in America today, enfeebling the economy with a mass of safety regulations and a fear of liability rulings..."
Henry Fairlie
Readers Digest Oct.1991

4 Risk Analysis

This chapter includes a description of electric shock and the factors that effect the consequences of electric shock, other new hazards that may be present with the electric vehicle, and other risk techniques that might have been used to estimate the risk of electric shock.

Electric Shock

Electric Shock occurs when a person comes into contact with electricity at two different potentials, completing a circuit and providing a path for the current to flow (see fig. 12). The current will enter the body at one point and exit at another. The path of the current through the body is one of the critical factors in determining the consequences of the shock.

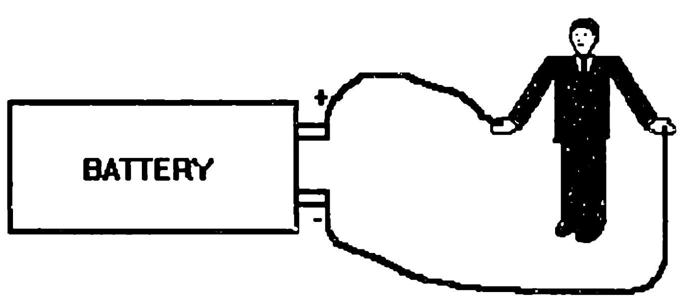


Figure 12
Electric Shock

Because of the "floating ground" on the electric vehicle, it is only possible to incur electric shock if both a positive and a negative conductor are touched. If only one wire is touched while the person is grounded, that point of contact will go to ground. Therefore, there will be no voltage drop across the body and no electric shock.

The consequences of electric shock vary greatly. The result may be as mild as a warm tingling or as severe as death (there are approximately 700 people electrocuted in the United States each year). The exact consequences are difficult to predict because they are dependent upon many factors, including:

1. **Current Path**. If the current passes though the chest cavity, the chances of fatality are much higher than for any other path.

2. **Voltage**. The larger the voltage, the higher the current will be given the same resistance. Usually, a larger current results in a more severe injury. Although it is impossible to determine when a voltage becomes dangerous, Underwriters Laboratory uses 42.4 volts as the threshold.

3. **Shock Duration**. The longer a person is part of the circuit, the more likely it is that the injury will be severe. Particularly in the cases of burns, it is important to minimize the time a person is exposed to shock.

4. **Current Type**. Alternating current is much more dangerous for the heart than direct current. Also, with alternating current, the chance of becoming "frozen" to the circuit is much greater. Strong muscular contractions make it impossible for a person to voluntarily release or "let-go" of the circuit. With direct current, there is a singular muscle contraction at the "make point",

when a person becomes a part of the circuit, and a singular contraction at the "break point", when the person becomes free from the circuit . These strong muscular contractions are often severe enough that the person appears to be thrown from the circuit. There have been documented cases where the contraction itself, not the fall, resulted in dislocations and broken bones.[16]

5. **Impedance**. The higher the impedance, the lower the current will be given the same voltage. This is a function of the area of surface contact and current density.

6. **Skin Dehydration.** If the skin is dry, such as when calluses are built up, the contact point is not very good and the shock tends to be less severe.

Other Hazards

In addition to shock, there are other new hazards potentially present due to the battery technology. Fires, possible illness due to electromagnetic fields, leakage of hydrogen or electrolyte, and the mass of the battery back in a collision are all concerns. These issues are being considered and addressed for the total vehicle, however, they fall outside the realm of this study.

Risk Analysis Techniques

There are techniques, other than fault tree analysis, that can be used to analyze the safety or reliability of a system. In many systems, there are inductive methods which

---

[16]Dean T. Stueland, Peter Stamas Jr., Timothy M. Welter, and David A. Cleveland, "Bilateral Humeral Fractures from Electrically induced Muscular Spasm," The Journal of Emergency Medicine, vol.7, January, 1989, 457-459.

provide a logical and scientific approach and serve to identify critical safety conditions without the refinements of fault tree analysis. Some of these methods include:

Parts Count Approach

The parts count approach is a "quick and dirty" technique that will result in a very conservative estimate of the actual risk of the system. The primary assumption with this approach is that if one component fails, the entire system will fail. This is done by making a list of all the components within a system and their associated probability of failure, then adding up all the failure probabilities to get an upper bound for the chance of system failure. This would be done as follows:

COMPONENT	FAILURE PROBABILITY
A	f(A)
B	f(B)
C	f(C)
.	.
.	.

Probability of System Failure = f(A) + f(B) + f(C) + . . .

This result is typically several orders of magnitude too high, particularly if there are redundancies in the system where two or more components have to fail in order for the system to fail. The parts count method can be useful in determining if a system is safe. That is, if this is used and the result is acceptable, than it would not be necessary to use any other method, because the risk would also be acceptable with any more refined method that may be used.

Failure Mode and Effects Analysis

Failure Mode and Effects Analysis (FMEA) is a slightly more detailed approach than the parts count method. A table or chart with five columns is usually employed. They are:

1. Component name or number
2. Failure probability associated with that component
3. The different ways that the component fails
4. Percent of failures attributable to each way the component fails
5. What effect that type of failure will have on the system. This is usually classified into critical or non-critical, but there can be any number of classifications.

1	2	3	4	5
Component	Failure Probability	Failure Mode	% Failures by Mode	Effects Crit. Non-Crit
A	1E-4	Open	90	x
		Short	10	x
				1E-5
B	1E-4	Open	90	
		Short	10	x
				x
				1E-5

figure 13
FMEA Table

In order to obtain the numbers in the critical column, you simply multiply the percent in column four by the appropriate probability in column 2. Once the table is complete, the probability of system failure is estimated by adding up the probabilities in the critical column. This is generally a more accurate approximation than the parts count method. The results of these two methods can vary by a large amount, particularly if the critical failures are a small percentage of the component failures. The main goal of failure mode and effects analysis is to identify single failure modes and to quantify them.

Failure Mode Effect and Criticality Analysis (FMECA)

FMECA is similar to FMEA in that attention is focused on the criticality of the failure. In addition to identifying the fault and the potential effects of the fault. The action to correct or contain the problem is also stated as well as the summary of findings. This analysis frequently uses a chart similar to FMEA with four columns: Column 1 would identify the potential hazard, the second column explains why this is a problem, column three explains what will be done to correct the problem, and column four is used to say whether the situation is resolved, or it needs further action for resolution.

Preliminary Hazard Analysis (PHA)

The preliminary hazard analysis method focuses on system failures which are potentially threatening to humans. The idea is to identify conditions that may be hazardous to humans, and to determine the seriousness of accidents which may result. Similar to fault tree analysis, preliminary hazard analysis should be conducted early in the design phase of a project so that if a redesign is necessary, it is still relatively simple and inexpensive.

The first step in a PHA is to identify all potential hazards within a system. Next, any events which could turn those hazardous conditions into an accident are identified. Finally, the nature of the resulting accident is determined and the measures to be taken are developed. Preliminary hazard analysis is usually done with a simple chart and a column for each stage.

Fault Hazard Analysis

Fault Hazard Analysis is useful for detecting faults that cross organizational boundaries. It is common to use a chart with columns, the first five of which are identical to FMEA. The rest are as follows:

6. Identification of upstream component that could initiate the fault
7. Factors that may cause secondary failures.
8. Remarks

Double Failure Matrix (DFM)

With Double Failure Matrix analysis, faults are put into one of four categories:

1. Negligible--loss of function has no effect on system
2. Marginal--fault will degrade the system, but will not cause system failure
3. Critical--this type of fault will seriously degrade the system, such as failure of a safety system
4. Catastrophic--this fault will produce severe consequences

The exact categorization will depend on the existing conditions. In conducting DFM analysis, different designs are considered and the number of ways each type of failure can occur for each design is determined. The results are then compared, and the design that has the fewest ways of having catastrophic or critical failures is chosen. Due to the nature of the analysis, DFM is only feasible for relatively simple systems.[17]

Reliability Theory

Reliability Theory utilizes basic statistics similar to fault tree analysis. However, with reliability theory the focus in on the probability of success of a system vs the

---

[17] Roberts, op. cit.

probability of a system failure. In addition, the objective of reliability analysis is usually to determine the probability that the system will not fail in such a way that it will no longer perform the intended function. With fault-tree analysis, the focus is typically on a particular failure that is potentially harmful and events that do not pertain to that failure would not be considered. These are the usual applications each of these theories are used for, however, they can both be applied to either problem.

Summary Comments

It is important to be aware of a common situation that can arise when doing any of these analyses. The result of any analysis is only as good as the input. Therefore, it is important that regardless of the method chosen, it does not become simply another form that an engineer has to fill out and then check off a list. Second, if the system is complex, it is important to have a number of participants in the process to get a more complete set of the possible ways that a system could fail.

"Automobile safety does not depend on a single feature or technology, but on the total safety system in a car."

Robert Stempel
June 1991

5 The Fault Tree

This chapter describes the fault tree methodology. It addresses what it is, how one is constructed, what the symbols mean and how they are used. Quantitative evaluation of a fault tree is discussed along with what useful information may be obtained. This chapter concludes by addressing when to do a fault tree, what is an appropriate application, and how probabilities are assessed.

Fault-tree analysis is used in an attempt to identify all the potential ways a defined system failure could occur and to estimate the probability of that failure. The main focus of fault-tree analysis is to determine the combination of events that would lead to a specified undesired event. Fault trees are particularly useful, although less accurate, when done early in the design process and used as a means of identifying the most appropriate allocation of resources to achieve a design goal.

The output of fault tree analysis is a qualitative understanding of all the possible ways the undesired event could occur. It can also be used to estimate the likelihood of the occurrence of the top event. The process of constructing the tree is very useful in that it stimulates discussion and provides insight into ways to rethink design issues. Once the tree is complete, it can be used to determine what combination of events must happen for the top event to occur, and to identify which of these paths are the dominant contributors to the risk.

There are three basic questions that need to be answered in fault tree analysis:

1. What is our concern? (define the top event)
2. How could it happen or come about?
3. What is the likelihood of failure?

The tree itself is a graphic representation of the different combinations of component failures that can cause system failure. It is a qualitative analysis. However, it can be analyzed quantitatively if the probabilities of the basic events are known.

Fault-tree Construction

There are several building blocks used to construct a fault tree. In most cases, however, there is need for only four.

The Basic Event (see fig 14) is represented symbolically by a circle. This is an initiating fault or basic component failure that does not need further development and is fully understandable by itself. The basic event is usually a fault that is associated with component hardware failure or human error. This event needs a probability assigned to it if the tree is to be evaluated quantitatively.

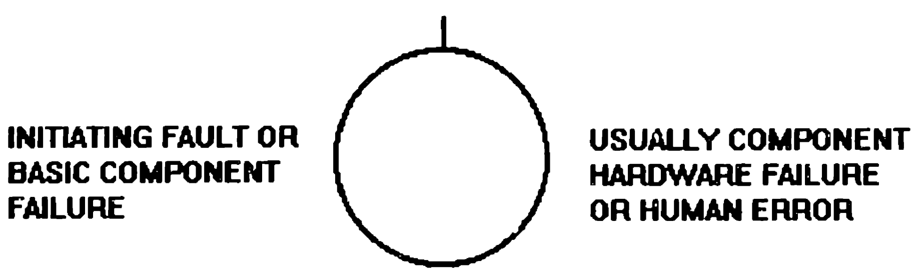


figure 14
The Basic Event

The intermediate event (see fig. 15) is represented graphically by the rectangle. This is an event which will be further broken down into either more intermediate events or into basic events. The main purpose of this event is to provide a road map or path through the tree. These intermediate fault events are very important to the structure and later dissection of the tree. If chosen carefully, later analysis will be much simpler.

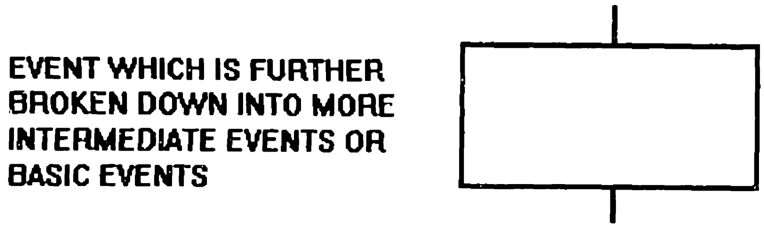


figure 15
The Intermediate Event

The OR gates and the AND gates (see fig. 16) determine the logic of the tree. The AND gate is represented graphically by the shield with the curved top and the flat bottom. The OR gate has the pointed top and the curved bottom. These gates are used to logically connect the different events in a fault tree. There can be any number of inputs to the gates.

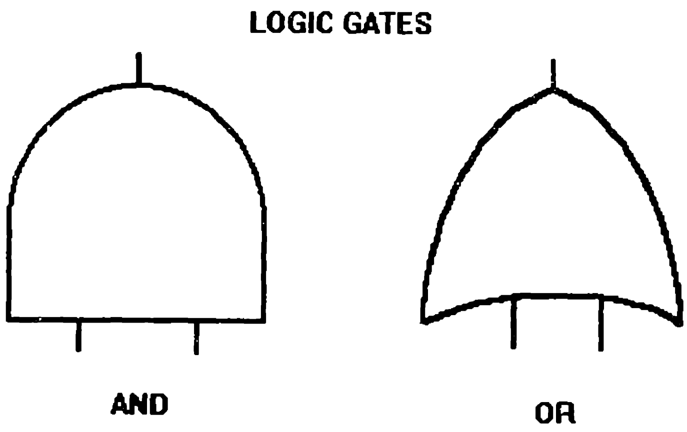


figure 16
The AND and OR gates

The AND gate is used to show that the output event will occur only if ALL of the input events occur simultaneously. For example, if the ice is too thin and I step on it, I will fall in. If either basic event did not occur at the same time, the top event would not occur. (figure 17).

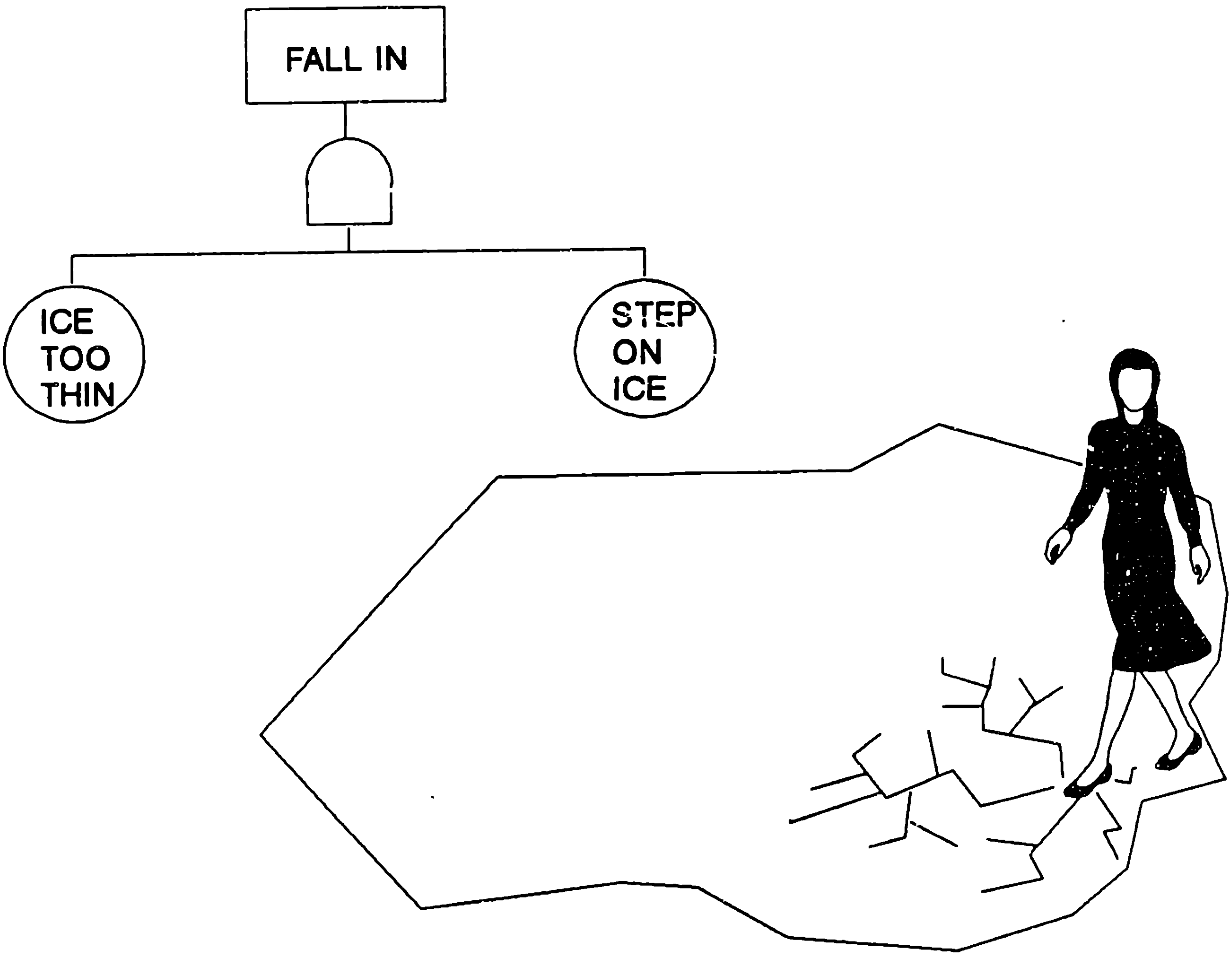


figure 17
The AND Gate

The OR gate indicates that if ANY of the input events occur, the output event will occur. For example, if the lightbulb burns out or the switch is not turned on, or the wiring is faulty, there will be no light. Use of the OR gate is illustrated in figure 18.

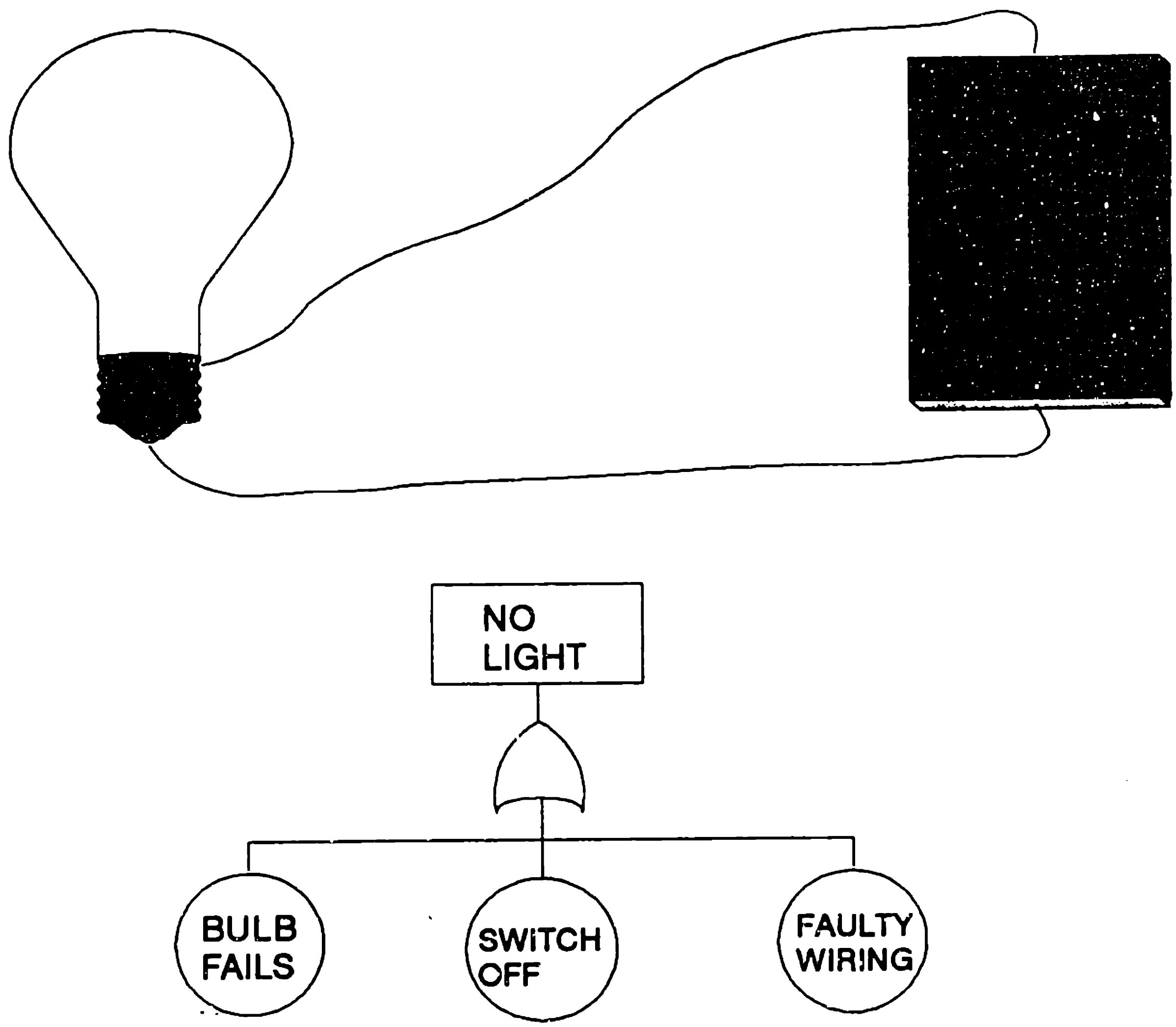


figure 18
The OR Gate

There are many other symbols that can be used in developing a fault tree. The complete list of elements used is shown in figure 19 .

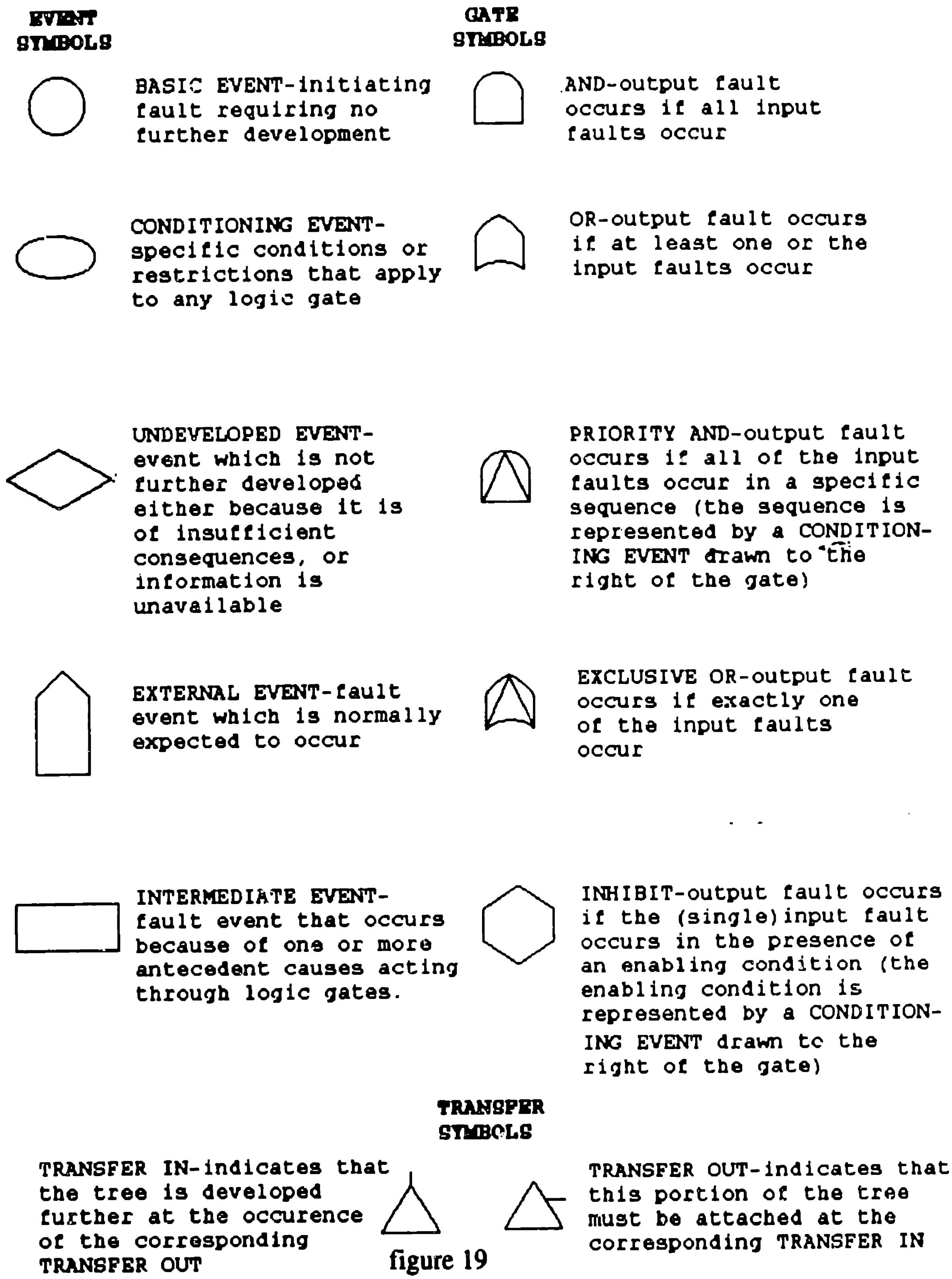


figure 19
List of All Symbols used in Fault Trees

The first step in developing a fault tree is to define an undesirable event. This event is shown in the top box. The next step is to attempt to make a complete set of all the ways that this event could possibly occur. That set is linked logically on the next level. The construction of a simple example will illustrate this.

Consider, for example, the simple network in figure 20. Our primary concern or undesired event is that the circuit fails open. In other words, we cannot pass current from the positive plate to the negative plate. We would begin by assigning "circuit fails open" to the top box.

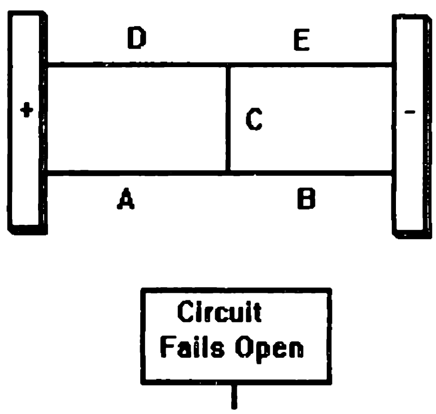


Figure 20
Network Example--Defining Undesired Event

Next, we ask what are the possible ways this could happen--what combination of events make the entire circuit fail open. For simplicity, I'll neglect the junction failures, although in reality we could not. We will have a system failure if the left portion of each wire fails, if the right portion of each wire fails, or if we have a crossover failure either by B,C and D failing or by A,C and E failing (see fig. 21).

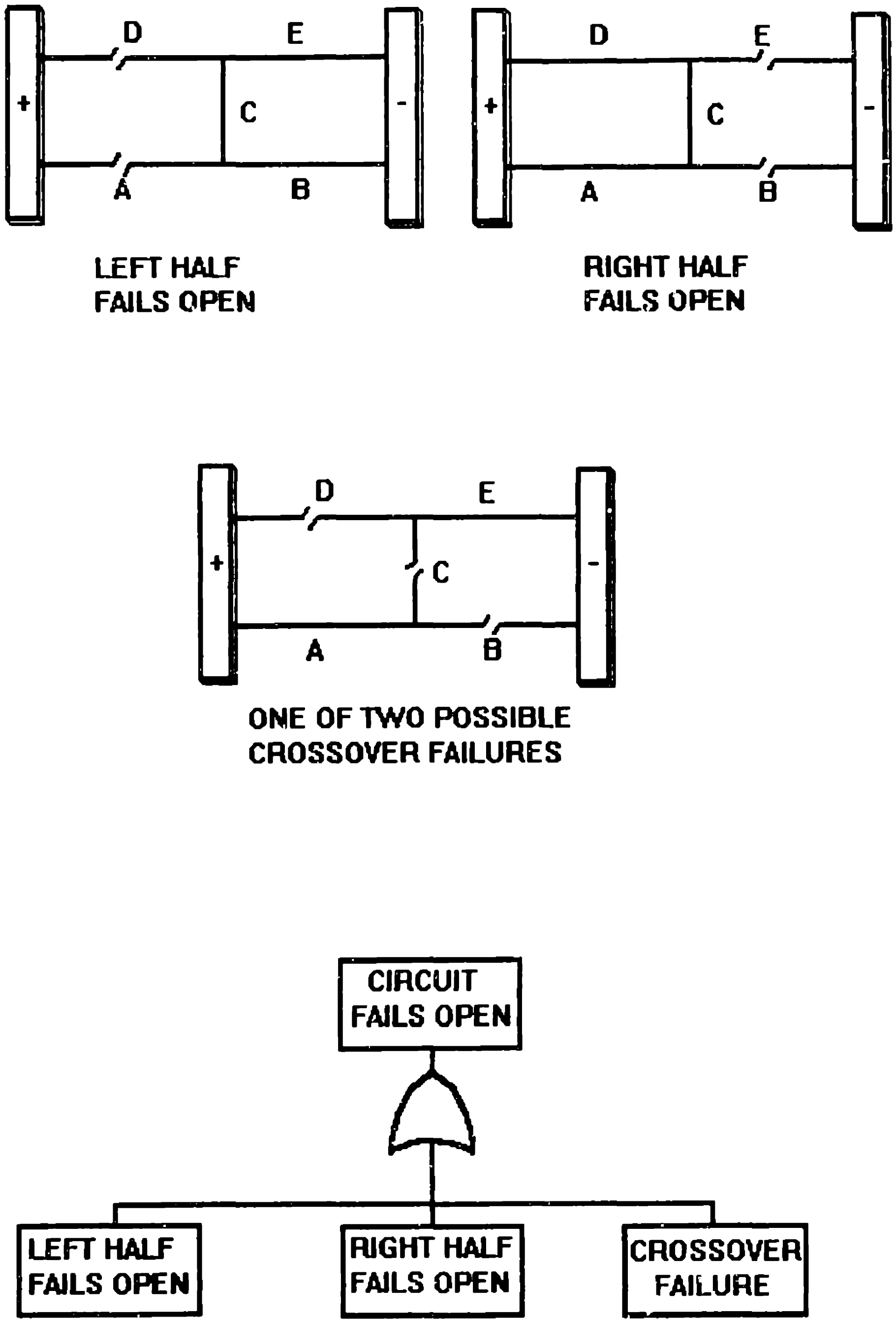


figure 21
Network Example--Development of Intermediate Events

These are represented in a fault tree with an OR gate--if any occur, the top event will occur. Below the OR gate we put in the intermediate events: left half fails open, right half fails open, and cross over failure. For each of these intermediate events we ask what are all the possible ways they can occur. In the case of the left half fails open, both A and D have to fail open. This is represented logically by an AND gate with each of these events located beneath the gate (see fig. 22)

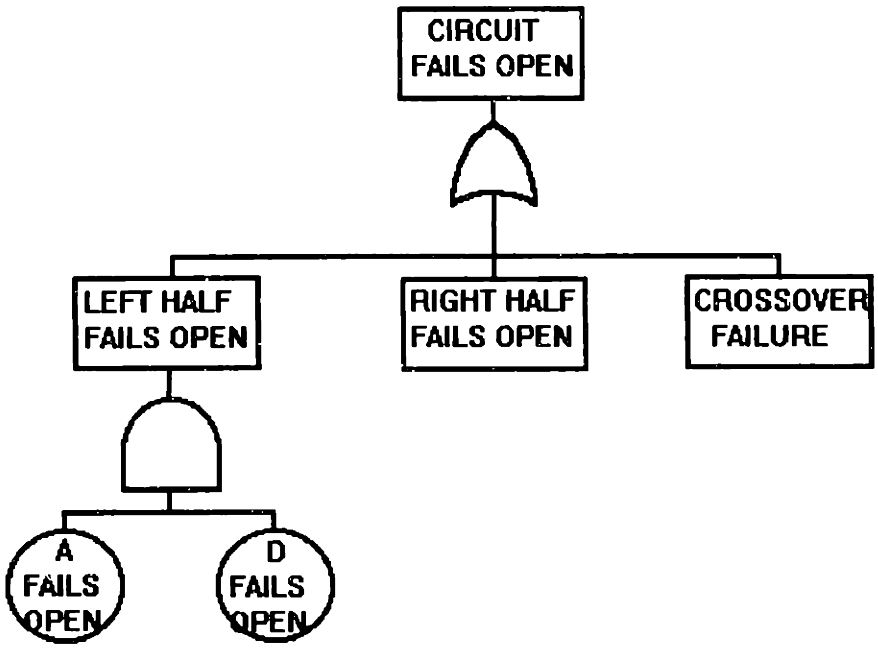


figure 22
Network Example--Left Half Fails Open

We would then continue to fill out this level of the tree for the other two intermediate events (see fig. 23)

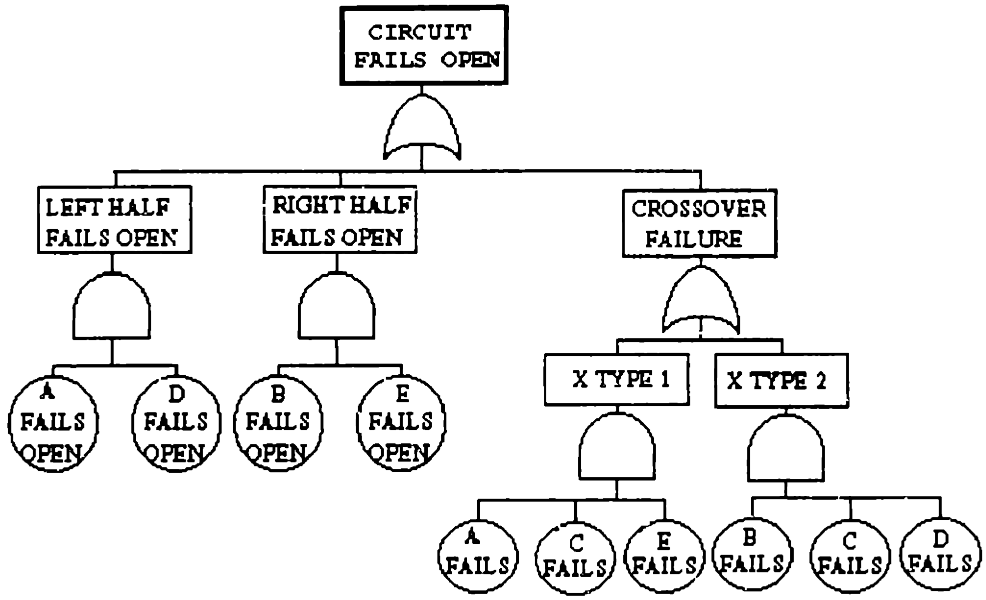


figure 23
Network Example--Development of Full Tree

For this simple example, we could now stop and we would have our basic events. If we were going to analyze the fault tree quantitatively, we would need to find reliability data on 20 gauge wire, or whatever we're using, for how often it fails open under comparable circumstances. We would then assign that number as the probability of failure for each of our basic events.

Evaluation of the fault tree

The first step in evaluating a fault tree is to construct a logical expression for the top event as a combination of the primary events. This results in groupings of events called "cut sets". A minimal cutset is a minimal set of basic events that need to occur simultaneously to cause the top event to occur.

To generate cutsets, the basic events are combined using Boolean algebra to form an expression for all the ways the system could fail. Wherever we have two events connected by a logical AND, or intersection, for example, A AND B, this is represented in engineering notation as AB. Whenever events are connected by a logical OR, called a union, for example, A OR B, the representation is A+B. For our network example, the system failure expressed as the union of the minimal cutsets is as follows:

$$\text{System Failure} = AD + EB + BCD + ACE$$

figure 24

Network Example--Minimal Cutsets

Where A,B,C,D and E are failure events--they are not probabilities. Expressed in words, if A and D fail or if E and B fail, or if B and C and D fail or if A and C and E fail, our system will fail. It is usually desirable to minimize the expression. If we have System Failure = ABC + AB + B, it is clear that if event B fails, the system fails regardless of whether A and C fail. Therefore, we would minimize this expression to System failure = B. The rules of Boolean algebra are used when necessary to minimize the cutsets. This expression is a qualitative description of the different combinations of events that need to occur for our system to fail.

If we are to analyze the tree quantitatively, probabilities need to be assigned to the primary events. Then, the cutset expression is converted to an equivalent expression of the probability of system failure. In general, whenever we have a logical AND, we multiply the probabilities of events. For example, to find the probability of (AB), multiply (probability of event A) * (probability of event B). When we have a logical OR, we add the probabilities of events and subtract the intersection of the events. For example, to find the probability of (A+B) add (probability of event A) + (probability of event B) - (probability of A and B). If we have small probabilities, the probability of the intersection becomes so small as to be negligible. In that instance, we can use the approximation of rare events and estimate the probability of system failure by simply adding the probabilities of events A and B. These algebraic rules assume that the basic events are independent. If independence cannot be assumed, the mathematics become much more complex.

For our simple example, we would multiply the probability that segment A would fail, P(A),and the probability that segment D would fail, P(D), then add that to the probability of failure for segment E, P(E), times the probability of failure for segment B, P(B) and so on. Assuming that we can use the rare event approximation, the final expression will be:

$$P(\text{circuit fails open}) = P(A)P(D) + P(E)P(B) + P(B)P(C)P(D) + P(A)P(C)P(E)$$

Analysis of Information

We can obtain several useful pieces of information from the expressions for system failure.

1. We can determine the chance of overall system failure. If the risk is unacceptable, we will make a decision to either improve the system or not produce it. Going back to our simple circuit example, we could switch to 18 gauge wire which would be thicker and therefore less likely to fail, or we could add another path between the two plates. This can also save resources. If the system is extremely reliable, we may be able to switch to a thinner wire, such as 22 gauge, and save cost and mass.

2. We can determine how much each cutset contributes to the system risk of failure. If we find only one cutset contributes the majority of the risk, it would be our dominant

path. Using our network example, if "left half fails open" accounts for 90% of the risk, we could correct that problem by adding an additional wire to the left half without the added expense of adding that wire to the right half as well. Or we could increase the gauge on the critical wires to a thicker, more reliable, 18-gauge without increasing all the wires. It doesn't matter which solution we choose, the point is that this helps us to identify where to utilize our resources instead of using a hit or miss approach.

3. A third piece of useful information is which basic event contributes most to the overall risk. Even though a part may be extremely reliable, if it is in enough cut sets, it can contribute a great deal to the risk. For example, if link C of our circuit contributes the majority of the risk, we could simply add a redundant link there. This information is also useful in reverse. If we find that something we added only for the sake of improving safety doesn't contribute at all to increasing safety, we can eliminate it. Or if we find that link C contributes a negligible amount of risk to the total system risk, we would not focus on improving its reliability even though link C by itself my be the most unreliable part.

When engineering a product that we want to be safe, we tend to design the system to look something like this:

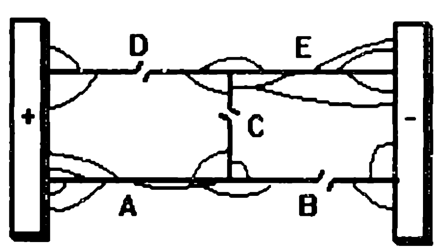


figure 25
Network Example--Band-Aid Engineering

The sad thing is we frequently miss the real source of risk (for example, if BCD were our critical path) while we over engineer all the smaller forms of risk. The end result is the total chance of system failure remains essentially unchanged between the two or worse yet, it may have increased, and we've created a very expensive circuit.

To summarize, frequently a few cut sets dominate the overall risk. When this happens, as it did for electric shock, it clearly identifies specific areas to concentrate our effort. The first step is to try to get better estimates of the basic events. For example, the fuse system being destroyed in the event of an accident--it is possible to get better estimates of that probability by performing crash analysis. Simultaneously, we need to entertain ideas for design alternatives. Finally, we can evaluate the cut sets that are insignificant contributors to the total risk to determine if we can redirect some of those resources to be more effective in reducing the overall risk.

Probability Assessments

One item I need to further elaborate on is the assignment of probabilities to basic events. If there are basic events that are component failures, it is sometimes possible to find existing reliability data to estimate the probability of failure. In certain cases, however, there is no data. For example, it is very difficult to find data on some types of human error. When no data exists, the probability must be estimated using other means. For this analysis, I used an interview technique that draws upon the experience and knowledge of "experts" to estimate the probability.

"Probability estimation is a process of encoding information. Since different people are likely to have different information, they can make different probability assignments to the same uncertain quantity. An interview process has been found to be an effective way of encoding a probability distribution."[18]

In order to determine probability distributions, the interviewer asks questions such that the respondent's answers can be translated into points on a distribution curve. There are generally two ways this is done. The first is a direct approach where the respondent answers questions with their estimate of a probability. The second approach is indirect. This technique offers the respondent a choice between two or more alternatives. Questions continue to be asked until the respondent is indifferent between the choices offered. These procedures have been shown to be remarkably accurate estimates of the true probabilities.

For the purposes of this research, probability distributions were obtained using a direct approach. For each respondent questioned, two key parameters were obtained for each probability distribution. The first parameter was that respondent's estimate of the median, and the second was their 95th percentile estimate. In the majority of cases, the probabilities were extremely small and the uncertainties large. Therefore, these distributions were assumed to be lognormal.

Interview Procedure

It was first necessary to carefully prepare for the interview process. Several hours were spent in identifying and avoiding the potential pitfalls that can be critical in this type of evaluation. We defined, agreed upon, and documented the procedure we would follow.

During the interview, we first introduced the process and explained what we were trying to accomplish. Next, we asked two sample questions, similar to the questions we would be asking later, to make sure the respondent understood the process. Finally, after

[18] E. Behrin, et al., Energy Storage Systems for Automobile Propulsion. 2 vols. Livermore, California: U.S.Department of Commerce National Technical Information Service, 15 Dec 1977, p.196.

all the questions about the assessment process were answered and we were sure that the respondent understood the process, we would begin asking the questions that were relevant to the analysis.

For each probability distribution we were trying to estimate, we would first describe the situation and make sure the situation was clearly understood. For example, we would explain that we were going to ask questions for the time the vehicle was on the assembly line after the fuse was installed. We always made sure to clarify exactly what that included or did not include. Using the above situation, we always explained that any time the vehicle was being repaired in the assembly plant was specifically excluded from this situation.

Next, we would explain the event. For example, "fuse is not pulled prior to servicing 324 volt component" would be explained to be any time the vehicle was being serviced by authorized or unauthorized service technicians throughout the life of the vehicle. We were careful to take as much time as necessary to completely clarify any situation or event to the respondent.

Finally, when we were confident that the respondent understood both the situation and the event, we would ask for an estimate of the probability, using language described below, to determine their assessment of the median. Next we asked a question to determine the respondent's 95th percentile estimate. A typical dialogue to determine a particular respondents distribution might be as follows:

Interviewer: "For this question we have the following situation: During service or repair of the vehicle. Please understand that this includes any time during the life of the vehicle that it may be serviced for any reason by authorized or unauthorized service technicians. This also includes any time that the vehicle might need to be in repair in the assembly plant. Do you understand exactly when I am referring to?

Respondent: Typically the respondent had a few questions they ask to clarify exactly what the situation was and to make sure that they understood what we had said. An example of one such question that was asked on occasion was,"Does that mean for the entire life of the vehicle?". To which we would respond "yes".

Interviewer: "The event is that the fuse is not pulled prior to servicing a 324 volt component. This should include service by both authorized and unauthorized service technicians and any repair worker in the assembly plant. This should also include service of any of the components that use 324 volts."

Respondent: Once again, there were typically a few questions to clarify the event.

Interviewer: "For the situation and event just described above, what is a number that you would estimate such that the true probability has an equally likely chance of being greater than or less than that number."

We typically had to rephrase this question in a few different ways to make sure that the person understood what we asked for. Different people had different ways of looking at these questions. We frequently spent as much as 50% of the interview time getting through the first question. Once the respondent had answered the first question, they had a fairly good understanding of the process and the remaining questions required much less explanation, and therefore, proceeded more rapidly.

Respondent: "Maybe 1/1000"

Interviewer: "Now what would be another number such that you think there is only one chance in twenty that the true probability would be greater than the number you give."

Respondent: "1/100"

Determining Distributions

This process was repeated for each probability we needed to estimate and for each respondent. Once the data was collected, it was entered into a spreadsheet where it was converted to useful point estimates and then entered into the fault tree for quantitative analysis.

The two parameters that we obtained from the interview process were the median and 95th percentile. There are two basic types of manipulation that were necessary with these numbers before they could be useful. First, we needed to combine all the estimates for a particular probability together to determine one point estimate of that probability. Second, because the IRRAS software uses means and not medians, we needed to convert the median estimates to means using the estimated distributions. For each of the probabilities we were trying to estimate, we went through the following steps:

1. Check to make sure all 95% responses were greater than the median responses.

2. Calculation of the geometric mean of the median responses. When the estimates are very small probabilities and they vary by orders of magnitude, the geometric mean is used (as opposed to a simple average) to more accurately represent the smaller

probability estimates. For example, if we calculated the mean of 1/100,000 and 1/100, it would be 1/200 which leaves our results biased toward the larger estimate. To calculate the geometric mean, simply multiply the respondent median probabilities together, then take the nth root of that product where n is the number of respondents for that question. For example, if there were four respondents that answered 10^{-4}, 10^{-5}, 10^{-4}, and 10^{-6}, we would multiply those together to get 10^{-19}. Then we would raise that to the 1/4 power to get 1.75×10^{-5}.

3. Estimation of the "k-factor". Next we want to adjust the median values to mean values (because we assume lognormal distributions, the mean and median are different points.). This adjustment is necessary because the mean is the parameter that is needed for the IRRAS software. In order to adjust the medians to the means, we need to find the k-factor in order to estimate the width of the distribution. The k-factor is simply a number that indicates how wide the distribution is--it is not a standard deviation. Because we were asking for the 95th percentile in our interview, we define k=(95 percentile estimate) / median. First, find the k-factor for each individual respondent, then take the geometric mean of all of the k-factors for each distribution. So if our above respondents answered 10^{-3}, 10^{-3}, 10^{-2}, and 10^{-5} respectively as their 95 percentile estimates, then we would calculate the k-factors as 10, 100, 100, and 10, and the overall distribution k-factor would be 32.

4. Estimate the standard deviation of the underlying normal distribution. For each of the lognormal distributions, there is an associated underlying normal or "Gaussian" distribution. We need to use the k-factor that we just calculated to estimate the standard deviation of the normal distribution as follows: Standard Deviation = ln k/1.65. Once again using our previous numbers, the standard deviation of the normal distribution would equal 2.09.

5. Calculate the mean of the lognormal distribution. We have gone through all of the above steps so that we could adjust the median to the mean to enter as data. To do this last step, calculate:

$$\text{mean}_{\ln} = \text{median}\ (e^{(\text{std.dev.}^2/2)})$$

Where the standard deviation is of the underlying normal, and the median is the geometric mean of the medians of the lognormal distributions we calculated in step 2.

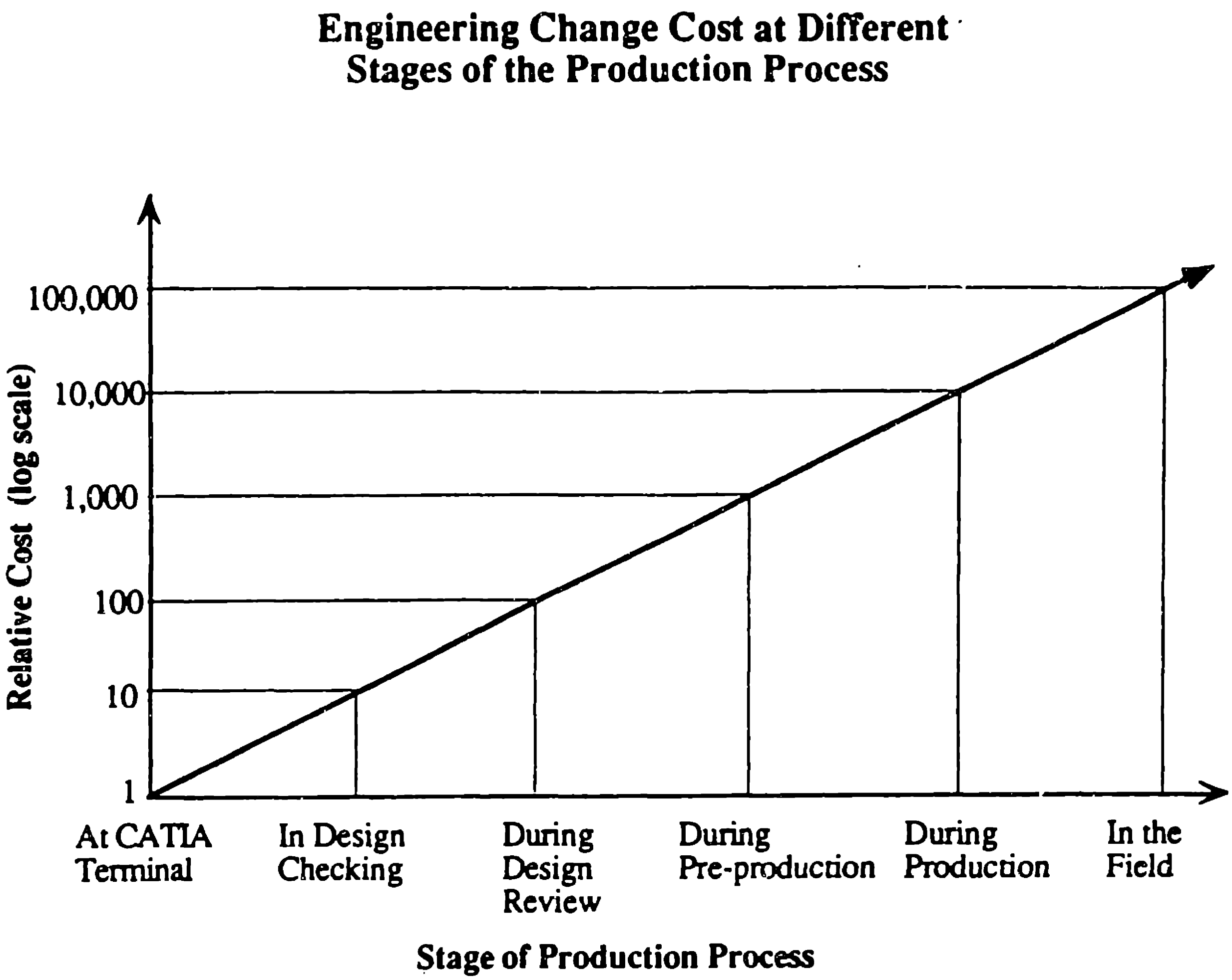
With numbers, mean=(1.75E-5) e (2.2) = 1.57E-4

Although this appears to be a very tedious process, if it is done on a spread sheet, it is not as unpleasant as it appears. The tabulations of the results from the electric shock fault tree can be found in Appendix B.

Timing

Fault tree analysis can be used any time in a product life cycle, and it is often used after a product is on the market in an attempt to further improve that product. However, it is particularly useful in the early design phases of a project so that changes that are indicated to be necessary or desirable are still relatively simple and inexpensive to make.

Previous research has shown that making changes early in the design process is drastically less expensive than making the same change later. One study, for example, found it could be as much as 100,000 times more expensive to make a change once the product is in use than it is to make that same change early in the design process. (figure 26). It is crucial that we identify necessary changes as early in the design of a new vehicle as possible.



Source: L.Labauve, Martin Marietta Corporation,
CATIA and VALISYS in a Concurrent Engineering Environment
Manufacturing Executive Conference, San-Francisco, June 1991

figure 26
Cost Associated with a Single Change

While fault tree analysis is less accurate very early in the design process, it is still useful in identifying areas to concentrate effort. Usually, there will be several orders of magnitude difference between the top cut sets and the lower ones. As the design begins to solidify, it is easy to go back into the model, make changes, and determine your new results. In fact, it is a matter of minutes to do a simple iteration once the model is complete.

This brings up another beneficial way to use this tool. It is simple to evaluate proposed design modifications and determine their effect on the overall system risk by simply updating the model.

Appropriate Uses

Like most analysis tools, fault trees are not appropriate in all cases. The trick is to determine which tools work best where. Obviously, we would not want to construct a fault tree for a simple component or for a system that we already have good reliability data on. It should merely confirm what we already know in those cases. It would also be a massive undertaking to do a fault tree analysis on an entire vehicle and would almost certainly delay the timing for the introduction of the vehicle. Nevertheless, once one vehicle is done, subsequent vehicle could be done in a much more condensed time frame.

However, the new systems where we don't have a lot of reliability information are certainly a good match for this tool. This methodology is very good for taking scattered information about subsystems or components and organizing it to obtain system performance information.

"Where there is no vision, the people perish"
Bible: Proverbs 29:18

6. The Electric Shock Fault Tree

This chapter describes the fault trees that were completed with respect to the electric vehicle. The results are presented and explained and potential consequences of electric shock are discussed.

Define the Undesired Event

Electric shock was defined as the undesired event, regardless of the expected severity of injury. Electrocution (fatality from electric shock), was rejected as the top event for two reasons. First, with the exception of a very small percentage, it is extremely difficult to determine what exact circumstances would result in a fatality. Furthermore, even the exact circumstances will have a different consequence for different people. To complicate this task, there is very little data for direct current electrocutions in this voltage range. Second, and most important, it was felt that any instance of electric shock would be undesirable regardless of the severity of injury sustained.

How could the Undesired Event occur?

The fault trees were constructed by answering how could the undesired event occur. What can possibly happen? What are all the possible ways that electric shock could occur, and where in the vehicle can the voltage potentially become exposed? The graphical representation of four fault trees was developed from that question with the common top event of electric shock (see fig.27). A fault tree was done in each of the following areas: assembly, use of the vehicle, service and repair of the vehicle, and in the event of a vehicle accident.

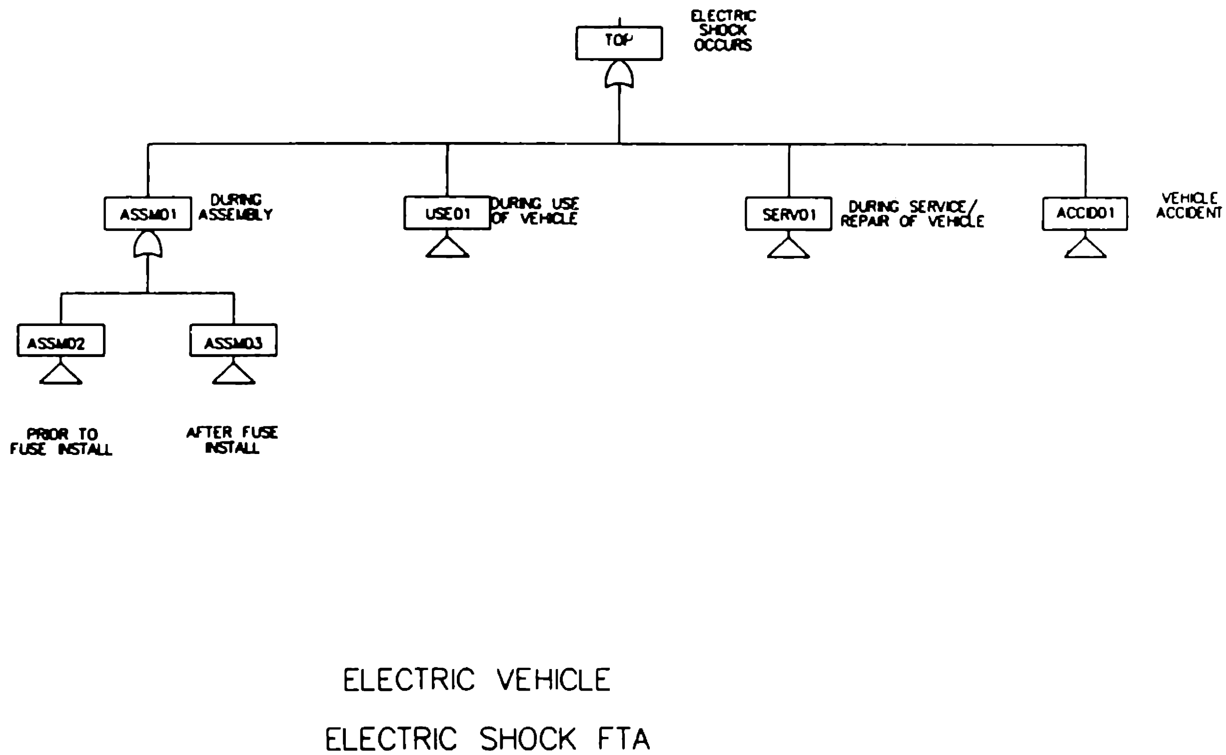


figure 27
Development of Fault Tree Top Event

During Assembly

Assembly was defined as from the point in time when the battery pack is placed beside the assembly line (this specifically excludes any assembly, shipping, or handling of the battery pack prior to its arrival at the assembly line.) until the vehicle leaves the assembly plant door, with the exception of any time that the vehicle may be in repair. Our major concern here was the safety of the plant personnel.

The assembly fault tree is divided into two main branches--one before the fuse is installed and one after the fuse is installed. This fault tree was divided in this way because the nature of the problem changes drastically once the fuse is installed. Before the fuse is installed, there are basically two ways for electric shock to occur (see fig. 28). It is possible to receive an electric shock either directly across the battery terminals themselves (this may be less than 324 volts) or through the fuse location. In either case, for electric shock to occur, the voltage has to be exposed and the person has to complete the circuit.

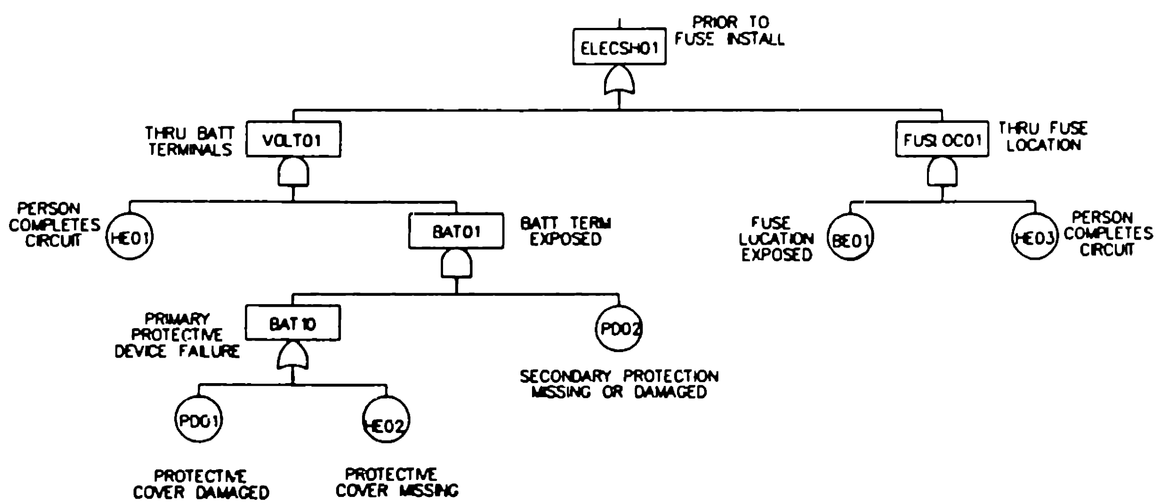


figure 28
Assembly Fault Tree--Prior to Fuse Install

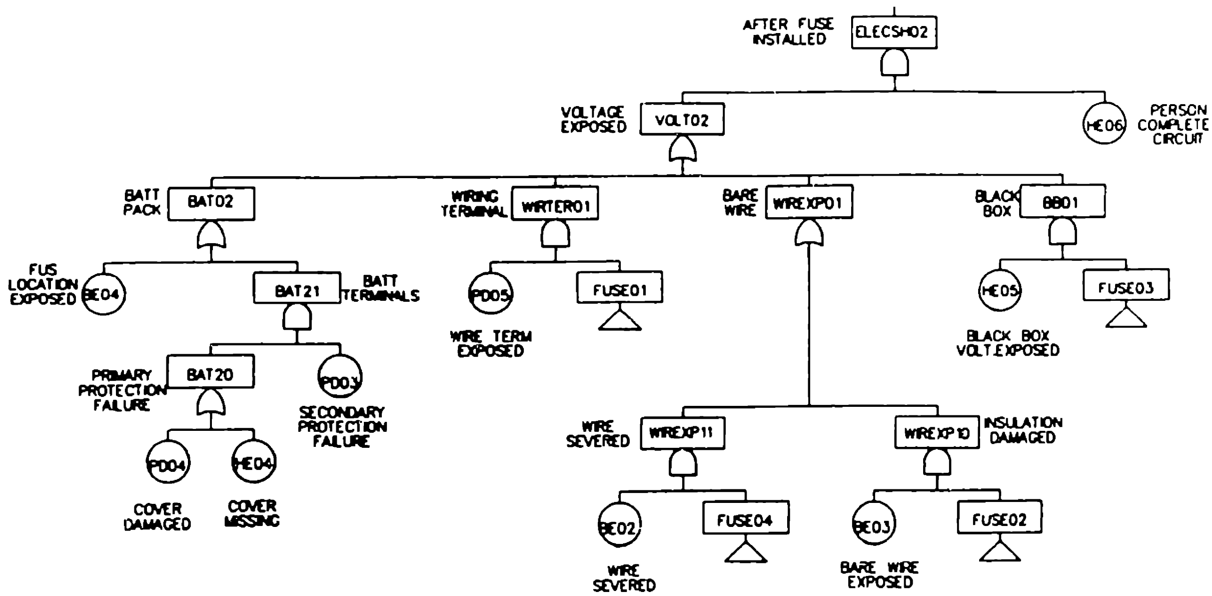


figure 29
Assembly Fault Tree--After Fuse Install

For the voltage to become exposed on the battery pack, both the primary protective device and the secondary protective device have to fail. At the time of this writing, the primary protective device was a plastic cover that enclosed the battery pack on three sides and attached to the battery tray on the bottom. The secondary protective device was a wax paraffin seal over each individual battery terminal within the battery pack.

After the fuse is installed, there are many more areas electric shock could be possible (see fig. 29). The structure of the fault tree still requires that the voltage must become exposed and the person must contact it. There are four areas where the voltage can potentially become exposed.

1. The battery pack. This includes the fuse location being exposed, for example, if the fuse is removed after the initial installation. This particular branch of the tree is similar to assembly prior to fuse installation. The probabilities associated with each basic event, however, will be different.

2. The wiring terminals. It is possible that the terminals themselves can either be pulled out or back out of a connector, or perhaps they were never properly seated in the first place. It is also a possibility that the connector remains intact, but disconnected, and contact to the terminals is made within the connector. In addition to the terminals being exposed, the fuse system would have to fail before the voltage would be exposed.

There are two ways the fuse system could fail to protect (see fig. 30). Either the system is defective--(a component failure), or we did not trigger the system to clear the fuse. The system will be triggered if either the "daisy chain" is interrupted or loss of isolation to the chassis is detected. For a more detailed explanation see chapter 3, the fuse system. The idea is that if a connector is disconnected or a terminal is not properly seated in a connector, it will either disrupt the daisy chain when it is pulled out, or contact metal and short to the chassis.

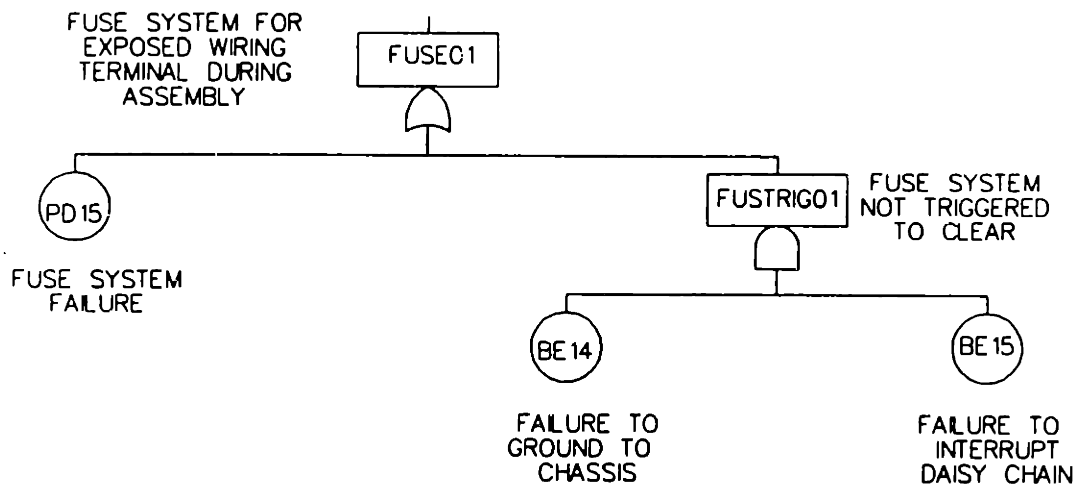


figure 30

Fuse System--During Assembly, Exposed Wiring Terminal

3. A bare wire. A wire may become damaged or severed during the assembly process. The fuse system would again have to fail for the voltage to be exposed. (see figs. 31 & 32). The fuse branches of the fault tree are graphically the same, but the basic event probabilities are different.

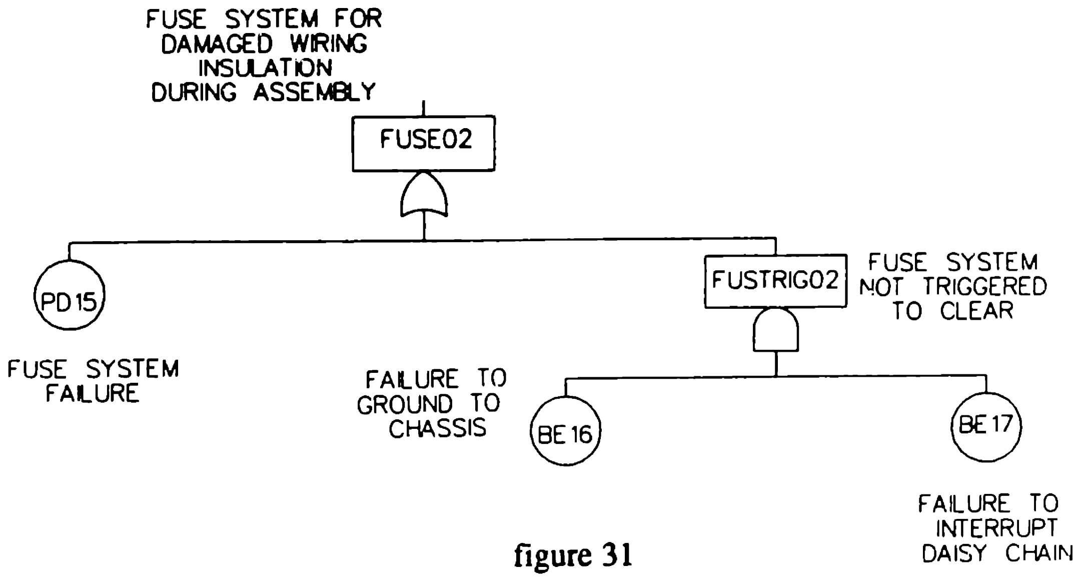


figure 31

Fuse System--During Assembly, Damaged Wiring

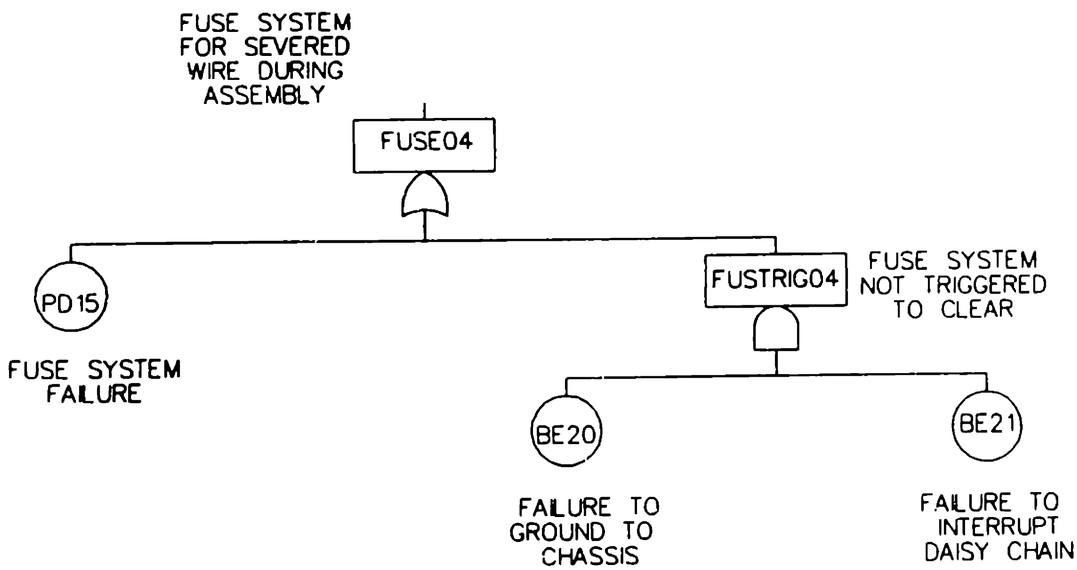


figure 32

Fuse System--During Assembly, Severed Wiring

4. The black boxes. Finally, we could have the voltage exposed through one of the "black boxes". By "black boxes", I mean any electronic box that carries 324 volts (there were four at the time of this writing). It is possible that a black box can be damaged in such a way as to expose the voltage, either by opening a box or dropping something on it, or even puncturing it. This too has a fuse system associated with it (see fig. 33)

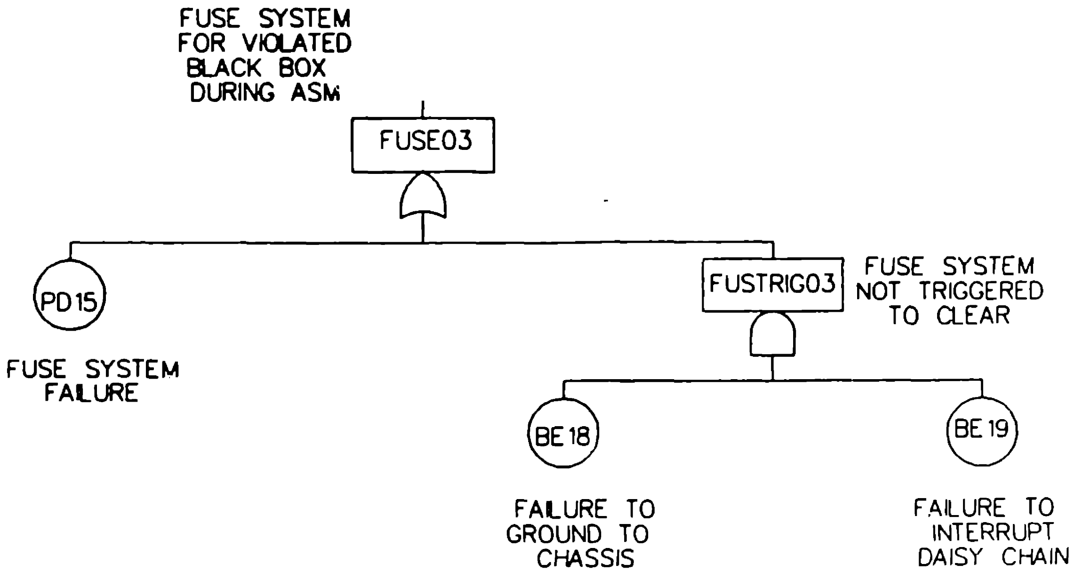


figure 33
Fuse System--During Assembly, Black Box Damaged

During Normal Use of the Vehicle

Normal use of the vehicle is defined as anything an owner might reasonably be expected to do to his or her car, including such things as aftermarket add-ons. This fault tree was concerned with the driver, occupant, children, and anyone who might be in or around the vehicle.

Once again, the voltage must be exposed, and the person must complete the circuit. The graphic representation and logic is the same as the assembly diagram after the fuse is installed. This fault tree with the associated fuse branches can be found in figures 34 through 38.

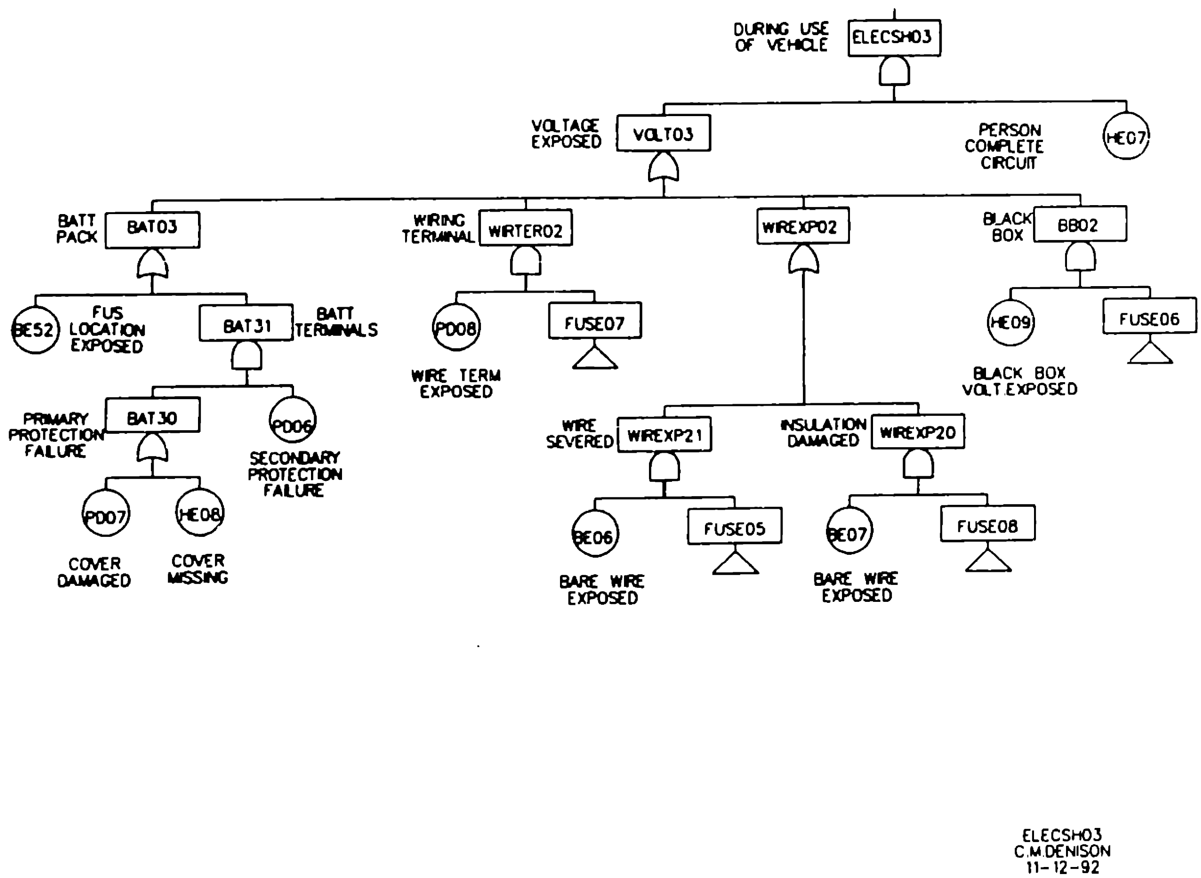


figure 34
Normal Use Fault Tree

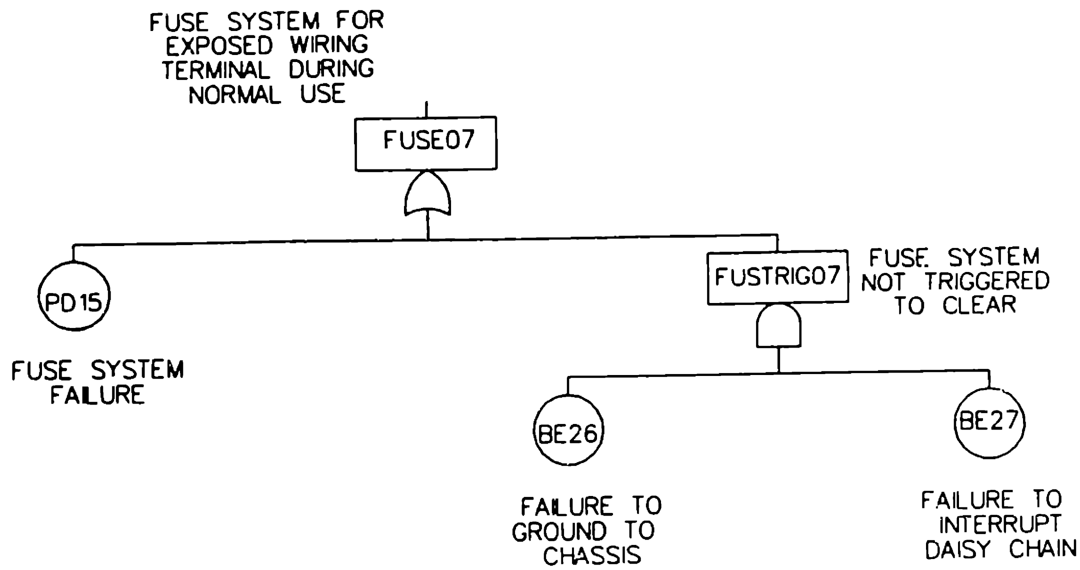


figure 35
Fuse System--Normal Use, Wiring Terminal Exposed

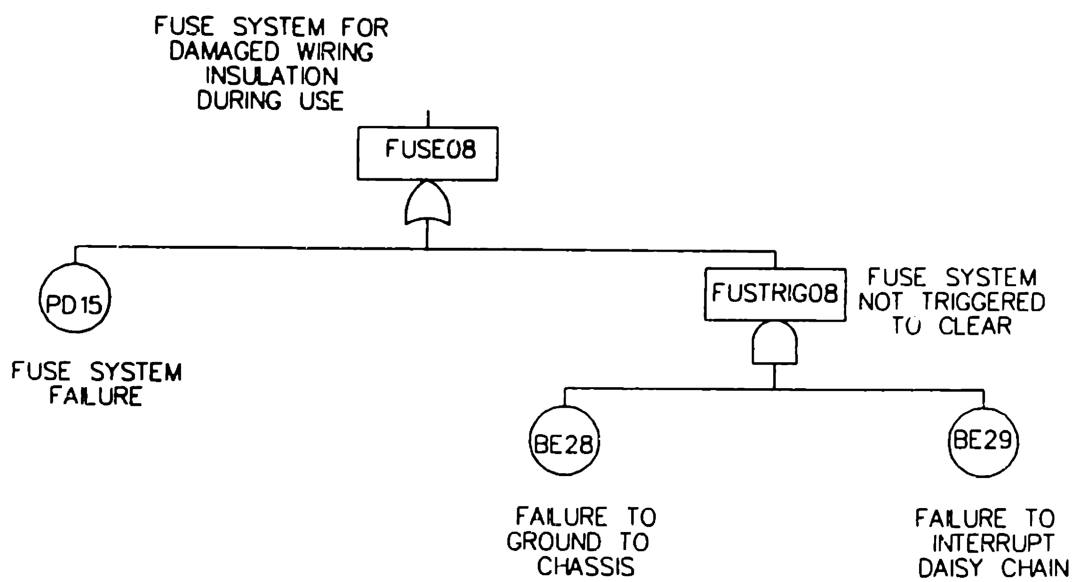


figure 36
Fuse System--Normal Use, Damaged Wiring

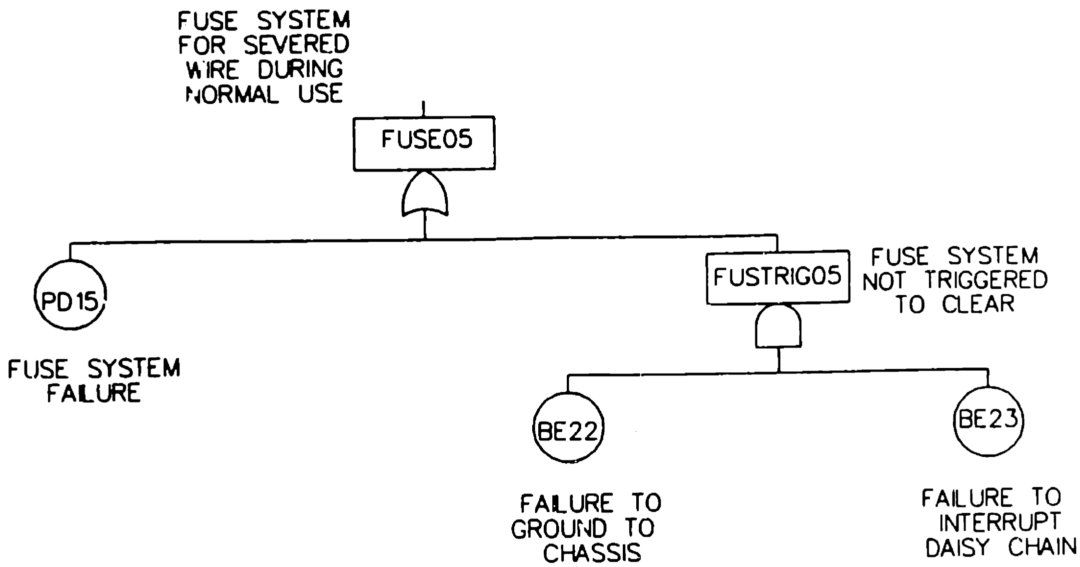


figure 37

Fuse System--Normal Use, Severed Wiring

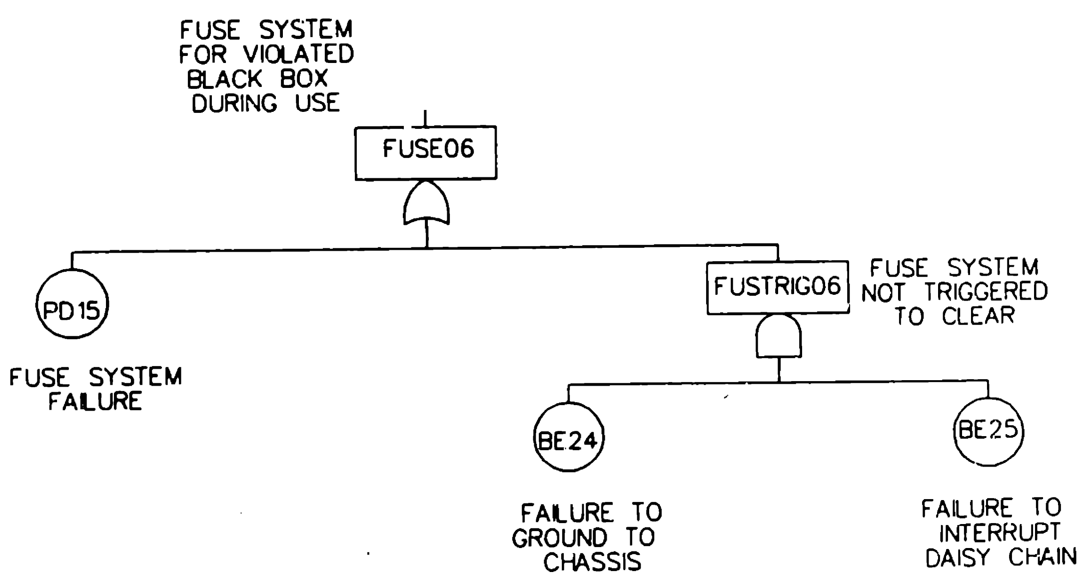


figure 38

Fuse System--Normal Use, Black Box Damaged

During Service and Repair

Service and repair is defined as any time the vehicle is being serviced for any purpose. This includes service by authorized as well as unauthorized service technicians and any repair done in the assembly plant.

This tree is graphically very similar to the fault tree for normal use. However, you'll notice that the fuse diagrams do have an extra basic event that needs to be considered: the chance that the service technician will not pull the fuse prior to servicing a 324 volt component.

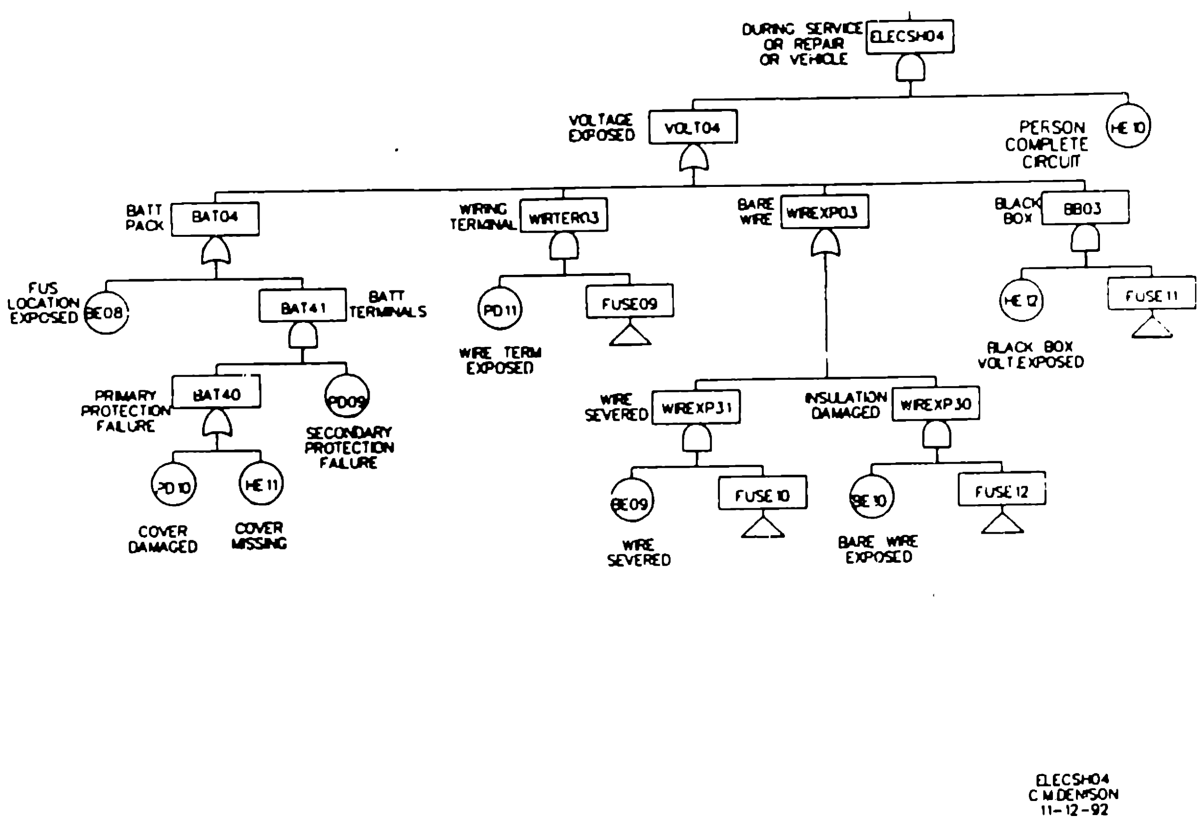


figure 39

Service and Repair Fault Tree

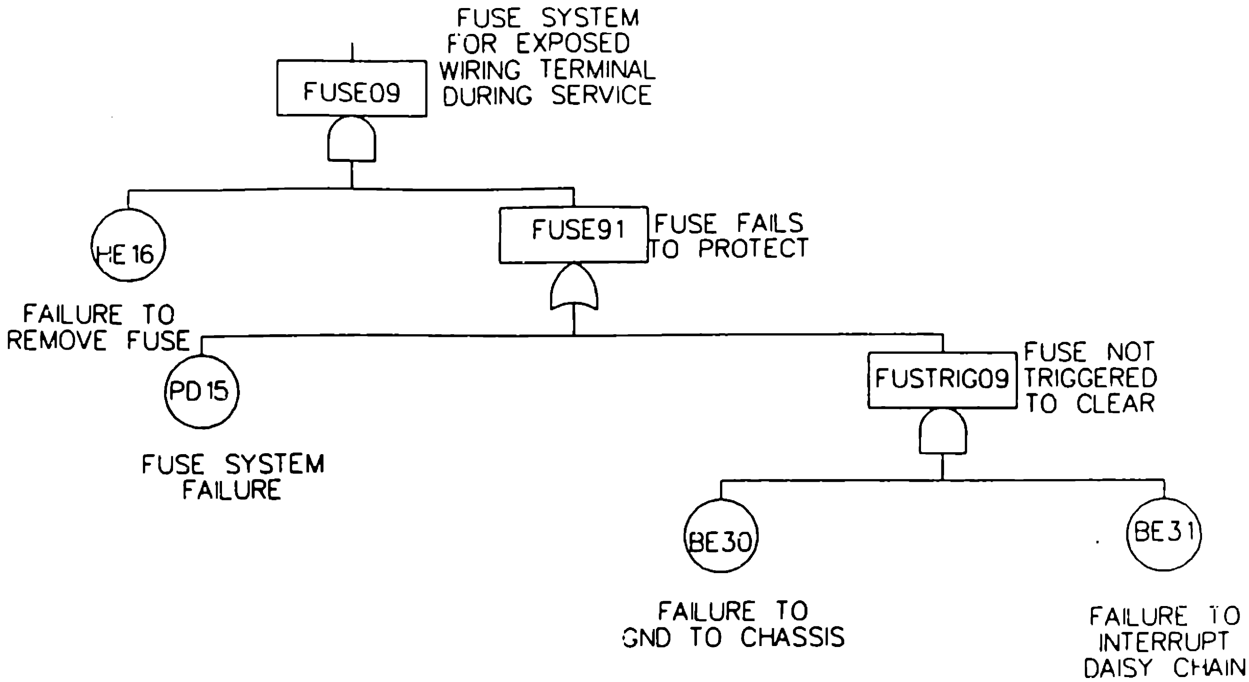


figure 40
Fuse System--Service and Repair, Wiring Terminal Exposed

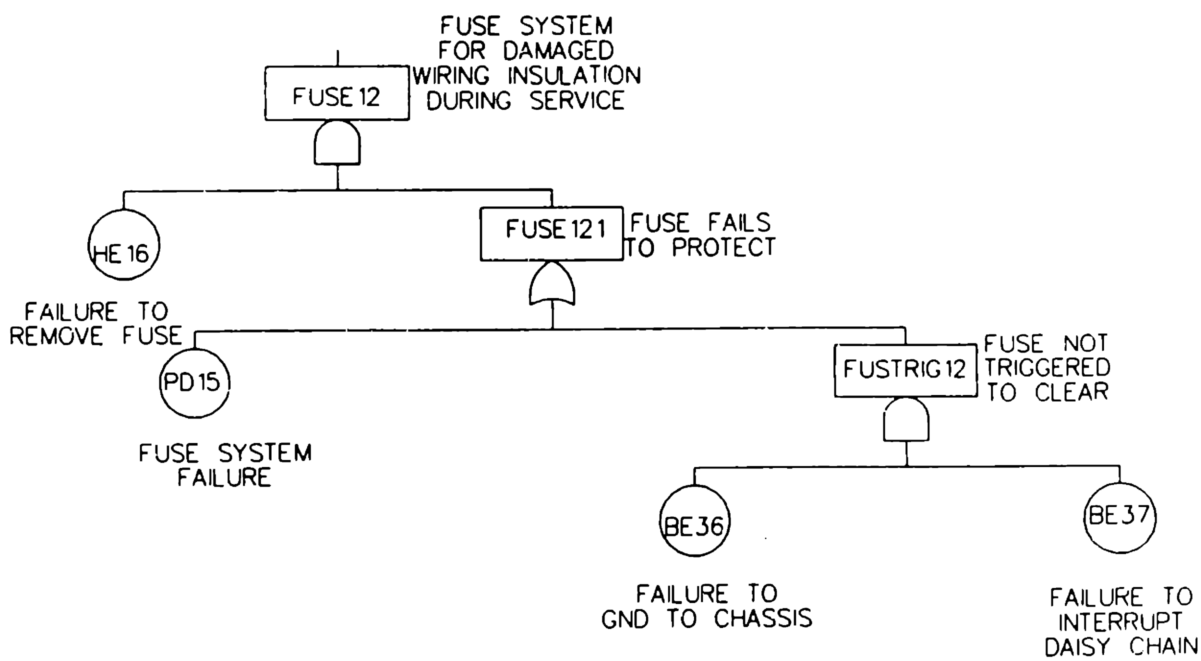


figure 41
Fuse System--Service and Repair, Damaged Wiring

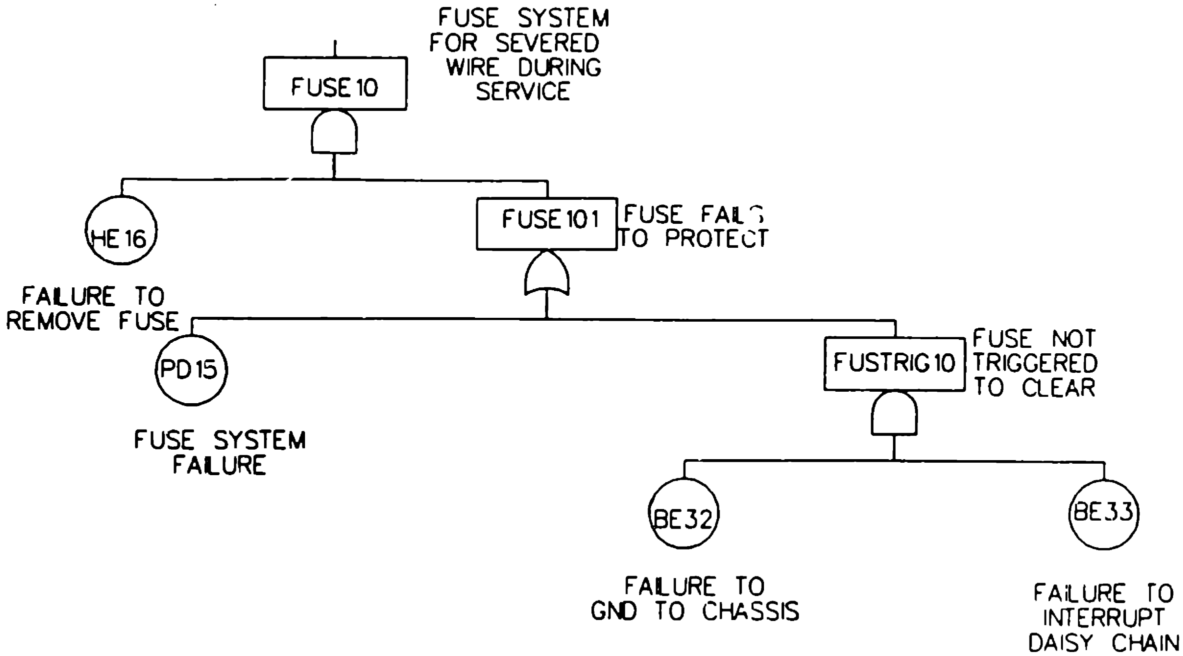


figure 42
Fuse System--Service and Repair, Severed Wiring

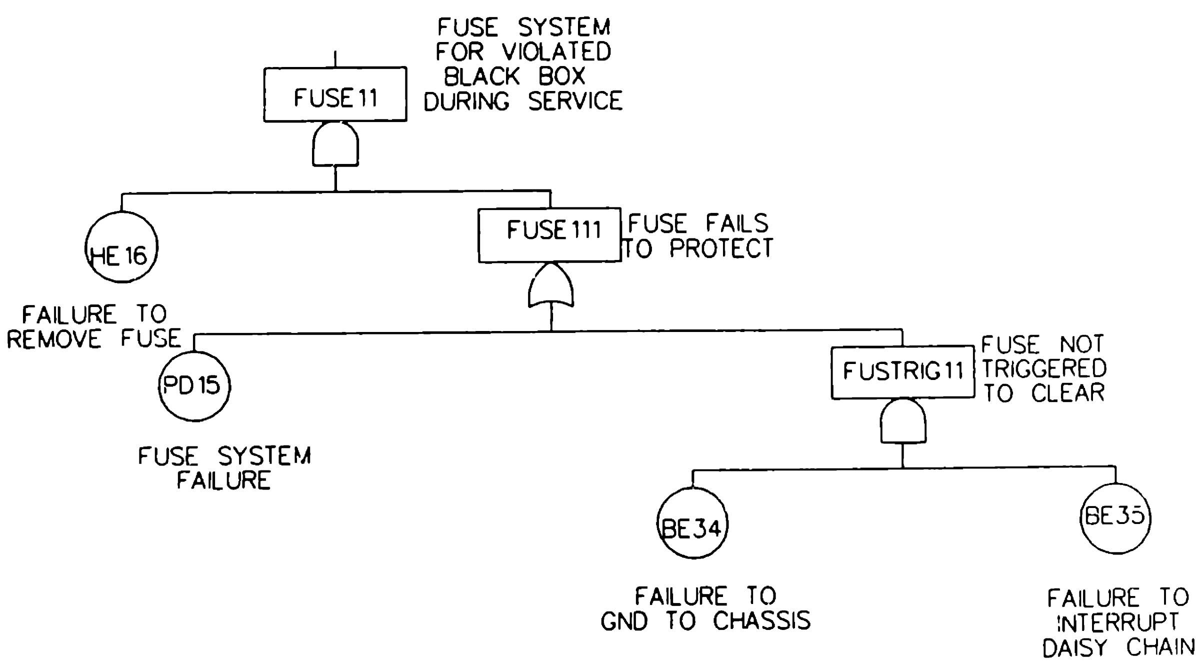


figure 43
Fuse System--Service and Repair, Black Box Damaged

In the Event of a Vehicle Accident

The event of an accident is defined as any time the vehicle is involved in an accident regardless of the severity. In this fault tree we were concerned about the driver and occupant of the vehicle as well as any rescue personnel (trained or untrained) that might happen upon the scene. The only difference, graphically, with this diagram is the addition of a basic event in the fuse diagrams to account for the possibility that the fuse system will be destroyed in the event of an accident.

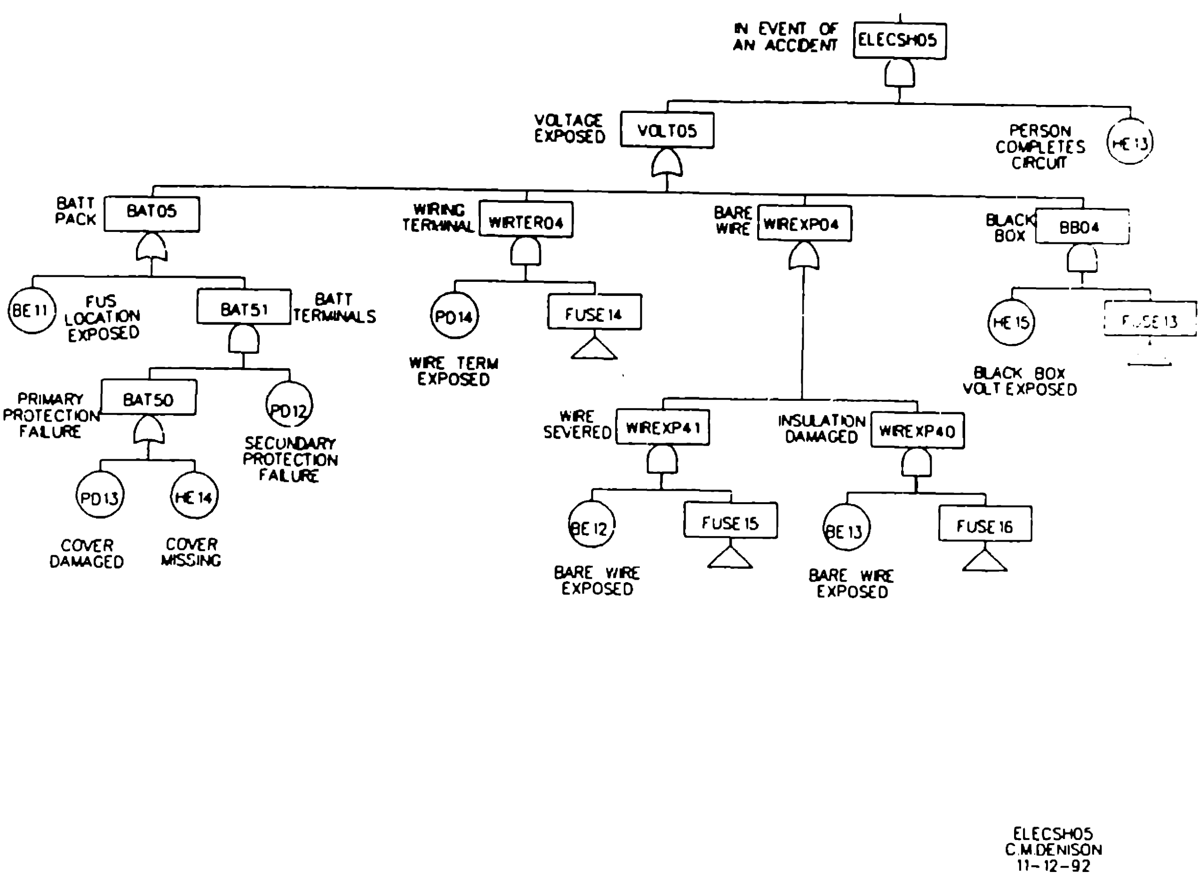


figure 44
Vehicle Accident Fault Tree

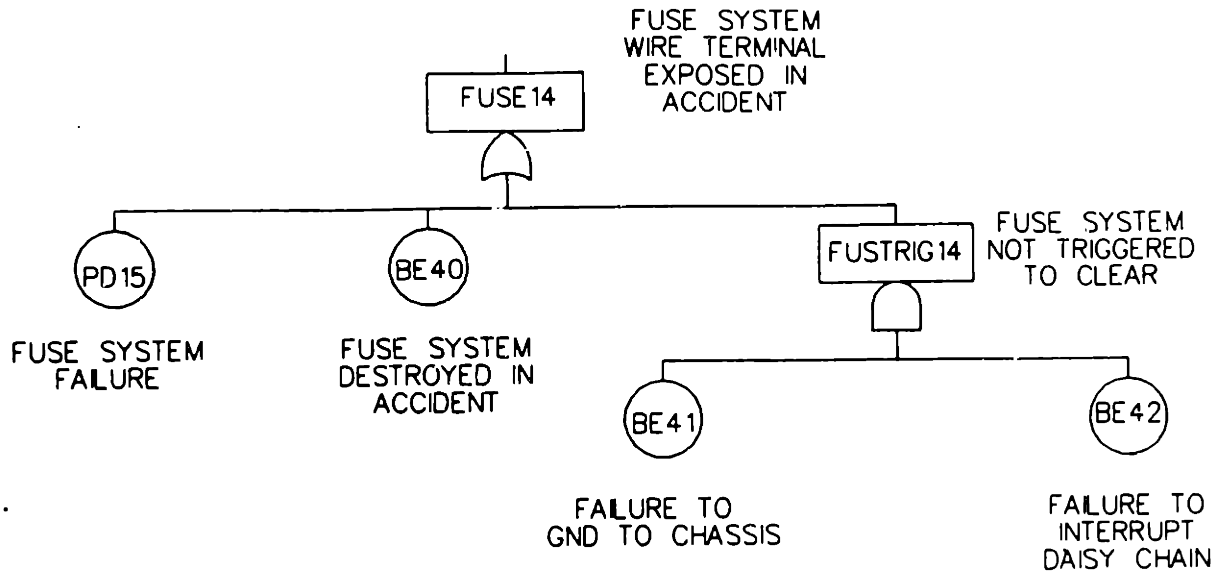


figure 45

Fuse System--Vehicle Accident, Wiring Terminal Exposed

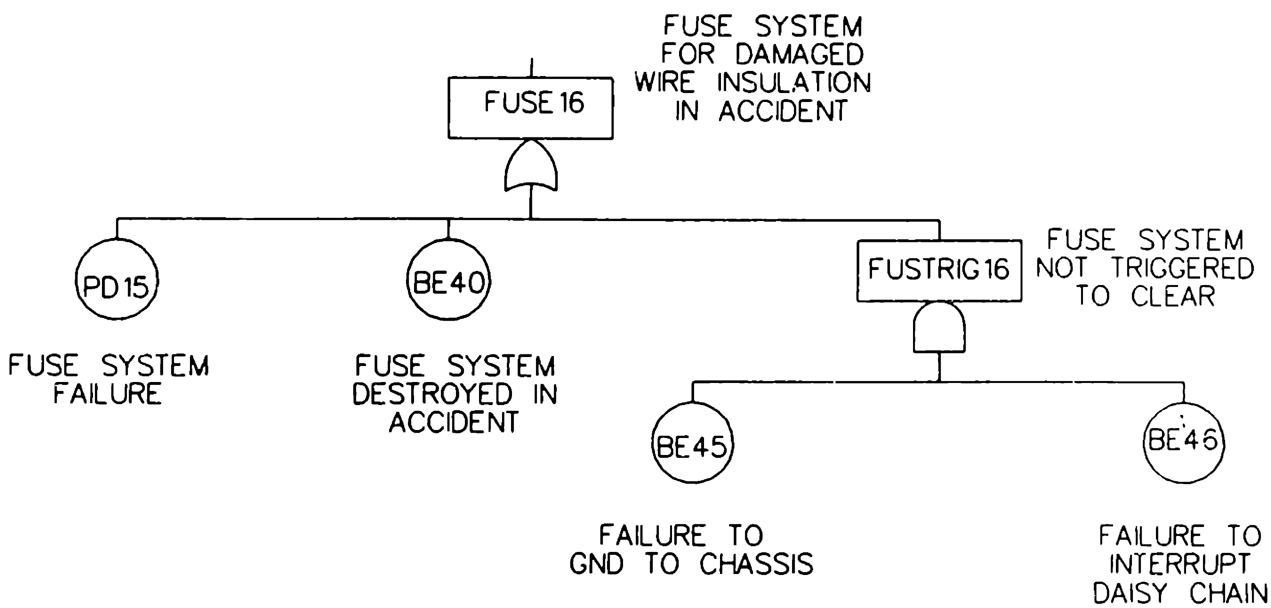


figure 46
Fuse System--Vehicle Accident, Damaged Wiring

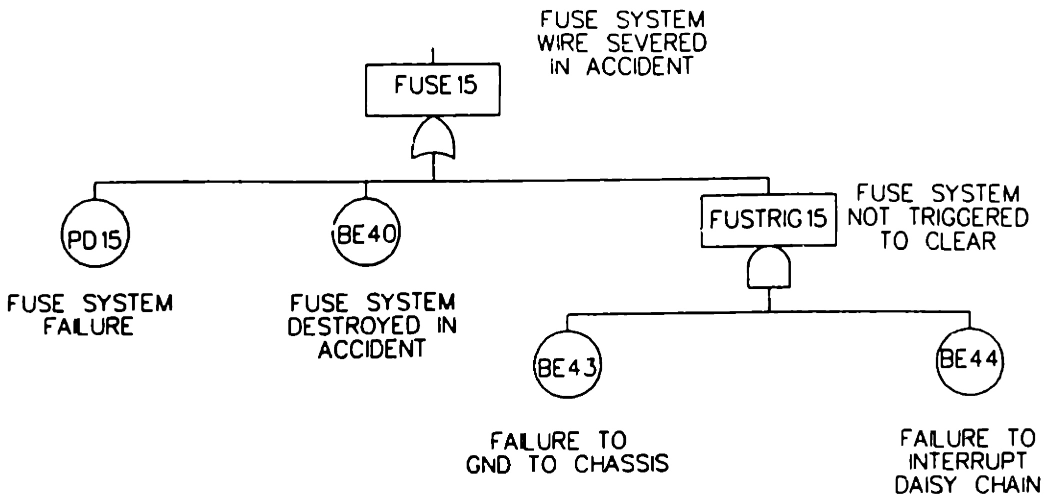


figure 47

Fuse System--Vehicle Accident, Severed Wiring

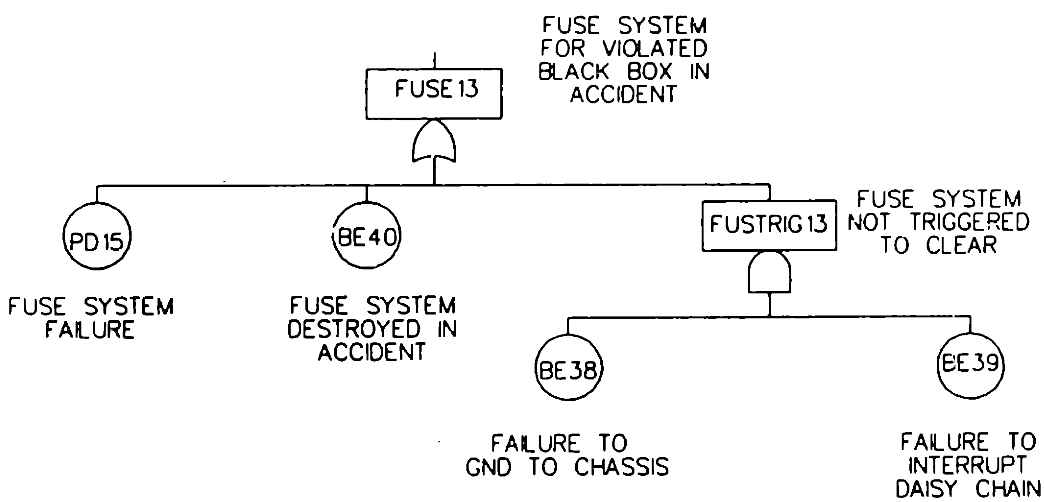


figure 48

Fuse System--Vehicle Accident, Black Box Damaged

Probability of the Events

For this analysis, there were 77 basic events, two of which had existing reliability data that could easily be found and assigned. The rest were more difficult to attain. I used an interview technique designed to determine how "experts" assess probabilities. During the interview process, respondents are asked questions in their area of expertise. For example, I might ask someone in the service area what they think the chances are that a service technician would not pull the fuse prior to servicing a 324 volt component. The questions are asked in such a way as to avoid biasing the answer. We then asked a second question to try to determine how uncertain they were of their answer. This allowed us to get both a median and a standard deviation for each probability distribution. Each estimate is based on the risk associated with one vehicle throughout the life of that vehicle.

For each estimate there were at least three and sometimes as many as 11 respondents. There are two points I want to make about this process. The first is that it was done as carefully and responsibly as it could be (see chapter 5 for detailed explanation) and the second is that there is a good deal of experience that has shown this technique provides a reasonably good estimate of the actual probability. The data that resulted from this interview process can be found in appendix B.

During Assembly

The results of the assembly fault tree show that there is one critical path that accounts for nearly all of the risk (see fig. 49). The dominant risk is that a person completes the circuit through the fuse location. What this means is that if we focus our attention on that one area, and reduce the risk of a person completing the circuit through the fuse location, it will significantly reduce the overall risk in the assembly process. In fact, the next largest risk is several orders of magnitude smaller, therefore, we could achieve a very large improvement from this one failure mode.

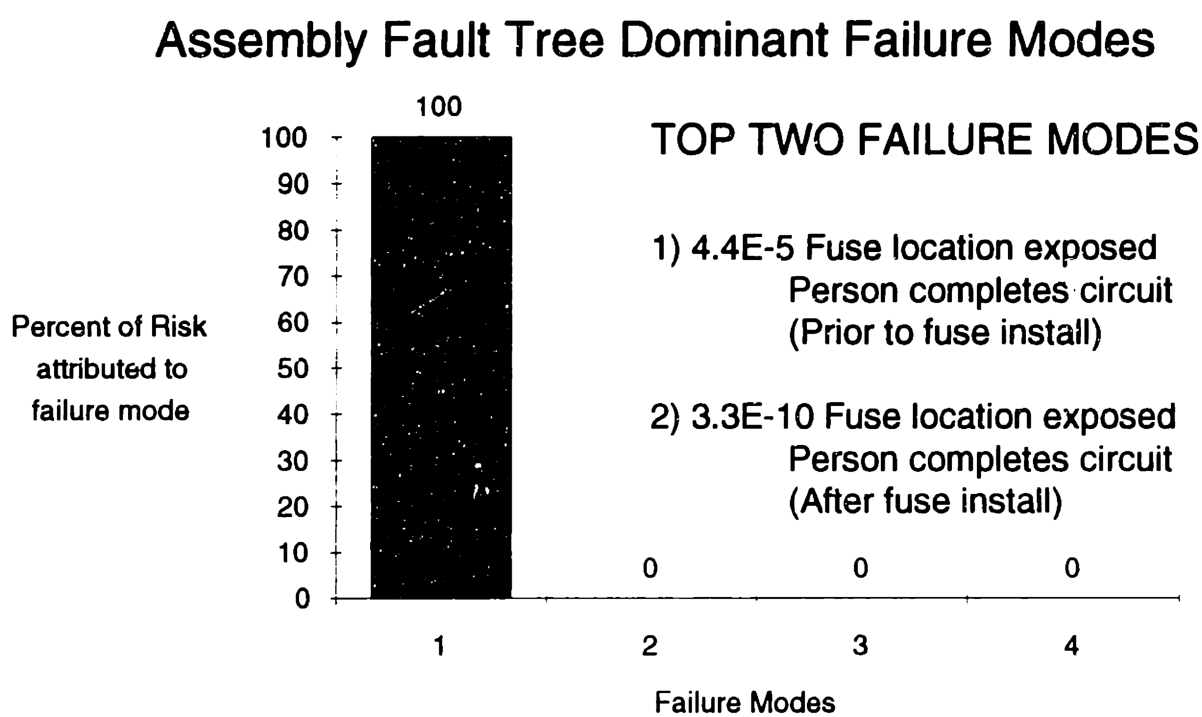


figure 49
Assembly Fault Tree Results

As can be seen from figure 49, the dominant failure mode has a risk associated with it of 4.4 x 10-5. This risk is per vehicle for the life of the vehicle. This means that for every 23,000 cars down the assembly line, we would expect to have one incident of electric shock. This number has been greatly improved since this analysis was done due to the design changes made to the fuse/manual disconnect. Also, all of the numbers generated have a large uncertainty associated with them and therefore, should not be taken to be highly accurate, but rather should be used as an indication of the relative importance of each cutset.

The full listing of minimal cutsets and their contributions toward the risk are listed in decreasing order of importance in Appendix C. The failure probability for each basic event can be found in appendix A.

Normal Use of Vehicle

There are only five cutsets that account for nearly all of the risk of electric shock during normal use of the vehicle (see fig.50). Notice that the dominant cutset, or most likely way that electric shock will occur, is again through the fuse location.

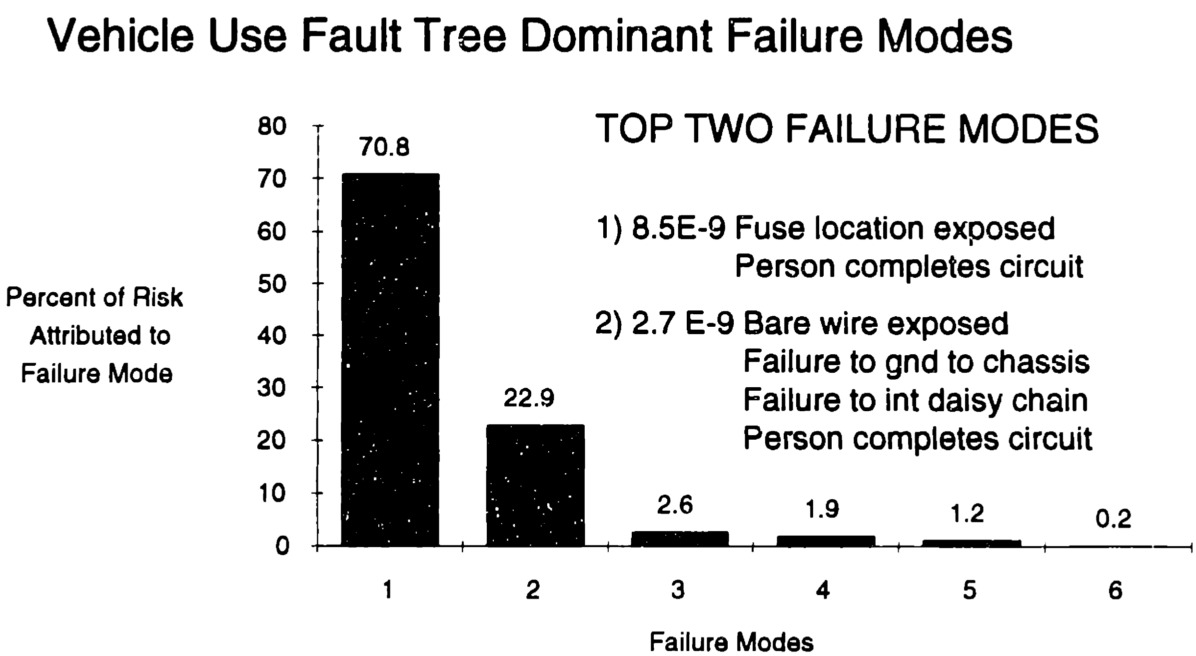


figure 50
Normal Use Fault Tree Results

This risk during normal use of the vehicle, about 1 in 100 million, is so small that we cannot truly understand what it means. When the results are this good (the probability for failure is very very low), there is always the possibility that the fault trees are incomplete--that an entire branch is missing because it never occurred to anyone that it could happen. So, if an incident of electric shock does occur during normal use of the vehicle, it will probably happen in a way that no one thought it could happen. It is a probability so rare that it has never happened to anyone involved in this analysis, or anyone they know of, or heard of. Therefore, they simply would not think of it ever happening.

During Service and Repair

We have only three cutsets that account for nearly all the risk during service and repair (see fig. 51).

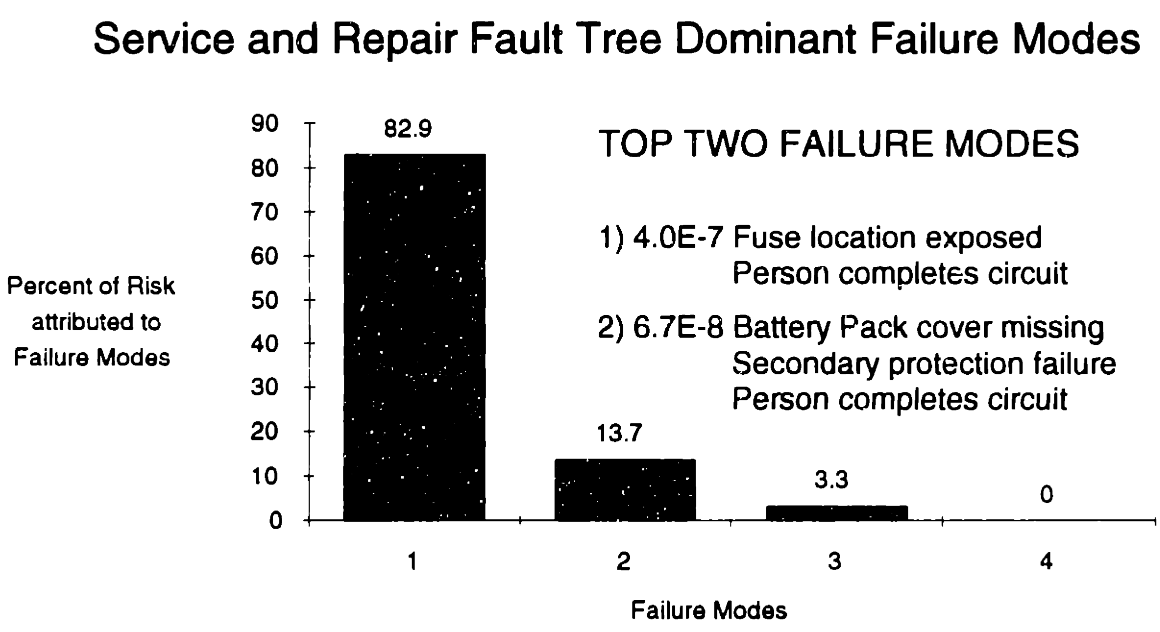


figure 51
Service and Repair Fault Tree Results

The critical path for this fault tree is, once again, the possibility of completing the circuit through the fuse location.

In the Event of an Accident

Once again, only a few cutsets contribute the vast majority of the risk (see fig. 52). Also once again, the critical path is completion of the circuit through the fuse location.

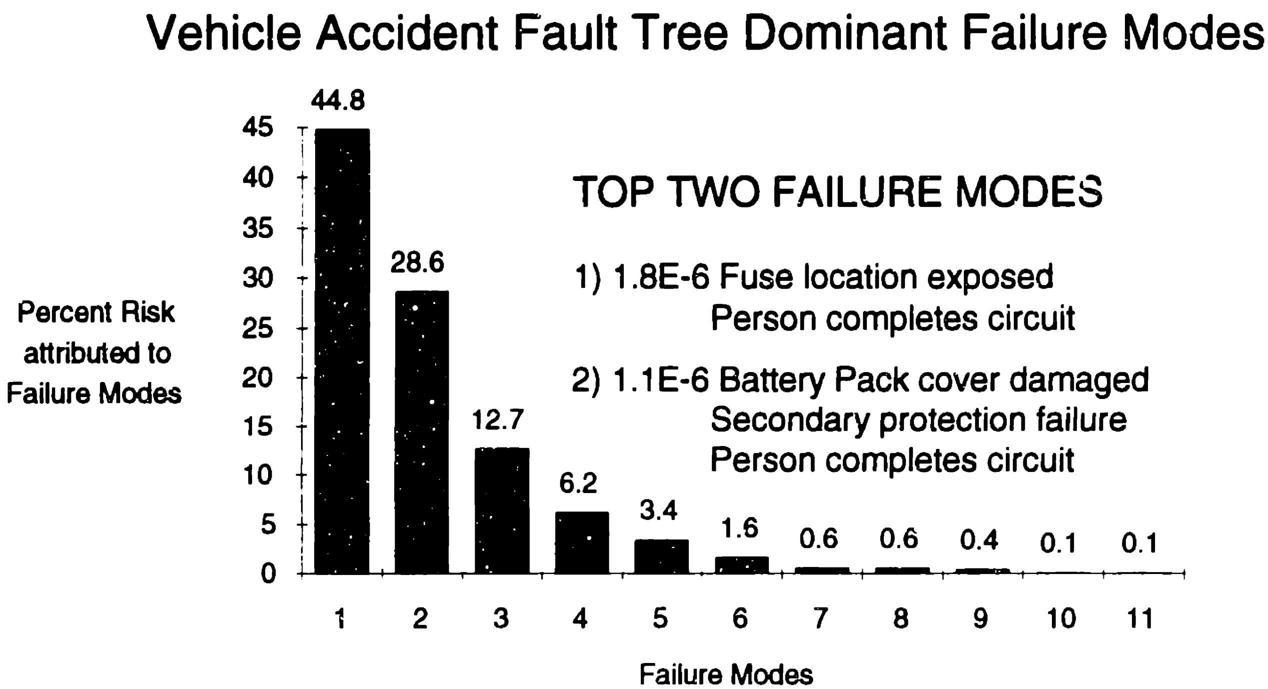


figure 52
Vehicle Accident Fault Tree Results

Consequences

It is particularly difficult to predict what the consequences of electric shock may be. Even if we have exactly the same circumstances, the results will vary, sometimes dramatically, from person to person. Underwriters Laboratory sets a "safe" voltage threshold at 42.4 volts regardless of type (ac or dc). However, there have been cases of electrocution at lower voltages and many people have survived electric shock from much higher voltages.

electrocution at lower voltages and many people have survived electric shock from much higher voltages.

In people who have suffered an incident of electric shock, there does appear to be evidence of a statistically significant increase of some medical problems, including:

Death	Cataracts	Fractured Bones
Eye Injury	Neurological Injury	Arrhythmias
Dislocations	Fetal Abortion	DORV[19]
Motor Neuron Syndrome	Burns	Tetanus
Arterial Thrombosis	Gangrene	Necrosis
Edema	Fibrosis	Epilepsy

There is strong debate among researchers whether these are truly a result of electric shock or if there is some other factor at play. In the case of certain things such as fetal abortion, research indicates that it is very unlikely that the electric shock was the direct cause.[20]

The problem is there is very little experience with dc voltage in this range and in similar applications. There is nothing definitive regarding the consequences and there is continuing debate among the scientific and medical community. One of the areas that is agreed upon, and we do understand, is the muscular reaction to electric shock. Based on studies done on animals and humans[21], it is clear that the muscles will contract and release with a great deal of force. With alternating current, the muscle contraction will frequently cause a person to "freeze" to the circuit. With direct current a person can

---

[19]Double Outlet Right Ventricle

[20] Interview with Dr. L.A.Geddes, Purdue University, 15 August, 1991.

[21] D.F. Dahlziel, ""The threshold of Perception Currents," AIEE Transactions on Power Apparatus and Systems, August 1954.

always "let-go"[22], but when they do, they are often "kicked" or "thrown" off the circuit due to another muscular response. So for direct current, there is an initial muscular contraction, no muscle response during the current flow, then a final muscular response when the circuit is broken (see fig. 52). These two responses are referred to as the "make shock" and the "break shock".

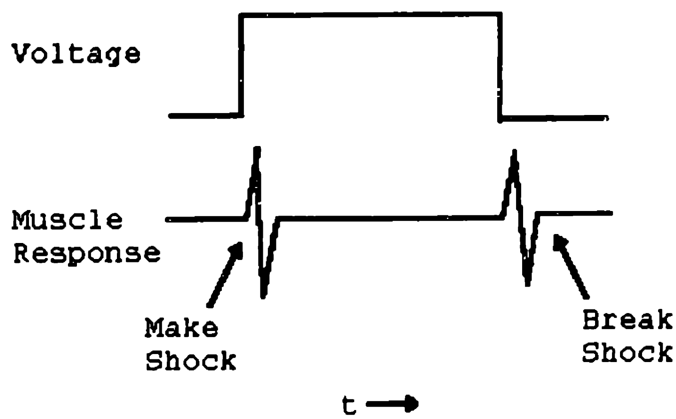


figure 53
Muscular Response due to dc Voltage

These very strong muscular contractions are the cause of several injuries. Frequently when the person releases the circuit, the body is thrown or falls with enough force to cause serious injury and occasionally death. Additionally, it has been well established that muscular contractions can break bones and in fact there have been several cases documented where the actual muscular contraction itself was the cause of fractures, most commonly to limbs, but occasionally to the skull, vertebrae or "collar bones"[23].

22 Ibid.

23 Dean T. Stueland, op. cit.

These muscular contractions can also cause heart fibrillation in humans. This is a situation where the heart begins to pump asynchronously. Fibrillation is a frequent cause of death with alternating current. It is not however, anywhere as likely with direct current, but still a possibility. There is a period of time during a heart beat at which the heart is very susceptible to fibrillation (see fig 54). The vulnerable period lasts approximately 50-70 milliseconds of a typical 1 sec heartbeat. If either muscular contraction occurs during that time, the heart could go into fibrillation.

Because the consequences are so difficult to determine and because a 324 volt electric shock is unquestionably undesirable, I defined electric shock as an undesired event, regardless of the exact consequences.

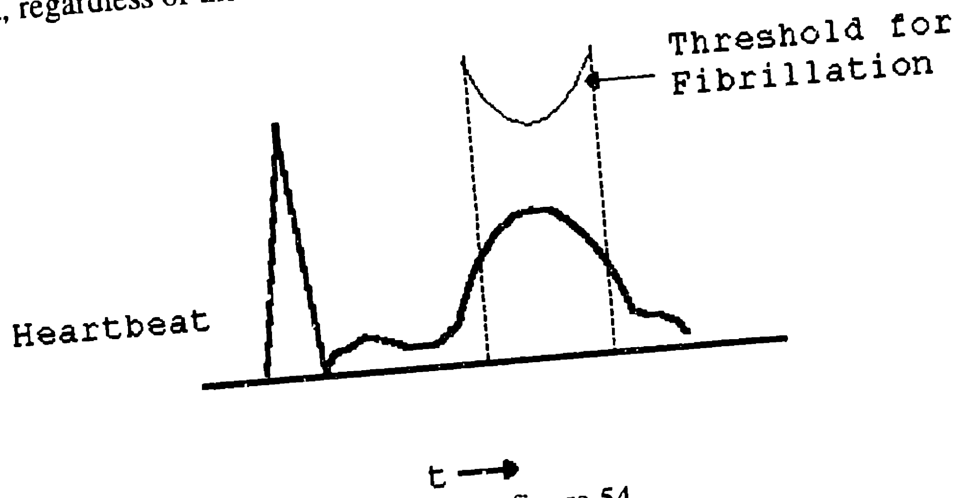


figure 54
Vulnerable Time for Heart Fibrillation

Interpretation of Results

Based on the results, I believe that this propulsion system is "safe". If the fuse system can be made even less accessible, the risk of electric shock can be dramatically reduced even from its current low level. There have been several safety measures put in place to protect against any unintentional electric shock and they would appear to be effective. The highest risk is present during the assembly of the vehicle (still very low), but this is also the most easily controlled environment.

Conclusions

One of the most obvious conclusions that can be drawn from the results is that if we focus our attention on a very few items and improve them, we can significantly reduce the overall risk. In all four cases, the fuse location being exposed, and a person completing the circuit, was the number one most critical path. Therefore, if we can reduce the possibility of the fuse location being exposed, we can significantly reduce the overall risk of electric shock.

There is a list of all the basic events in Appendix A. This list is ordered by decreasing Fussell-Vesely importance (F-V). The Fussell-Vesely importance number is an indication of how much that particular event contributed to the failure probability. This list also shows the risk reduction ratios and risk increase ratios. The risk reduction ratio shows what factor the risk can be reduced by if the probability of failure for that particular event was zero. The risk increase ratio shows by what factor the risk would increase if that basic event always failed.

This list can be used to determine which basic events to focus on. If a basic event is a part of the most critical cutset, the temptation is to try to improve it. However, in the case of an event that when it is perfect (the event risk is zero), the overall risk will remain the same, then additional risk reduction effort should not be focused on that event, but rather on the other basic events that can improve the overall risk.

There are two conclusions we can draw from this list for GM's Impact. The first is that both basic events and cutsets are significant and need to be analyzed as a total system. Although a basic event is a part of the dominant failure mode it does not necessarily mean that GM would need to improve it. One of the other basic events may be the culprit. The second is that human error is the most significant basic event in all four trees analyzed. This will frequently be the case in "real world" experience. While human error cannot be engineered out, per se, products can be engineered so that human error is not as much of a factor. The conclusion I draw from this is that GM needs to consider not only how GM products are intended to be used, but also, how they may be misused. In fact, during the course of this study, GM engineers made design improvements to specifically address human error.

As mentioned earlier, electric shock was chosen as the top undesired event. Based on the information that the medical community has, specific data is lacking. Therefore, I concluded that we want to avoid any electric shock, regardless of the severity.

I also make a very cautious conclusion that the risk associated with electric shock due to GM's electric propulsion system design appears to be minimal, certainly less than the risks associated with gasoline internal combustion engines, provided the fault tree is complete.

Finally, I concluded that safety and low cost are not mutually exclusive. Given the correct analysis, GM can save money and have a safer vehicle by avoiding "band-aid" engineering and focusing attention on the truly critical areas.

Safe Handling Recommendations

This section suggests possible ways to reduce the impact of human error on the risk of electric shock. Some of these recommendations are currently being implemented, others are under investigation. This is not meant to be an exhaustive list, and these recommendations are based only on this study. The final decisions will be made, I'm sure, by incorporating the results of several analyses. Also, these recommendations are made with regard to the electrical safety only. Other concerns such as safely handling the mass of the battery pack are not included.

The single largest contributor to risk in all of the fault trees is human error. This is difficult to control because it is hard to predict the many different ways that people might contact the vehicle. To address this problem, I would recommend the following:

> Insert the fuse system as one of the last operations on the assembly line and remove the fuse system as the first operation during service. As can be seen from the fault trees, this will keep the risk minimal as the window of exposure has been reduced to only three of the four major branches on each of the trees.

> All subsequent vehicle assembly operations within the motor compartment or pertaining to the propulsion system should be one handed after the battery pack is installed. This will greatly reduce the probability of getting across a live circuit. It will also help to minimize the consequences if there is an incident of electric shock. The idea is that the current will more likely be isolated in a single limb. This may not be practical and therefore additional consideration should be given to "error-proofing" the design.

> Increase public awareness of the danger in tampering with electric vehicles. This should be done similar to seat belt awareness advertising--not as an inducer of fear, but rather as an educational presentation.

Increase awareness through training. Engineers, technicians, assemblers, and rescue personnel should be trained simply to be aware of the potential risk when they handle these parts. Battery pack assemblers and service technicians should receive more extensive training on how to safely handle the batteries once the protective covers are removed.

Battery pack assembly and disassembly should be carefully controlled. I would recommend isolating the area for this activity and also carefully restricting entry and exit to only those personnel who have received the additional training. The design relys heavily on the protective covers over the batteries and once they are removed, the risk is increased significantly

In addition to the actions mentioned above to minimize human error, there are design changes that can help reduce the chances or likelihood of this error.

Change the design of the fuse location so that it is even more difficult to attain inadvertent access. (This particular recommendation has already been addressed by General Motors based on the strong result of the fault trees.)

Color code 324 volt components. This suggestion has some drawback. For those people who are color blind, it is ineffective. Also, the inflatable restraint system is color coded yellow already and we may create more problems if we try to color code too many things. A third argument against this is that if there should be a mistake and a 324 volt wire is not the color it is supposed to be, an operator might mistakenly believe it was safe handling that wire when in fact they wouldn't be. Given all of the above arguments, this option may still prove advantageous. In fact GM has already acted on this recommendation and the 324 volt wires are color-coded.

Labels and warnings should be added to all 324 volt components so that in the event of an accident, a potential rescuer will be able to easily identify and avoid high voltage components. These labels should either contain clear graphics, or should be multi-lingual. We may also be able to discourage any would be mechanics from attempting to service their own vehicle without the proper knowledge. I would suggest that along with a high voltage warning, we incorporate a reminder to pull the fuse prior to servicing these parts.

Design safety mechanisms such that safety is maintained even if a person short cuts or by-passes safety procedures. The human error element makes it necessary to have both a manual and automatic disconnect mechanism for protection.

In addition to the above recommendations, I would also like to suggest the following:

There were very divergent opinions regarding whether the fuse system would be destroyed in accidents above 35 miles per hour. This accounts for a very small percentage of accidents (less than 2%) therefore, it did not change the result of this analysis. However, in the interest of avoiding an incident of electric shock, and the very bad publicity that would accompany an accident such as this, I would recommend that GM incorporate into crash tests a check on the fuse system location to make sure that it is located in the best possible place to avoid its destruction even in high speed accidents.

Finally, I would strongly recommend that fault tree analysis be performed on the assembly and service of the battery pack itself. I would also suggest the other new safety critical systems on this car be analyzed similarly.

Consumption is the sole end and purpose of production; and the interest of the producer ought to be attended to only so far as it may be necessary for promoting that of the consumer.
Adam Smith (1723-1790)
Wealth of Nations 1776

7. The Concept of Acceptable Risk

The focus of this chapter is the issues that need to be considered when decisions are made regarding how much risk society is willing to accept. The risk associated with the current product--internal combustion engined vehicles--is assumed "acceptable", as evidenced by the fact that people continue to purchase and use them. Other factors that influence the decision and that are included in this chapter are: perceptions of risk, vehicle sales in the event of an electrical accident, and possible litigation.

It is not possible to eliminate all risk. Therefore, it is necessary to find some point at which the risk is acceptable. By that I mean some point at which the benefits of increased safety are outweighed by the benefits of a better product. For example, we could eliminate the risks of vaccinations, which cause several deaths each year, by restricting or banning their use. However, most people view the risks as acceptable given the benefits received. Following are some of the considerations that were taken into account when trying to define an "acceptable" risk for electric vehicles.

Internal Combustion Engines

To effectively evaluate the safety of an electric vehicle, we need to understand the safety issues of internal combustion vehicles to use as a baseline for comparison. This section is a discussion of the risks associated with driving an internal combustion engined vehicle and what factors effect that risk. The intrinsic risk of the method of propulsion is discussed in the context of the extrinsic risk of the vehicle itself. Data on risk associated with internal combustion engined vehicles is given as a guide to compare the risk that was calculated for electric shock potential of electric vehicles.

Extrinsic vs Intrinsic Risk

The study of the risk associated with the voltage on this vehicle is interesting and useful due to the unique nature of the application. It is important, however, to note that overall vehicle safety is not a function of the method of propulsion or energy used. The intrinsic risks associated with the propulsion system are usually orders of magnitude less than the dominant extrinsic risks associated with driving a vehicle. For example, there are nearly 50,000 automobile related fatalities each year in the United States, of those fatalities, slightly less than 500 are directly attributable to the propulsion system.[24] Consequently, major swings in the intrinsic risk are reflected as minor swings in overall vehicle safety. Nevertheless, it is still important to understand and to minimize the intrinsic risk because of the potential negative effect an incident of electric shock could have on vehicle sales, litigation, and public perception.

Extrinsic Vehicle Risks

The greatest source of injury and death in an automobile is an accident. The major contributor to that risk is the consumption of alcohol. While the percentage of alcohol related fatalities has been decreasing over the past decade, in 1989 they still accounted for over 49% of fatal accidents[25]. Once an accident has occurred, there are many factors that affect the risk and severity of injury:

---

[24]U.S. Department of Transportation National Highway Traffic Safety Administration, Fatal Accident Reporting System 1989--A Decade of Progress (Washington D.C.: National Center for Statistics & Analysis, 1989).

1. Use of seat belts or other restraint systems.[26]
2. Crash characteristics of the particular vehicle
3. The g-loads imposed on the occupants
4. Vehicle size and weight
5. The propulsion system and energy storage device[27]

This list remains the same whether the propulsion system is gasoline internal combustion or electric. There are five basic causes of injury in vehicle accidents. They are:

Ejection-- This is the leading cause of injury and death in vehicle accidents.[28] The frequency of ejection has decreased significantly with the increased awareness and use of seat belts as well as certain design improvements such as the safety door latch. In accidents where an occupant was completely ejected from the automobile, 72.4% were killed in 1989.[29]

Hard Structure Contact -- Hitting a hard structure, such as a steering wheel or windshield, within the interior of the car is another significant cause of serious injury or death in vehicle accidents. There have been

[25]Ibid.

[26]There have been several studies conducted to determine the effectiveness of seat belts. They indicated that the risk of fatal or serious injury is reduced between 40 and 55 percent for front seat passengers.nhtsa

[27] E. Behrin, et al, op. cit..... .

[28]Ibid.

[29]U.S.Department of Transportation National Highway Traffic Safety Administration, General Estimates System 1989--A Review of Information on Police-Reported Traffic Crashes in the United States, (Washington D.C.: NHSTA, 1990).

major design improvements to reduce this risk such as collapsible steering wheels, padded instrument panels, and laminated windshields. However, this remains one of the leading causes of injury and death.

Structural Collapse -- In this case, rather than the person contacting the object, the actual structure of the car collapses into the person causing injury or death. Again, design changes have been made to reduce this risk. Strengthened B-pillars, transverse beams in the doors, and roll bars are just a few.

Acceleration (g) loading -- The g-loads themselves can be enough to cause injury or death. The head and neck are particularly susceptible to an injury of this type.

Fire -- Fire occurs in about .2% of all accidents, but 3% of all fatal accidents and it is the most harmful event in about 1% of motor vehicle fatalities[30]. Despite these rather low statistics, fire is one of the most feared occurrences in vehicle accidents. Because of the sensationalist nature of fire, the media tends to give it considerable press and certainly the entertainment industry uses it as well. The result of this over-exposure is that we, the public, tend to think that fires occur much more frequently than they do.

---

[30]Ibid.

Internal Combustion Engine Comparison

The propulsion system can cause injury or death either by direct contact or fire. Direct contact such as getting body parts caught in fan belts or flywheels exploding, is such a rare event that it is statistically negligible[31]. However, the fire problem, as noted above, is very real. In 1989, there were 436 deaths in the United States that were a direct result of fire associated with a motor vehicle accident.[32] There were almost 45,555 deaths total in the United States in 1989 as a result of vehicle accidents.

In the case of a vehicle accident, probably the most direct comparison between the two types of propulsion systems would be the risk of fire with internal combustion to the risk of electric shock for the electric vehicle. However, it is not possible to make a direct comparison between the two for several reasons. There is still the possibility that if an electric vehicle is in an accident with an internal combustion engined vehicle, there may still be a gasoline fire. I also cannot totally eliminate the possibility of a fire as a result of the batteries on the electric vehicle. Also, in this work, I am considering electric shock as the undesirable event, regardless of the severity of the consequences, whereas in the case of fire, we only have statistics for fatalities due to fire.

During the assembly process, it is also difficult to find a direct comparison. It is not appropriate to compare to the fuel system as there is no fuel in the vehicle during the assembly process. This would be comparable to building the electric vehicle with the batteries not charged. One data point that can be used as a point of reference is the current number of injuries from 12 volt batteries. In every assembly plant, regardless of volume, there are usually one or two serious injuries from working with batteries each

---

[31]E. Behrin, et al, op.cit.

[32]NHSTA, FARS, op cit.

year[33]. These injuries typically involve burns because of heat dissipation from rings or watches that become a direct short from the positive terminal to ground. Obviously, there is a discrepancy once again between the severity of the consequences. In some cases the severity might be comparable, but certainly, the risk of death is much less when a person becomes a part of a 12 volt circuit as opposed to a 324 volt circuit. I would also expect that there will be more care taken with the electric vehicle batteries.

During normal use, service, and repair of the vehicle, the most appropriate comparison would be injuries that are a direct result of the internal combustion propulsion system (flywheels exploding, getting fingers or hands caught, etc.). Unfortunately, this type of statistic is not readily available. The medical community does not consistently and accurately record the data that would be necessary to determine this--the cause of death might be "excessive loss of blood", not "hit by flywheel". Also, there may be occasions when there was no medical attention sought. It is known that this is a very rare occurrence--much less likely than fire.[34]

Perception of Risk

The amount of risk that is considered acceptable in the current product is only one factor in what might be considered acceptable for a new product. Based on several studies done on risk perception, it is clear that perception of risk is not necessarily a rational thing. Nor is it founded in factual data[35]. Why, for example, do communities violently oppose locating a nuclear reactor or a liquid natural gas terminal near them

---

[33]Interview with Rob Hart and Al McCarthy, GM-UAW Health and Safety, Warren, Michigan 15 July 1991.

[34]E. Behrin, et al, op.cit.

[35]Paul Slovic, Baruch Fischhoff, and Sarah Lichtenstein, Facts and Fears: Understanding Perceived Risk pp 181-216.

despite the many experts assuring them of the safety? Why, on the other hand, do people continue to live on the San Andreas fault, despite the many warnings of experts?

In all forms of analysis, including this one, there is a certain amount of subjectivity. Even when there are "hard facts" however, there are other aspects that need to be considered when making decisions on acceptable levels of risk. First, there are several factors that effect our judgment of risk. These are sometimes appropriate guides, but frequently our view is distorted or biased because of them. They include:

Availability -- If a person can easily recall an instance of something happening, they will generally judge that it is more likely to happen. One factor that may lead to a distorted view of risk is media attention. In research conducted on this subject, accidents were thought to cause as many deaths as diseases, when in fact, diseases claim almost 15 times as many lives.[36] Media coverage of diseases was found to be negligible in this study, whereas dramatic and sensational events received a disproportionate amount of coverage. A strong similarity was found between the media coverage and the biased judgements. Certainly, movies such as Jaws can provide a dramatic example of how our perception of a particular risk can be distorted because of exposure. The VietNam war claimed about as many U.S. lives per year as do auto accidents, yet the public response is very different to these two events, in part because of the media coverage.

One of the most interesting and surprising findings of this thesis was the mental attitude I discovered. It became clear very early that people view batteries as safe. While they may be very cautious in their home with the 110 or 220 volt utility service, they were very casual with regard to the battery pack that was delivering 324 volts. The

---

[36]Ibid.

only explanation may be that people think of electricity in terms of its context. The feeling of security could have come from the association with cars, or batteries--people don't get electrocuted from either. There was a distinct look of shock on faces as the realization hit home that these batteries were capable of severe injury to humans.

In an interview conducted with representatives from GM's marketing department[37], it was clear their opinions were similar. They had two specific concerns. First, they commented that "negatives and dirt make for much more interesting news articles.--they attract media attention". Second, they were concerned about the possibility of maiming someone and the possible negative publicity that this would cause because "the visual impact is important". They cited Kimberly Bergalis as an example.[38]

Overconfidence -- A second factor that distorts our view of risk is overconfidence. This is an area engineers need to pay particular attention to. First, many product designers tend not to consider human error when they think of the ways a system can fail. As the results of the fault tree show, this is an important component of system failure. Second, there is a tendency to not consider how people will react to safety measures. Some people will frequently do simple repairs on their household wiring without shutting off power, because there is a fuse system to protect them if something should go wrong. If there was no fuse protection system, there might be more caution in the first place. Third, there is a tendency to overlook common mode failures. For example, the cables controlling the safety systems at a nuclear reactor in Browns Ferry,

---

[37]Interview with Sean McNamara and Amy Rader, Electric Vehicle Platform, General Motors Corporation, Warren, Michigan, Sept 26, 1991 1-2pm

[38]Kimberly Bergalis contracted AIDS from her Florida dentist. She received a great deal of publicity while lobbying for AIDS testing for people in the medical profession. Her appearance was so gaunt that it illicited a strong emotional response from those who saw her.

Alabama were all placed close to each other. A single fire disabled all five emergency core cooling systems. [39]

Desire for Certainty -- Most people have difficulty dealing with uncertainty, even on a very simple level. It causes anxiety[40]. One of the ways that people manage uncertainty is simply to deny it (our destiny or fate is already set). Also, we may try to convince ourselves that we have some control over it. When people are confronted with a risk that they can't deny, they will frequently try to outlaw the risk(control it). The response by many to nuclear power is a clear example of this.

It won't happen to me -- This is a well known and documented way of thinking. People feel immune to the hazards of everyday life. We need to be aware of this phenomenon and, if possible, engineer to specifically address this phenomenon in the design of safety systems.

In addition to having possibly flawed perceptions of risk, the public also has the expectation that new products must be safer than old ones. Once again, nuclear power is an excellent example--even though nuclear power is expected to be related to only 100 deaths each year[41], it is still feared much more than smoking which is expected to kill approximately 150,000 people in the U.S. per year.[42] One conclusion drawn from a study on perception of risk was that new technologies are less well understood or familiar

---

[39]Slovic, et al.

[40]Ibid.

[41]Ibid.

[42]Ibid.

and therefore incite more fear. The GM marketing personnel interviewed confirmed this. They stated that in recent years, the overall safety standards that the public, and therefore the government, requires has been drastically increased.

Another aspect that influences the perception of a products safety is how early in the product life an accident occurs. If there is an incident of electric shock in an electric vehicle early, it will be taken as a signal that the product is not safe. However, if the vehicle is out on the market and in significant use for several years before anything happens, it will probably be regarded as a one time occurrence--not as a signal that the vehicle is not safe. In general, this is a logical and appropriate response, except when that one early data point causes us to always view something as unsafe even given additional contradictory data.

In the study conducted by Slovic, et. al., they state, "accidents signaling either a possible breakdown in safety control systems or the possibility that the mishap might proliferate were judged more worrisome and in need of greater awareness and greater public effort to prevent reoccurrences. The number of people killed appeared to be relatively unimportant in determining these aspects of seriousness. An accident that takes many lives may have little or no impact on perceived risk if it occurs as part of a familiar, well-understood and self-limiting process. In contrast, a small accident may greatly enhance perceived risk and trigger strong corrective action because it increases the judged probability of future accidents."[43]

The GM marketing personnel confirmed these findings. "Timing is crucial. If the electric vehicle has been on the road for a few years before an accident happens, it

---

[43]Ibid.

could survive the press. However, if it occurs early in the life cycle, it will probably kill the car". GM and others also were concerned that if a consumer finds out something unexpected, then they worry about what else GM didn't tell them[44]. GM marketing further commented that the system for shutting down power has to be "fool-proof". It cannot be complicated or tricky.

Once opinions are formed regarding the safety of a product, they are very difficult to change. Even in the face of contrary evidence, opinions persist. The initial impression determines the way the subsequent evidence is viewed. New evidence is viewed as reliable and informative if it supports one's beliefs. It is viewed as unreliable, or flawed if it opposes one's belief. For example, the accident at Three Mile Island was viewed as either an indication of the effectiveness of the safety systems if the technology was viewed as safe, or proof that nuclear power is unsafe if the technology was viewed as unsafe prior to the accident. In addition, it has been said that you can prove just about anything with statistics, and there does always seem to be someone willing to dispute the experts. So not only do we process information to suit our opinions, we are also frequently able to find "facts" to support us.

There are many people who mistakenly believe that the benefits of electric vehicles will be seen, and that these benefits will outweigh the possible risk of electric shock. It has been shown that perceived benefit plays a secondary role to perceived risk[45]. The marketing studies also indicate that good publicity for the environment and economy is not nearly enough to outweigh the impact of an electrocution.

[44] Joani Nelson-Horchler, Safety: A Tough Sell, Industry Week, Vol: 236, Iss 1, Jan 4, 1988, pp:24.

[45] Slovic, et al. op cit.

There have been numerous studies that try to compare different risk factors with perceptions of risk to try to determine risk conversion factors (RCF). That is, how much safer does one product have to be for it to be viewed as "acceptable". Litai, et al, have identified nine characteristics that detemermine how risk is perceived[46]. Associated with each of these characteristics they quantified a risk conversion factor. For example, for the characteristic of "origin", the public on average will accept a risk 20 times greater if it is natually occuring versus a man-made one. These factors are important for determining how much safer an electric vehicle needs to be. A listing of the characteristics and their associated RCF as determined from Litai, et al, can be found in appendix D.

Based on perceptions of risk and expectations of safety, GM cannot simply achieve the same safety level of existing internal combustion engined vehicles and assume that will be acceptable. The automobile industry and GM needs this vehicle to be considerably safer immediately upon introduction to the market. They cannot afford to let customers test products.

Marketing Concerns

According to E. Behrin,et al, "there are two primary factors that govern the penetration of a product into the consumer marketplace: the degree to which the technical performance of the product matches the consumer's perceived need and the degree to which the cost of the product matches the consumer's judgment as to the value received."[47] I would like to argue that the perceived safety of the product, particularly with automobiles, is also a primary factor.

---

[46]D.Litai, D.D.Lanning, and N.C. Rasmussen, The Public Perception of Risk, Proceedings, Meeting of Society of Risk Analysis, Washington D.C., June 1981.

There have been several cars that have failed due to alleged safety problems. Even when the allegations did not prove to be founded, the vehicle sales dropped off dramatically. The Audi 5000, the Citation, the Jeep CJ, the Pinto, the Suzuki Samurai, and the Corvair have all had the misfortune of being labelled "unsafe". The sales data for some of the above vehicles, are shown in Appendix E.

In addition to the marketing risk that GM is taking with the Impact, it is also possible that if another electric vehicle, made by a different manufacturer, has a safety problem, that it will reflect poorly on General Motors. Because of this, GM should consider sharing any safety information they obtain with the auto industry.

Based on GM marketing research conducted in Los Angeles, consumers are concerned about the possibility of electrocution. There were repeated comments concerning charging of the vehicle. Specifically mentioned were charging during the rain, children playing around the vehicle, and running over the chord with a lawn mower. In addition to the comments made by consumers, there have also been articles in the media expressing concern over the high voltage of these vehicles.

Children are a particularly sensitive issue. If a child is hurt or killed, the consequences will be much worse than an adult because of the emotional response that will be created. People feel that children don't know better, and that they should be able to play and be curious without being killed.

---

[47] E. Behrin, et al, Energy Storage Systems for Automobile Propulsion, vol 2. detailed report Lawrence Livermore Laboratory, Livermore, California UCRL - 52303 - vol. 2 U.S Department of Commerce December 1977

One of the curious things that has repeatedly shown up in studies of risk, is that the public is willing to accept risks associated with voluntary things. Mountain climbing, bungi jumping, and parachuting are approximately 1000 times greater in risk than what people will accept from an involuntary activity.[48]

Product Liability Issues

Whenever a new product is introduced, the possibility of product liability lawsuits must be considered. While there is nothing that can be done to guarantee there will be no lawsuits against a product, there are things that can lessen the probability. The Consumer Products Safety Commission (CPSC)[49], which is the government's primary regulator for product safety, and has the power to recall products it deems unsafe, has recommended the following 10 actions be taken to protect consumers and avoid costly product liability litigation:

1. Establish and observe a written corporate safety policy.
2. Create an independent safety review process.
3. Identify and evaluate the severity and foreseeability of product hazards.
4. Conduct a design review assessing the risk of injury by considering the hazards, the environment, and the foreseeable use.
5. Attempt to eliminate hazards.
6. Warn users of product dangers and motivate them to avoid injury
7. Promote only the safe use of a product
8. Maintain safety-related records during the product's useful life.

---

[48]Slovic, et al, op cit..

[49]CPSC established in 1972 with the passage of the Consumer Product Safety Act

9. Continuously monitor the safety performance of the product in the hands of users.
10. Promptly notify product users and institute recall procedures when necessary to substantially reduce or eliminate injury.[50]

The CPSC has publicly stated that their list of top priority items is based on the following nine criteria:

1. The frequency of accidents.
2. The severity of accidents
3. The amenability of regulatory prevention
4. The chronic nature of risks
5. Benefit-cost ratios
6. The unforeseen nature of risks
7. The probability of exposure
8. The vulnerability of the population to risks
9. Agency resource usage.[51]

In addition to the actual cost of litigation, there is indirect cost associated with damage to a company's reputation. It was found that stock prices for publicly traded companies fell an average of 7% of net worth following the unexpected announcement of a product recall.[52]

---

[50]William F.Kitzes, Safety management and the Consumer Product Safety Commission, Professional Safety, Vol:36, Iss:4, Apr 1991, pp:25-30.

[51]Lacy Glenn Thomas,Revealed Bureaucratic Preference: Priorities of thr Consumer Product Safety Commission , Rand Jrnl of Economics Vol: 19, Iss 1, Spring 1988, pp:102-113.

[52]Paul H Rubin, Dennis Murphy, and Gregg Jarrell, Risky Products, Risky Stocks , Regulation Vol: 12 Iss 1 Date: 1988 pp: 35-39 Jrnl Code: RGO ISSN: 0147-0590.

No one can deny that product liability litigation in our society has reached astronomical proportions and the settlements awarded have been steadily increasing as well. Given the type of injury that would result from an incident of electric shock, the emotional response of a jury would be fairly predictable.

Consequently, in making decisions about what level of risk is acceptable with this product, GM needs to consider several things. First, the way that risk is perceived and what influences that perception, ie. biased media coverage, desire for certainty, etc. Second, GM needs to consider the marketing implications that our decision will have. It is possible to have a very safe product, yet not be able to sell it if a poor decision leads to the label of "unsafe". Third, GM has to consider product liability litigation. Any one of the above three issues can destroy GM's product if they end up on the wrong side of the equation, regardless of how safe the analysis shows GM's electric car to be.

Where safety is critical GM should use other available techniques to check the accuracy of the system (including engineering judgement) and verify that all agree. I would also like to add a note of caution that GM should not base safety decisions solely on the numerical results of analysis such as this one. Other considerations such as marketing and litigation should be taken into account when deciding what level of risk is acceptable.

Closing Remarks

Based on the fault tree analysis conducted, General Motors has made several design changes to the Impact electric propulsion system. They have also implemented some of the recommendations and continue to incorporate many of the others. The fuse/manual disconnect has been supplemented with an electro-mechanical switch connected in series between the batteries and the fuse location that is automatically open whenever the fuse system is removed. This greatly reduces the chances of electric shock through the fuse location as it is now inert. The 324 volt circuitry has also been color coded. The inclusion of the "daisy chain" feature was justified by analyzing the fault tree with and without the feature.

Because of the very favorable results of the fault tree analysis and the ensuing design changes made by General Motors, it would appear as if the Impact has the potential to fall within the "acceptable level of risk" range for a new product of this type. This will not be known with any certainty, of course, until the vehicle is in the market. However, General Motors is proactively pursuing this goal in very constructive fashion by analyses such as this one, and it would appear that they are properly addressing the issues that arise.

Appendix A

Basic Events

Event	Description	Prob	K	Location
BE01	Fuse location exposed--assembly prior to fuse	1.0	0	Elecsh01
BE02	Wire severed--assembly after fuse install	3.3-6	4.5	Elecsh02
BE03	Wire ins dam--assembly after fuse install	6.6-5	5.3	Elecsh02
BE04	Fuse location exp--assembly after fuse install	2.1-6	13.3	Elecsh02
BE06	Cable severed--normal use	1.2-4	84.1	Elecsh03
BE07	Wire ins dam--normal use	4.4-5	13.6	Elecsh03
BE08	Fuse location exposed--service/repair	8.5-5	4.5	Elecsh04
BE09	Wire severed--service/repair	9.3-6	27.1	Elecsh04
BE10	Wire ins dam--service/repair	2.3-4	17	Elecsh04
BE11	Fuse location exp--vehicle accident	9.5-4	6.1	Elecsh05
BE12	Wire severed--vehicle accident	1.1-2	36.8	Elecsh05
BE13	Wire ins dam--vehicle accident	3.1-2	3.4	Elecsh05
BE14	Failure to gnd to chassis--wire term--assembly	2.9-1	2.4	Fuse01
BE15	Fail to int daisy chain--wire term--assembly	2.8-3	7.5	Fuse01
BE16	Fail to gnd to chassis--ins dam--assembly	6.6-3	1.1	Fuse02
BE17	Fail to int daisy chain--ins dam--assembly	6.0-1	1.4	Fuse02
BE18	Fail to gnd to chassis--black box--assembly	8.4-5	6.2	Fuse03
BE19	Fail to int daisy chain--black bos--assembly	4.4-6	6.9	Fuse03
BE20	Fail to gnd to chassis--sev wire--assembly	6.6-3	1.1	Fuse04
BE21	Fail to int daisy chain--sev wire--assembly	2.3-2	5.9	Fuse04
BE22	Fail to gnd to chassis--sev wire--normal use	5.4-2	2.9	Fuse05
BE23	Fail to int daisy chain--sev wire--normal use	1.2-2	7.1	Fuse05
BE24	Fail to gnd to chassis--black box--normal use	1.9-3	2.8	Fuse06
BE25	Fail to int daisy chain--black box--normal use	1.9-6	6.3	Fuse06
BE26	Fail to gnd to chassis--term exp--normal use	2.0-1	2.1	Fuse07
BE27	Fail to int daisy chain--term exp--normal use	3.7-3	11.2	Fuse07
BE28	Fail to gnd to chassis--ins dam--normal use	5.4-2	2.9	Fuse08
BE29	Fail to int daisy chain--ins dam--normal use	6.0-1	1.4	Fuse08
BE30	Fail to gnd to chassis--term exp--service/repair	8.9-2	2.8	Fuse09
BE31	Fail to int daisy chain--term exp--service/rep	2.7-4	31	Fuse09
BE32	Fail to gnd to chassis--sev wire--service/repair	5.5-3	2.1	Fuse10
BE33	Fail to int daisy chain--sev wire--service/repair	4.3-3	6.3	Fuse10
BE34	Fail to gnd to chassis--black box--service/rep	1.0-5	8.4	Fuse11
BE35	Fail to int daisy chain--black box--service/rep	2.5-6	6.8	Fuse11
BE36	Fail to gnd to chassis--ins dam--service repair	5.5-3	2.1	Fuse12

BE37	Fail to int daisy chain--ins dam--service repair	6.4-1	1.4	Fuse12
BE38	Fail to gnd to chassis--black box--accident	3.3-3	2.9	Fuse13
BE39	Fail to int daisy chain--black box--accident	1.7-2	6.1	Fuse13
BE40	Fuse system destroyed--accident	1.2-3	2.5	Fuse13 Fuse14 Fuse15 Fuse16
BE41	Failure to gnd to chassis--term exp--accident	9.0-2	3.0	Fuse14
BE42	Failure to int daisy chain--term exp--accident	5.7-3	11.5	Fuse14
BE43	Failure to gnd to chassis--sev wire--accident	9.8-3	4.3	Fuse15
BE44	Failure to int daisy chain--sev wire--accident	9.4-2	3.5	Fuse15
BE45	Failure to gnd to chassis--ins dam--accident	9.8-3	4.3	Fuse16
BE46	Failure to int daisy chain--ins dam--accident	2.4-1	1.9	Fuse16
FUSLOC2	Fuse location exposed--normal use	4.4-6	6.1	Elecsh03
HE01	Person completes circuit--prior to fuse install	5.9-4	7.1	Elecsh01
HE02	Protective cover missing--prior to fuse install	1.7-6	11.0	Elecsh01
HE03	Person completes circuit--prior to fuse install	4.4-5	12.6	Elecsh01
HE04	Primary cover missing--after fuse install	5.5-7	12.6	Elecsh02
HE05	Black box--after fuse install	1.9-4	3.6	Elecsh02
HE06	Person completes circuit--after fuse install	1.7-4	22.1	Elecsh02
HE07	Person completes circuit--normal use	1.9-3	6.7	Elecsh03
HE08	Primary cover missing--normal use	3.4-4	16.5	Elecsh03
HE09	Black box-norml use	1.4-4	5.0	Elecsh03
HE10	Person completes circuit--service/repair	4.8-3	4.8	Elecsh04
HE11	Primary cover missing--service/repair	5.9-3	35.9	Elecsh04
HE12	Black box--service repair	3.6-3	15.8	Elecsh04
HE13	Person completes circuit--accident	2.0-3	12.0	Elecsh05
HE14	Primary cover missing--accident	4.3-3	25.4	Elecsh05
HE15	Black box--accident	2.3-1	1.6	Elecsh05
HE16	Failure to remove fuse--service/repair	2.3-2	17.2	Fuse09 Fuse10 Fuse11 Fuse12
PD01	Primary cover damaged--prior to fuse install	2.1-4	11.3	Elecsh01
PD02	2nd protect device failure--prior to fuse install	6.1-4	17.2	Elecsh01
PD03	2nd protect device failure--after fuse install	3.2-5	14.8	Elecsh02
PD04	Primary cover damaged--after fuse install	4.5-6	11.7	Elecsh02
PD05	Terminal exposed--after fuse install	8.6-5	11.9	Elecsh02
PD06	2nd protect device failure--normal use	3.5-4	8.3	Elecsh03
PD07	Primary cover damaged--normal use	4.6-5	12.0	Elecsh03
PD08	Terminal exposed--normal use	2.2-4	4.6	Elecsh03
PD09	2nd protect failure--service/repair	2.4-3	8.8	Elecsh04
PD10	Primary cover damaged--service/repair	1.4-3	9.4	Elecsh04
PD11	Terminal exposed--service/repair	1.5-3	21.5	Elecsh04
PD12	2nd protect failure--accident	3.1-2	10.1	Elecsh05
PD13	Primary cover damaged--accident	2.0-2	9.8	Elecsh05

PD14	Terminal exposed--accident	7.5-3	6.9	Elecsh05
PD15	Fuse system failure--product defect	1.0-5	3	Fuse01-16

Probability Assessments

	Q	1	Q	2	Q	3
	median	95%	median	95%	median	95%
expert						
1						
2	1.00E-04	1.00E-03	1.00E-03	1.00E-03		
3			1.00E-04	1.00E-03	1.00E-07	1.00E-05
4	1.00E-07	1.00E-06	4.00E-05	4.00E-04	2.00E-08	8.00E-08
5	1.00E-06	1.00E-05	1.00E-05	2.00E-05		
6	2.00E-04	1.00E-03	1.00E-05	1.00E-03		
7	1.00E-04	5.00E-04				
8	2.00E-04	1.00E-02	2.00E-03	2.00E-01	1.00E-06	2.00E-05
9	1.00E-04	1.67E-03	1.00E-04	1.67E-03	1.00E-04	1.00E-03
10						
11	5.00E-06	1.25E-05	5.00E-05	1.00E-04	1.00E-05	2.50E-05
12						
13						
14						
15						
16						
17	1.00E-04	1.00E-01	1.00E-06	1.00E-04	1.00E-08	1.00E-07
18	1.00E-07	2.00E-07	1.00E-03	5.00E-03	1.00E-06	1.00E-05
19						
20						
21						
geo mn of median	1.35E-05	1.71E-04	7.25E-05	8.18E-04	5.72E-07	6.31E-06
k	12.64328		11.2817		11.0409	
std dev of normal	1.537652		1.468595		1.455519	
mean	4.40E-05		2.13E-04		1.65E-06	
Basic Event	HE	3	PD	1	HE	2

Q 4		Q 5		Q 6		Q 7	
median	95%	median	95%	median	95%	median	95%
1.00E-03	5.00E-02	2.00E-05	8.00E-05	2.00E-05	1.67E-04		
3.33E-03	1.00E+00	4.00E-05	1.60E-04	1.00E-07	1.00E-05	1.00E-08	1.00E-06
1.00E-04	3.00E-04	3.00E-06	6.00E-06	1.00E-07	2.00E-07	2.00E-08	4.00E-08
2.00E-06	1.00E-05	1.00E-04	1.00E-03	1.00E-06	2.00E-06		
1.00E-06	1.00E-05	1.00E-03	1.00E-02	1.00E-06	1.00E-04		
		1.00E-03	5.00E-03				
2.00E-03	4.00E-02	2.00E-02	1.00E+00	1.00E-06	5.00E-05	1.00E-07	1.00E-05
2.00E-04	1.00E-03	1.00E-03	2.00E-03	1.00E-04	1.00E-03	1.00E-04	1.00E-03
1.00E-04	1.00E-03			1.25E-05	3.75E-05	2.00E-06	2.50E-06
1.00E-04	1.00E-02	1.00E-03	1.00E-02	1.00E-07	1.00E-06	1.00E-08	1.00E-07
1.00E-03	1.00E-02	1.00E-03	2.00E-02	2.00E-06	2.00E-05	1.00E-07	2.00E-06
1.39E-04	2.39E-03	2.94E-04	2.08E-03	1.48E-06	1.74E-05	1.69E-07	2.13E-06
17.18772		7.087858		11.74854		12.58499	
1.723755		1.186899		1.493169		1.534851	
6.13E-04		5.94E-04		4.51E-06		5.50E-07	
PD 2		HE 1		PD 4		HE 4	

Q	8	Q	9	Q	10	Q	11
median	95%	median	95%	median	95%	median	95%
				1E-08	0.000001		
1.00E-04	1.00E-02	1.00E-05	1.00E-03	1.25E-05	1.00E-04		
1.00E-08	1.00E-07					1.00E-06	1.00E-06
1.00E-06	5.00E-06	1.00E-07	2.00E-07				
2.00E-06	1.00E-05	2.00E-06	5.00E-06				
1.00E-06	1.00E-05	1.00E-06	1.00E-05				
1.00E-06	2.00E-06						
2.00E-03	2.00E-01	1.00E-07	1.00E-05				
1.00E-04	1.00E-03	1.00E-04	1.00E-03				
3.33E-06	5.00E-06					5.00E-05	1.00E-04
1.00E-04	1.00E-01	1.00E-08	1.00E-07				
1.00E-04	1.00E-03	1.00E-07	2.00E-06				
				2.50E-07	5.00E-07	2.22E-07	4.00E-07
				1.00E-04	1.00E-03	1.00E-05	2.00E-04
8.33E-06	1.23E-04	6.13E-07	8.18E-06	1.33E-04	4.73E-04	3.25E-06	9.46E-06
14.80811		13.33521		3.556559		2.913679	
1.633439		1.569944		0.768966		0.648131	
3.16E-05		2.10E-06		1.79E-04		4.00E-06	
PD	3	BE	4	HE	5	HE	5

Q	12	Q	13	Q	14	Q	15
median	95%	median	95%	median	95%	median	95%
1.00E-05	1.00E-04	1.00E-06	1.00E-05	1.00E-05	4.00E-05	1.00E-04	1.00E-03
2.00E-05	5.00E-05	5.00E-06	1.00E-05	2.50E-05	1.00E-04	2.00E-05	2.00E-04
		5.00E-08	1.00E-07	1.00E-04	5.00E-04	3.00E-05	6.00E-05
		1.00E-04	1.00E-03	1.00E-04	1.00E-03	1.00E-05	1.00E-03
2.50E-07	4.00E-07						
2.00E-05	1.00E-04						
5.62E-06	2.11E-05	2.24E-06	1.00E-05	3.98E-05	2.11E-04	2.78E-05	3.31E-04
3.760603		4.472136		5.318296		11.89207	
0.802775		0.907798		1.01282		1.500528	
7.76E-06		3.38E-06		6.64E-05		8.58E-05	
HE	5	BE	2	BE	3	PD	5

Q	16	Q	17	Q	18	Q	19
median	95%	median	95%	median	95%	median	95%
				1.00E-03	1.00E-02	1.00E-03	1.00E-02
1.00E-07	1.00E-06						
3.00E-03	7.00E-03	1.00E-05	1.00E-04	1.00E-05	1.00E-04		
1.00E-03	1.00E-01						
2.00E-04	1.00E-03						
				5.00E-01	9.00E-01	2.00E-03	1.00E-02
		2.00E-05	2.00E-04			1.25E-01	6.25E-01
		1.00E-05	1.00E-04			1.00E-01	5.00E-01
1.00E-05	1.00E-02						
1.00E-06	1.00E-05						
		2.50E-09	4.00E-09	4.00E-09	1.00E-08		
		1.00E-05	1.00E-04	1.00E-05	2.00E-04		
2.90E-05	6.42E-04	2.19E-06	1.52E-05	4.57E-05	2.83E-04	1.26E-02	7.48E-02
22.10503		6.931448		6.178009		5.946036	
1.876246		1.173375		1.103634		1.080439	
1.69E-04		4.35E-06		8.41E-05		2.25E-02	
HE	6	BE	19	BE	18	BE	21

Q	20	Q	21	Q	22	Q	23
median	95%	median	95%	median	95%	median	95%
8.00E-01	9.00E-01	1.00E-05	1.00E-07	6.00E-01	9.50E-01	6.00E-01	9.00E-01
		1.00E-04	1.00E-03			9.00E-01	9.90E-01
6.00E-01	9.00E-01	2.00E-01	5.00E-01	1.00E-02	2.00E-02	3.33E-01	5.00E-01
5.00E-01	8.50E-01	2.50E-01	5.00E-01	5.00E-05	5.00E-04	2.50E-02	2.50E-01
5.00E-01	7.50E-01	2.50E-01	7.50E-01	1.00E-05	1.00E-03	2.50E-01	7.50E-01
5.89E-01	8.48E-01	6.60E-03	7.15E-03	1.32E-03	9.87E-03	2.57E-01	6.09E-01
1.440277		1.084472		7.501543		2.366726	
0.221112		0.049147		1.221278		0.522126	
6.03E-01		6.61E-03		2.77E-03		2.95E-01	
BE	17	BE16	BE20	BE	15	BE	14

Q 24		Q 25		Q 26		Q 27	
median	95%	median	95%	median	95%	median	95%
1.00E-03	1.00E-02	1.00E-03	5.00E-02	1.00E-04	2.00E-03	1.00E-04	1.00E-03
1.00E-04	4.00E-04	1.00E-03	1.00E+00	1.00E-03	1.00E-02	1.00E-04	2.00E-04
1.00E-04	1.00E-02	1.00E-01	3.33E-01	1.00E-02	3.00E-02	1.00E-06	1.00E-05
1.00E-02	2.00E-02	1.00E-06	1.00E-05	1.00E-03	1.00E-02	1.00E-03	2.00E-03
5.62E-04	5.32E-03	5.62E-04	2.02E-02	1.00E-03	8.80E-03	5.62E-05	2.51E-04
9.457416		35.92143		8.801117		4.472136	
1.361696		2.170505		1.318108		0.907798	
1.42E-03		5.93E-03		2.38E-03		8.49E-05	
PD 10		HE 11		PD 9		BE 8	

Q	28	Q	29	Q	30	Q	31
median	95%	median	95%	median	95%	median	95%
				1.00E-04	1.00E-03		
1.00E-08	1.00E-07	1.00E-05	1.00E-04				
2.00E-06	4.00E-06	2.00E-06	4.00E-06	1.00E-03	1.00E-02	2.00E-06	4.00E-05
				2.00E-03	1.00E-02		
						1.00E-06	1.00E-05
						1.00E-06	1.00E-04
2.50E-06	5.00E-06	1.25E-05	2.50E-05	1.00E-05	5.00E-03		
2.00E-04	4.00E-04	1.00E-03	2.00E-03	2.50E-01	1.00E+00		
1.78E-06	5.32E-06	2.24E-05	6.69E-05	8.71E-04	1.38E-02	1.26E-06	3.42E-05
2.990698		2.990698		15.84893		27.14418	
0.663943		0.663943		1.674607		2.000705	
2.22E-06		2.79E-05		3.54E-03		9.32E-06	
HE	12	HE	12	HE	12	BE	9

Q	32	Q	33	Q	34	Q	35
median	95%	median	95%	median	95%	median	95%
				1.00E-06	2.00E-06		
				3.33E-01	5.00E-01		
				5.00E-02	5.00E-01		
1.00E-05	1.00E-04	1.00E-03	1.00E-02	1.00E-03	2.00E-03	1.00E-05	1.00E-04
				5.00E-02	1.00E-01		
1.50E-04	7.50E-04	2.00E-04	2.00E-03			1.00E-05	1.00E-04
1.00E-04	1.00E-02	1.00E-04	1.00E-02			1.00E-05	1.00E-04
				1.00E-03	1.00E-01		
						3.33E-09	5.00E-09
						1.00E-06	1.00E-05
5.31E-05	9.09E-04	2.71E-04	5.85E-03	3.07E-03	1.47E-02	1.27E-06	8.71E-06
17.09976		21.54435		4.785595		6.843924	
1.720645		1.860675		0.948855		1.165673	
2.33E-04		1.53E-03		4.81E-03		2.51E-06	
BE	10	PD	11	HE	10	BE	35

Q	36	Q	37	Q	38	Q	39
median	95%	median	95%	median	95%	median	95%
1.00E-05	1.00E-04						
1.00E-05	1.00E-04	1.00E-06	1.00E-05	9.80E-01	9.90E-01	1.00E-06	2.00E-06
		1.25E-01	6.25E-01	5.00E-01	8.50E-01	5.00E-01	7.50E-01
		1.00E-01	5.00E-01	5.00E-01	7.50E-01	2.50E-01	7.50E-01
4.00E-07	1.00E-06						
1.00E-05	2.00E-04						
4.47E-06	3.76E-05	2.32E-03	1.46E-02	6.26E-01	8.58E-01	5.00E-03	1.04E-02
8.408964		6.299605		1.370828		2.030084	
1.290484		1.115447		0.191161		0.443884	
1.03E-05		4.32E-03		6.37E-01		5.52E-03	
BE	34	BE	33	BE	37	BE32	BE36

Q 40		Q 41		Q 42		Q 43	
median	95%	median	95%	median	95%	median	95%
						1.00E-03	1.00E-01
				1.00E-03	1.00E+00		
				9.50E-01	9.90E-01		
						1.00E-04	2.00E-04
						1.00E-03	2.00E-01
		9.00E-01	9.90E-01				
				1.00E-01	5.00E-01		
1.00E-05	1.00E-04	1.00E-03	5.00E-03	1.00E-03	1.00E-02		
				1.00E-02	1.00E-01		
						5.00E-01	8.00E-01
3.00E-04	9.00E-03	1.25E-01	5.00E-01				
1.00E-05	1.00E-03	2.50E-01	7.50E-01				
						5.00E-01	7.00E-01
				2.00E-05	1.00E-03		
3.11E-05	9.65E-04	7.28E-02	2.08E-01	5.17E-03	8.89E-02	7.58E-03	7.41E-02
31.07233		2.85027		17.21771		9.782765	
2.082617		0.634796		1.724811		1.382195	
2.72E-04		8.91E-02		2.29E-02		1.97E-02	
BE 31		BE 30		HE 16		PD 13	

Q	44	Q	45	Q	46	Q	47
median	95%	median	95%	median	95%	median	95%
				1.00E-06	1.00E-05		
2.00E-05	1.00E-04	2.00E-03	5.00E-01	2.00E-03	1.00E-01		
1.00E-04	1.00E-03	1.00E-04	1.00E-02	1.00E-05	2.00E-05		
1.00E-01	3.00E-01	1.00E-02	2.00E-02	1.00E-07	1.00E-06		
5.00E-02	1.00E-01	5.00E-01	7.00E-01	1.00E-02	5.00E-02	1.00E-01	2.00E-01
1.00E-05	3.50E-01	2.00E-01	3.00E-01	1.00E-03	1.00E-02	5.00E-01	6.50E-01
6.31E-04	1.60E-02	1.15E-02	1.16E-01	5.21E-04	3.16E-03	2.24E-01	3.61E-01
25.36517		10.09806		6.069622		1.612452	
1.959623		1.40142		1.092907		0.289549	
4.30E-03		3.07E-02		9.47E-04		2.33E-01	
HE	14	PD	12	BE	11	HE	15

Q 48		Q 49		Q 50		Q 51	
median	95%	median	95%	median	95%	median	95%
						1.00E-06	4.00E-05
						2.50E-06	2.50E-05
						2.00E-01	5.00E-01
						2.00E-01	5.00E-01
1.00E-02	5.00E-02	1.00E-01	2.00E-01	2.00E-01	3.00E-01		
		1.00E-03	5.00E-03	1.00E-04	5.00E-04		
1.00E-05	1.00E-02	1.00E-02	1.00E-01	1.00E-04	1.00E-02		
1.00E-02	1.00E-01	3.00E-01	4.00E-01	1.00E-01	3.00E-01		
						1.00E-03	1.00E-01
1.00E-03	3.68E-02	2.34E-02	7.95E-02	3.76E-03	2.59E-02	6.31E-04	7.58E-03
36.84031		3.398088		6.887247		12.01124	
2.185814		0.741341		1.169498		1.506572	
1.09E-02		3.08E-02		7.45E-03		1.96E-03	
BE 12		BE 13		PD 14		HE 13	

Q	52	Q	53	Q	54	Q	55
median	95%	median	95%	median	95%	median	95%
1.00E-02	1.00E-01	1.00E-07	1.00E-06				
3.00E-01	5.00E-01	4.00E-01	6.00E-01	1.00E-02	5.00E-02	1.00E-02	5.00E-02
2.50E-05	2.50E-04			2.50E-01	7.50E-01	5.00E-01	8.50E-01
1.00E-03	5.00E-02			1.00E-01	5.00E-01	5.00E-01	7.50E-01
9.00E-01	9.50E-01	5.00E-01	7.85E-01	1.00E-01	2.00E-01	9.90E-01	1.00E+00
9.24E-03	5.68E-02	2.71E-03	7.78E-03	7.07E-02	2.47E-01	2.23E-01	4.23E-01
6.149786		2.866357		3.499636		1.894387	
1.100859		0.638207		0.759187		0.387209	
1.69E-02		3.33E-03		9.43E-02		2.40E-01	
BE	39	BE	38	BE	44	BE	46

Q	56	Q	57	Q	58	Q	59]
median	95%	median	95%	median	95%	median	95%
1.00E-06	1.00E-05	1.00E-02	1.00E-01	1.00E-03	1.00E-02	1.00E-06	3.00E-06
5.00E-02	1.00E-01	5.00E-04	1.00E-02	5.00E-01	7.00E-01	5.00E-03	1.00E-02
5.00E-01	7.50E-01	5.00E-05	5.00E-04	5.00E-02	1.50E-01		
5.00E-02	5.00E-01	1.00E-04	1.00E-02	1.00E-01	5.00E-01		
1.00E-02	5.00E-02	9.90E-01	1.00E+00	7.50E-01	9.00E-01	2.00E-01	5.00E-01
6.60E-03	2.85E-02	1.90E-03	2.19E-02	7.15E-02	2.16E-01	1.00E-03	2.47E-03
4.31736		11.5101		3.0219		2.466212	
0.886451		1.480742		0.670234		0.547081	
9.77E-03		5.69E-03		8.96E-02		1.16E-03	
BE43	BE45	BE	42	BE	41	BE	40

Q	60	Q	61	Q	62	Q	63
median	95%	median	95%	median	95%	median	95%
						1.00E-06	1.00E-05
1.00E-03	3.00E-03	4.00E-05	1.00E-03	1.00E-03	5.00E-02	5.00E-05	1.00E-03
5.00E-06	1.00E-05					1.00E-06	2.00E-06
1.00E-06	5.00E-03	1.00E-06	1.00E-05	1.00E-06	2.00E-05	2.00E-07	5.00E-07
1.00E-06	2.00E-06	1.00E-01	3.00E-01	1.00E-03	1.00E-02	2.00E-05	1.00E-04
				1.00E-06	2.00E-06	1.00E-06	1.00E-05
2.00E-04	1.00E-03	1.00E-05	1.00E-03				
1.00E-05	1.00E-04			1.00E-01	2.00E-01		
1.47E-05	1.76E-04	7.95E-05	1.32E-03	1.58E-04	1.32E-03	2.42E-06	1.47E-05
12.00937		16.54875		8.325532		6.069622	
1.506477		1.700794		1.284441		1.092907	
4.57E-05		3.38E-04		3.62E-04		4.39E-06	
PD	7	HE	8	PD	6	FUSLOC2	BE05

Q	64	Q	65	Q	66	Q	67
median	95%	median	95%	median	95%	median	95%
		2.00E-07	2.00E-06			1.00E-06	5.00E-06
		1.00E-04	1.00E-03	1.00E-03	2.00E-02		
1.00E-04	2.00E-04						
				1.00E-05	1.00E-04		
		1.00E-03	2.00E-03	1.00E-03	2.00E-03		
						1.00E-07	1.00E-06
						1.00E-04	1.00E-01
		1.00E-05	1.00E-04			1.00E-05	1.00E-02
2.50E-06	5.00E-06	2.50E-05	5.00E-05	3.33E-09	1.00E-08		
1.00E-04	5.00E-04	5.00E-05	2.50E-04	2.50E-03	1.00E-02		
2.92E-05	7.94E-05	2.51E-05	1.31E-04	3.84E-05	2.09E-04	3.16E-06	2.66E-04
2.714418		5.210007		5.44923		84.08964	
0.605198		1.000352		1.02756		2.68599	
3.51E-05		4.14E-05		6.51E-05		1.17E-04	
HE	9	HE	9	HE	9	BE	6

Q	68	Q	69	Q	70	Q	71
median	95%	median	95%	median	95%	median	95%
2.00E-06	1.00E-05						
				1.00E-04	1.00E-03		
		1.00E-04	2.00E-04	1.00E-03	2.00E-03		
				1.00E-02	1.00E-01		
1.00E-05	5.00E-05	3.00E-05	1.50E-04			2.00E-05	2.00E-04
1.00E-04	1.00E-02	1.00E-03	1.00E-02			1.00E-05	1.00E-04
				1.00E-03	1.00E-02		
						5.00E-08	8.00E-08
						1.00E-07	1.00E-06
1.26E-05	1.71E-04	1.44E-04	6.69E-04	1.00E-03	6.69E-03	1.00E-06	6.32E-06
13.57209		4.641589		6.687403		6.324555	
1.580615		0.930337		1.151652		1.117842	
4.39E-05		2.22E-04		1.94E-03		1.87E-06	
BE	7	PD	8	HE	7	BE	25

Q	72	Q	73	Q	74	Q	75
median	95%	median	95%	median	95%	median	95%
9.00E-01	9.90E-01	1.00E-05	1.00E-04	8.00E-01	9.00E-01	5.00E-01	7.00E-01
9.00E-01	9.90E-01	1.00E-02	1.00E-01			1.00E-04	1.00E-03
		1.25E-01	6.25E-01	5.00E-01	8.50E-01	5.00E-01	7.50E-01
		1.00E-01	5.00E-01	5.00E-01	7.50E-01	1.50E-01	5.00E-01
8.00E-07	2.00E-06						
1.00E-05	2.00E-04						
1.60E-03	4.45E-03	5.95E-03	4.20E-02	5.85E-01	8.31E-01	4.40E-02	1.27E-01
2.788938		7.071068		1.420902		2.892508	
0.621613		1.185462		0.212904		0.643711	
1.94E-03		1.20E-02		5.98E-01		5.41E-02	
BE	24	BE	23	BE	29	BE22	BE28

Q	76	Q	77
median	95%	median	95%
5.00E-01	8.00E-01		
1.00E-02	1.00E-01	9.00E-01	9.90E-01
5.00E-05	5.00E-04	2.50E-02	7.50E-02
1.00E-05	1.00E-03	2.50E-01	7.50E-01
1.26E-03	1.41E-02	1.78E-01	3.82E-01
11.24683		2.147229	
1.466719		0.463138	
3.69E-03		1.98E-01	
BE	27	BE	26

Assembly Fault Tree

Cutsets

Cut no.	Total %	% Cutset	Frequency	Cutsets
1	100.0	100.0	4.4x10-5	HE03, BE01
2	100.0	0	3.5x10-10	BE04, HE06
3	100.0	0	7.7x10-11	PD01, HE01, PD02
4	100.0	0	4.4x10-11	BE16, BE03, HE06, BE17
5	100.0	0	1.1x10-11	BE14, HE06, PD05, BE15
6	100.0	0	6.0x10-13	HE02, HE01, PD02
7	100.0	0	3.2x10-13	HE05, HE06, PD15
8	100.0	0	1.4x10-13	HE06, PD05, PD15
9	100.0	0	1.1x10-13	BE03, HE06, PD15
10	100.0	0	8.5x10-14	BE20, BE02, HE06, BE21
11	100.0	0	2.4x10-14	PD04, HE06, PD03
12	100.0	0	5.7x10-15	BE02, HE06, PD15
13	100.0	0	2.9x10-15	HE04, HE06, PD03
14	100.0	0	1.1x10-17	BE18, HE05, HE06, BE19

Assembly Fault Tree

Basic Events Importance

Event	# of occur	Probability	Fussell-Vesely	Risk Reduction Ratio	Risk Increase Ratio
HE03	1	4.4x10-5	1.0	8.974x10+4	2.273x10+4
BE01	1	1.0	1.0	8.974x10+4	1.0
HE06	11	1.69x10-4	9.367x10-6	1.0	1.055
BE04	1	2.1x10-6	8.065x10-6	1.0	4.841
HE01	2	5.94x10-4	1.776x10-4	1.0	1.003
PD02	2	6.13x10-4	1.776x10-6	1.0	1.003
PD01	1	2.13x10-4	1.763x10-6	1.0	1.008
BE03	2	6.64x10-5	1.019x10-6	1.0	1.015
BE16	1	6.61x10-3	1.016x10-6	1.0	1.0
BE17	1	6.03x10-1	1.016x10-6	1.0	1.0
PD05	2	8.58x10-5	2.726x10-7	1.0	1.003
BE15	1	2.77x10-3	2.693x10-7	1.0	1.0
BE14	1	2.95x10-1	2.693x10-7	1.0	1.0
HE02	1	2.65x10-6	1.366x10-8	1.0	1.008
PD15	4	1.0x10-5	1.331x10-8	1.0	1.001
HE05	2	1.907x10-4	7.327x10-9	1.0	1.0
BE02	2	3.38x10-6	2.064x10-9	1.0	1.001
BE21	1	2.25x10-2	1.933x10-9	1.0	1.0
BE20	1	6.61x10-3	1.933x10-9	1.0	1.0
PD03	2	3.16x10-5	6.207x10-10	1.0	1.0
PD04	1	4.51x10-6	5.501x10-10	1.0	1.0
HE04	1	5.5x10-7	7.065x10-11	1.0	1.0
BE19	1	4.35x10-6	0	1.0	1.0
BE18	1	8.41x10-5	0	1.0	1.0

Normal Use of Vehicle Fault Tree

Cutsets

Cut no.	Total %	% Cutset	Frequency	Cutsets
1	70.8	70.8	8.5x10-9	HE07, FUSLOC02
2	93.8	22.9	2.7x10-9	BE28, BE07, HE07, BE29
3	96.4	2.6	3.1x10-10	BE26, PD08, HE07, BE27
4	98.4	1.9	2.3x10-10	HE08, HE07, PD06
5	99.6	1.2	1.4x10-10	BE22, BE06, HE07, BE23
6	99.9	0.2	3.2x10-11	PD07, HE07, PD06
7	99.9	0	4.3x10-12	PD08, HE07, PD15
8	99.9	0	2.7x10-12	HE07, HE09, PD15
9	99.9	0	2.2x10-12	BE06, HE07, PD15
10	100.0	0	8.5x10-13	BE07, HE07, PD15
11	100.0	0	9.9x10-16	BE24, HE07, HE09, BE25

Normal Use of Vehicle Fault Tree

Basic Events Importance

Event	# of occur	Probability	Fussell-Vesely	Risk Reduction Ratio	Risk Increase Ratio
HE07	11	1.94x10-3	1.0	1.082x10+7	5.155x10+2
FUSL OC02	1	4.39x10-6	7.089x10-1	3.435	1.615x10+5
BE07	2	4.39x10-5	2.294x10-1	1.298	5.226x10+3
BE29	1	5.98x10-1	2.293x10-1	1.298	1.154
BE28	1	5.41x10-2	2.293x10-1	1.298	5.01
PD08	2	2.22x10-4	2.655x10-2	1.027	1.206x10+2
BE26	1	1.98x10-1	2.619x10-2	1.027	1.106
BE27	1	3.69x10-3	2.619x10-2	1.027	8.072
PD06	2	3.62x10-4	2.243x10-2	1.023	6.294x10+1
HE08	1	3.38x10-4	1.976x10-2	1.020	59.43
BE06	2	1.175x10-4	1.251x10-2	1.013	107.4
BE22	1	5.41x10-2	1.232x10-2	1.012	1.215
BE23	1	1.20x10-2	1.232x10-2	1.012	2.014
PD07	1	4.57x10-5	2.671x10-3	1.003	5.945
PD15	4	1.0x10-5	8.478x10-4	1.001	85.77
HE09	2	1.416x10-4	2.288x10-4	1.0	2.615
BE24	1	1.94x10-3	9.241x10-8	1.0	1.00
BE25	1	1.87x10-6	9.241x10-8	1.0	1.044

Service and Repair Fault Tree

Cutsets

Cut no.	Total %	% Cutset	Frequency	Cutsets
1	82.9	82.9	4.0x10-7	BE08, HE10
2	96.6	13.7	6.7x10-8	HE11, HE10, PD09
3	99.9	3.3	1.6x10-8	PD10, HE10, PD09,
4	100.0	0	9.0x10-11	BE36, BE10, HE10, HE16, BE37
5	100.0	0	4.0x10-12	BE30, HE10, PD11, HE16, BE31
6	100.0	0	3.9x10-12	HE10, HE12, PD15, HE16
7	100.0	0	1.6x10-12	HE10, PD11, PD15, HE16
8	100.0	0	2.5x10-13	BE10, HE10, PD15, HE16
9	100.0	0	2.4x10-14	BE32, BE09, HE10, HE16, BE33
10	100.0	0	1.0x10-14	BE09, HE10, PD15, HE16
11	100.0	0	1.0x10-17	BE34, HE10, HE12, HE16, BE35

Service and Repair Fault Tree

Basic Events Importance

Event	# of occur	Probability	Fussell-Vesely	Risk Reduction Ratio	Risk Increase Ratio
HE10	11	4.81x10-3	1.0	4.437x10+7	2.079x10+2
BE08	1	8.49x10-5	8.290x10-1	5.858	9.764x10+3
PD09	2	2.38x10-3	1.708x10-1	1.206	72.6
HE11	1	5.93x10-3	1.378x10-1	1.160	24.10
PD10	1	1.42x10-3	3.30x10-2	1.298	5.01
PD08	2	2.22x10-4	2.655x10-2	1.034	24.21
HE16	8	2.29x10-2	2.035x10-4	1.0	1.009
BE10	2	2.33x10-4	1.837x10-4	1.0	1.788
BE36	1	5.52x10-3	1.832x10-4	1.0	1.033
BE37	1	6.37x10-1	1.832x10-4	1.0	1.0
PD15	4	1.00x10-5	1.195x10-5	1.0	2.195
PD11	2	1.53x10-3	1.171x10-5	1.0	1.008
BE31	1	2.72x10-4	8.292x10-6	1.0	1.03
BE30	1	8.91x10-2	8.292x10-6	1.0	1.0
HE12	2	3.57x10-3	7.983x10-6	1.0	1.002
BE09	2	9.32x10-6	7.122x10-8	1.0	1.008
BE33	1	4.32x10-3	5.003x10-8	1.0	1.00
BE32	1	5.52x10-3	5.003x10-8	1.0	1.0
BE34	1	1.03x10-5	0	1.0	1.0
BE35	1	2.51x10-6	0	1.0	1.0

Accident Fault Tree

Cutsets

Cut no.	Total %	% Cutset	Frequency	Cutsets
1	44.8	44.8	1.8x10-6	BE11, HE13
2	73.4	28.6	1.1x10-6	PD13, HE13, PD12
3	86.2	12.7	5.3x10-07	BE40, HE13, HE15
4	92.4	6.2	2.5x10-07	HE14, HE13, PD12
5	95.8	3.4	1.4x10-07	BE46, BE13, HE13, BE45
6	97.5	1.6	7.0x10-08	BE40, BE13, HE13
7	98.2	0.6	2.5x10-08	BE39, HE13, HE15, BE38
8	98.8	0.6	2.4x10-08	BE40, BE12, HE13
9	99.2	0.4	1.9x10-08	BE44, BE12, HE13, BE43
10	99.6	0.4	1.6x10-08	BE40, HE13, PD14,
11	99.8	0.1	7.4x10-09	BE42, HE13, PD14, BE41
12	99.9	0.1	4.5x10-09	PD15, HE13, HE15
13	99.9	0	6.0x10-10	PD15, BE13, HE13
14	100.0	0	2.1x10-10	PD15, BE12, HE13
15	100.0	0	1.4x10-10	PD15, HE13, PD14

Accident Fault Tree

Basic Events Importance

Event	# of occur	Probability	Fussell-Vesely	Risk Reduction Ratio	Risk Increase Ratio
HE13	15	1.96x10-3	1.0	2.438x10+7	5.098x10+2
BE11	1	9.47x10-4	4.482x10-1	1.812	4.738x10+2
PD12	2	3.07x10-2	3.487x10-1	1.535	12.01
PD13	1	1.97x10-2	2.862x10-1	1.401	15.24
BE40	4	1.16x10-3	1.549x10-1	1.183	1.344x10+2
HE15	3	2.33x10-1	1.352x10-1	1.156	1.445
HE14	1	4.30x10-3	6.247x10-2	1.067	15.47
BE13	3	3.08x10-2	5.123x10-2	1.054	2.612
BE45	1	9.77x10-3	3.418x10-2	1.035	4.464
BE46	1	2.40x10-1	3.418x10-2	1.035	1.108
BE12	3	1.09x10-2	1.079x10-2	1.011	1.979
BE39	1	1.68x10-2	6.205x10-3	1.006	1.361
BE38	1	3.33x10-3	6.205x10-3	1.006	2.857
PD14	3	7.45x10-3	5.922x10-3	1.006	1.789
BE43	1	9.77x10-3	4.752x10-3	1.005	1.482
BE44	1	9.43x10-2	4.752x10-3	1.005	1.046
BE42	1	5.69x10-3	1.797x10-3	1.002	1.314
BE41	1	8.96x10-2	1.797x10-3	1.002	1.018
PD15	4	1.00x10-5	1.335x10-3	1.001	134.5

Appendix D

Risk Conversion Factors

Risk "Factors" Included in Study

Volition	Voluntary	-	Involuntary
Severity	Ordinary	-	Catastrophic
Origin	Natural	-	Man-Made
Effect manifestation	Immediate	-	Delayed
Exposure pattern	Continuous	-	Occasional
Controllability	Controllable	-	Uncontrollable
Familiarity	Old	-	New
Benefit	Clear	-	Unclear
Necessity	Necessary	-	Luxury

Comparison of RCF Values

RCF	Value (E. F.)				
	This Study	Rowe (1)	Starr (2)	Kinchin (3)	Otway and Cohen (4)
Natural/Man-Made	20	10(2)			
Ordinary/Catastrophic	30	50			
Voluntary/Involuntary	100	100(10)	~ 1000		1 - 1000
Delayed/Immediate	30(11)	20%/yr** (2)		30	
Controllable/Uncontrollable	5-10	100(10)			
Old/New	10				
Necessary/Luxury	1(7)				
Regular/Occasional	1				

* Where no E. F. is given, a value of ~10 may be assumed.

** Must be compounded by number of years of delay.

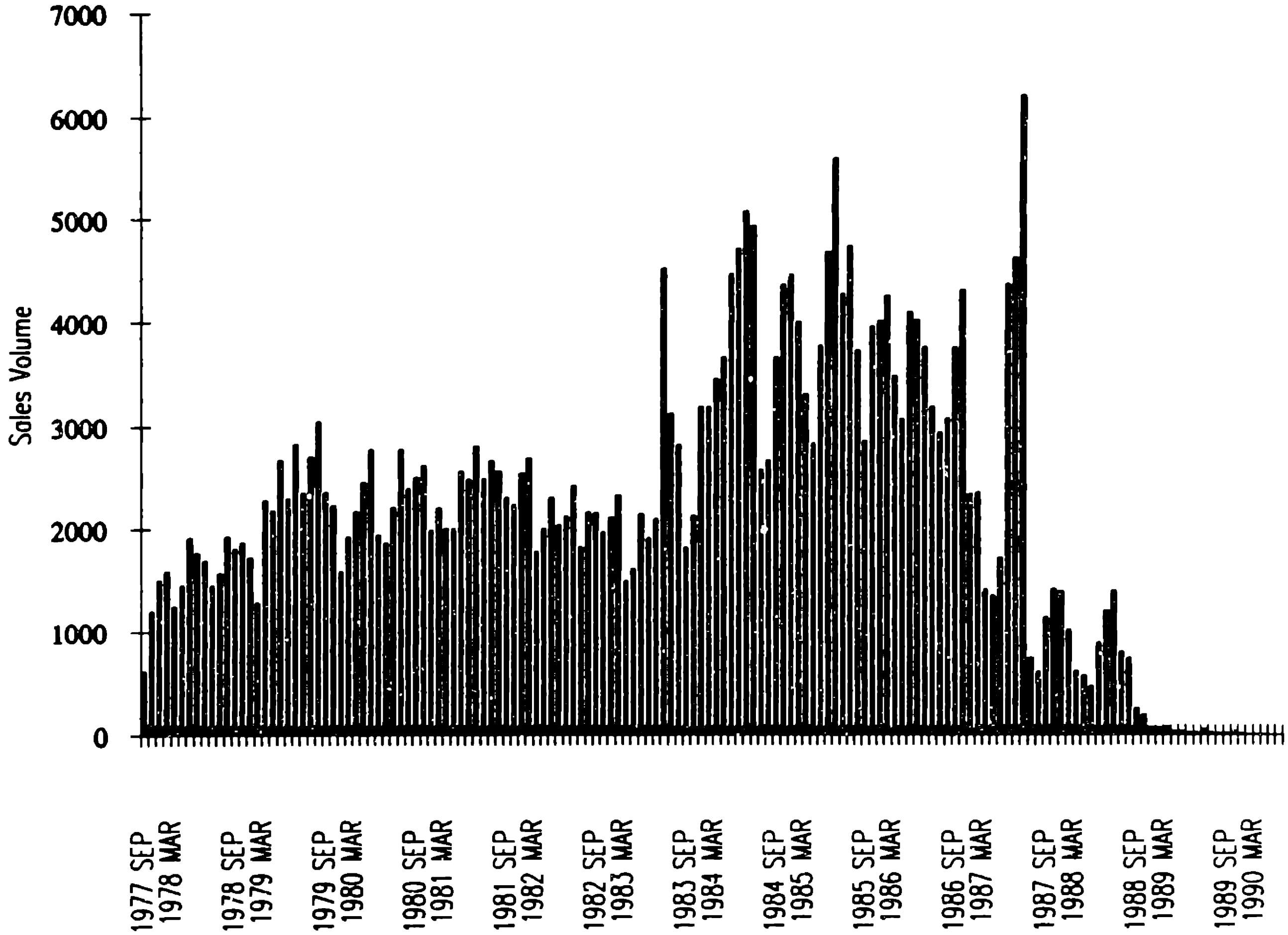
An error factor of ~10 is associated with each of the quoted values.
Mortality rates are per person per year in the exposed population.

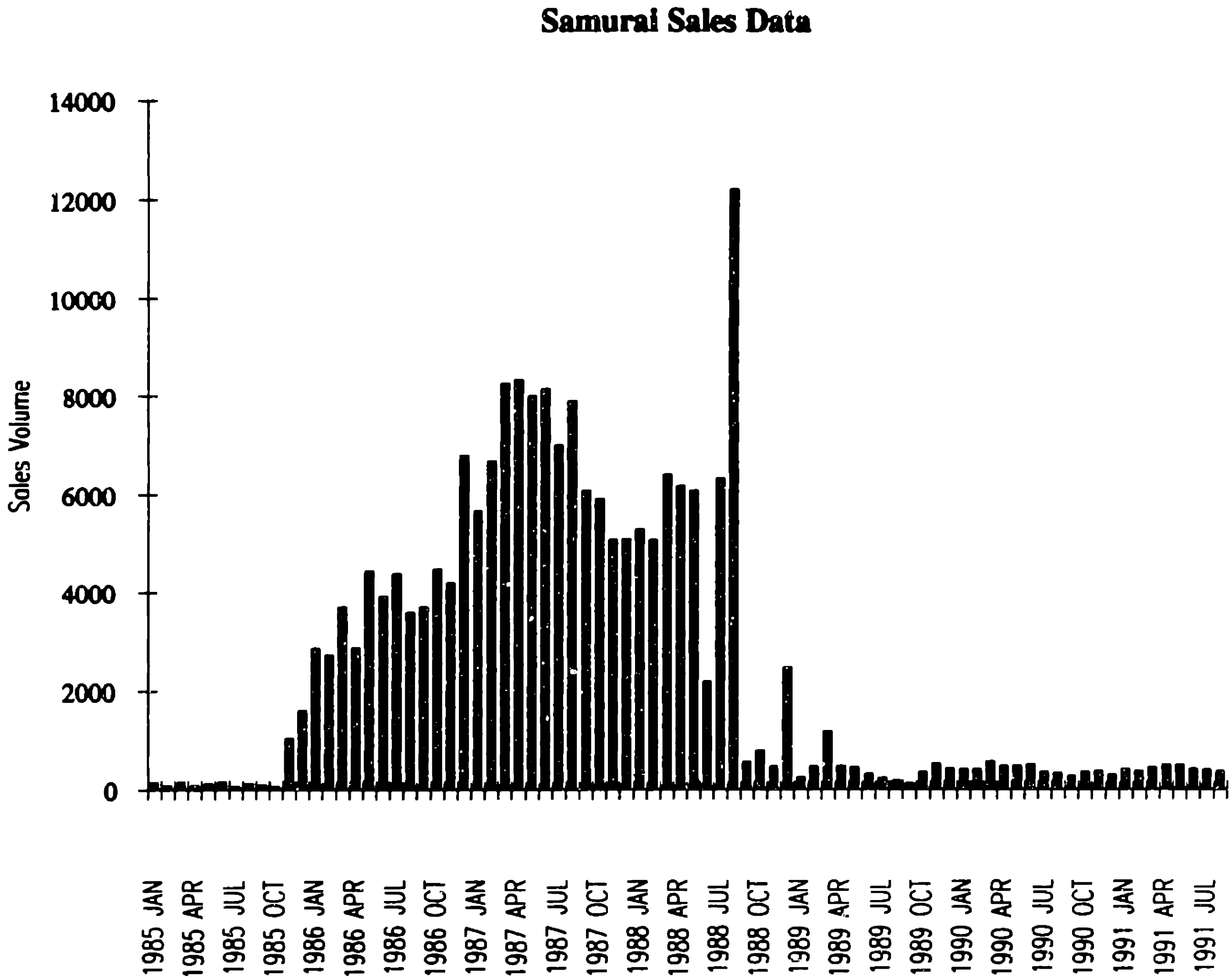
Mean Values of Risk Accepted by U.S. Society for Major Risk Categories

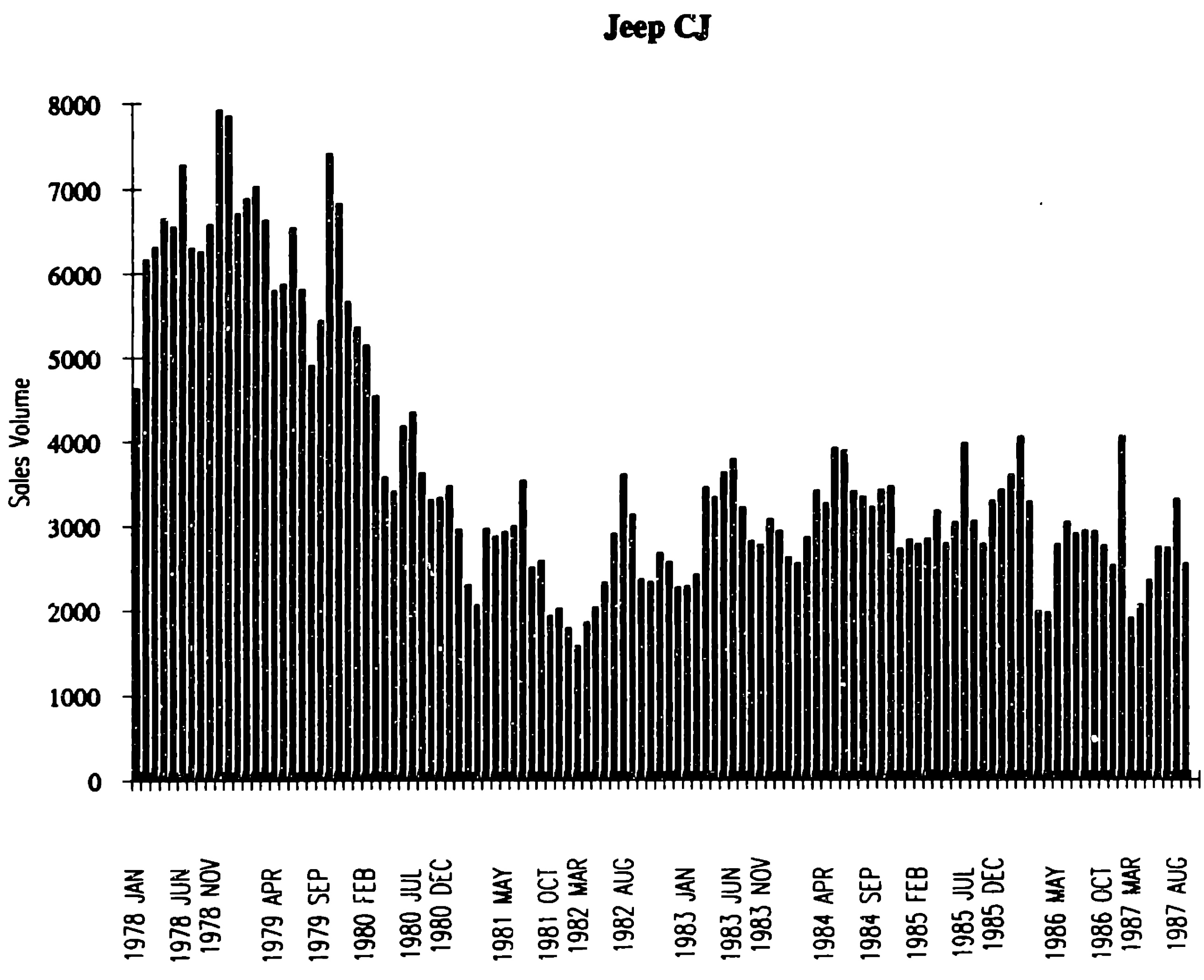
			Controllable Risk				Uncontrollable Risk			
			Ordinary		Catastrophic		Ordinary		Catastrophic	
			Immediate Risk	Delayed Risk	Immediate Risk	Delayed Risk	Immediate Risk	Delayed Risk	Immediate Risk	Delayed Risk
Man-Made Hazard	Involuntary	Old Risk	1.3×10^{-6}	4×10^{-5}	5×10^{-8}	1.5×10^{-6}	3×10^{-7}	10^{-5}	10^{-8}	3×10^{-7}
Man-Made Hazard	Involuntary	New Risk	1.3×10^{-7}	4×10^{-6}	5×10^{-9}	1.5×10^{-7}	3×10^{-8}	10^{-6}	10^{-9}	3×10^{-8}
Man-Made Hazard	Voluntary	Old Risk	1.3×10^{-4}	4×10^{-3}	5×10^{-6}	1.5×10^{-4}	3×10^{-5}	10^{-3}	10^{-6}	3×10^{-5}
Man-Made Hazard	Voluntary	New Risk	1.3×10^{-5}	4×10^{-4}	5×10^{-7}	1.5×10^{-5}	3×10^{-6}	10^{-4}	10^{-7}	3×10^{-6}
Natural Hazard	Invol-untary	Old Risk	3×10^{-5}(?)	10^{-3}(?)	10^{-6}	-	6×10^{-6}(?)	2×10^{-4}(?)	2×10^{-7}(?)	-

Sales Data
Vehicles with Alledged Safety Defects

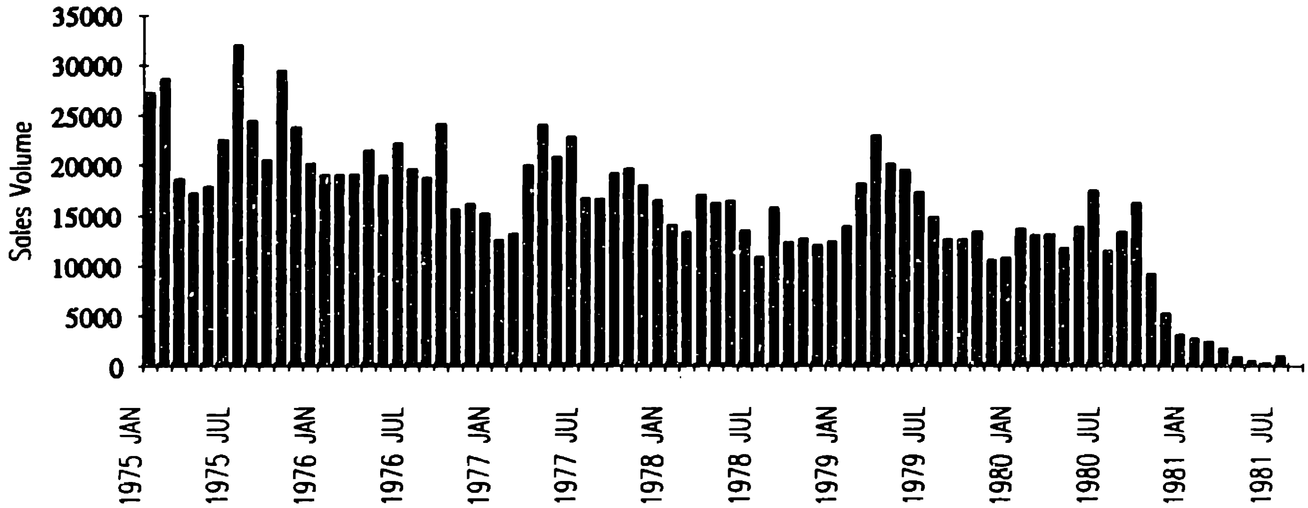
Audi 5000



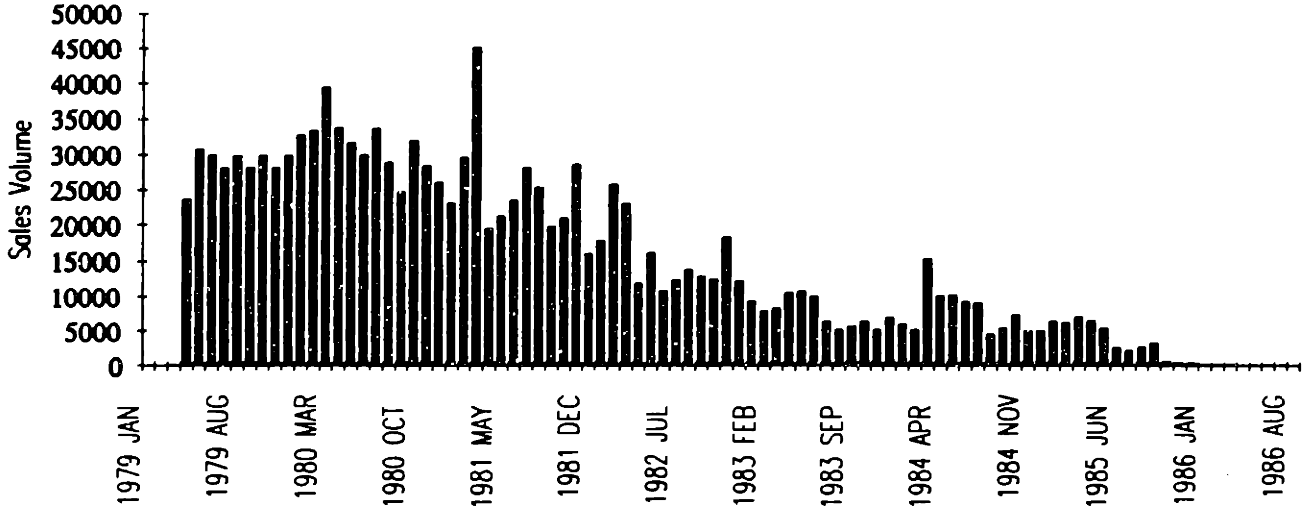

Samurai Sales Data
14000
12000
10000
8000
6000
4000
2000
0
Sales Volume
1985 JAN
1985 APR
1985 JUL
1985 OCT
1986 JAN
1986 APR
1986 JUL
1986 OCT
1987 JAN
1987 APR
1987 JUL
1987 OCT
1988 JAN
1988 APR
1988 JUL
1988 OCT
1989 JAN
1989 APR
1989 JUL
1989 OCT
1990 JAN
1990 APR
1990 JUL
1990 OCT
1991 JAN
1991 APR
1991 JUL


Jeep CJ
Sales Volume
8000
7000
6000
5000
4000
3000
2000
1000
0
1978 JAN
1978 JUN
1978 NOV
1979 APR
1979 SEP
1980 FEB
1980 JUL
1980 DEC
1981 MAY
1981 OCT
1982 MAR
1982 AUG
1983 JAN
1983 JUN
1983 NOV
1984 APR
1984 SEP
1985 FEB
1985 JUL
1985 DEC
1986 MAY
1986 OCT
1987 MAR
1987 AUG

Pinto Sales Data



Citation Sales Data



U.S. Vehicle Deliveries

	Citation	Pinto	Jeep Wrangler YJ CJ	Audi 5000	Suzuki Samurai
1988 JAN	0	0	0	610	5292
1988 FEB	0	0	0	568	5085
1988 MAR	0	0	0	471	6406
1988 APR	0	0	0	886	6165
1988 MAY	0	0	0	1202	6074
1988 JUN	0	0	0	1403	2199
1988 JUL	0	0	0	798	6327
1988 AUG	0	0	0	738	12208
1988 SEP	0	0	0	252	560
1988 OCT	0	0	0	190	787
1988 NOV	0	0	0	77	483
1988 DEC	0	0	0	72	2483
1989 JAN	0	0	0	74	263
1989 FEB	0	0	0	36	472
1989 MAR	0	0	0	35	1179
1989 APR	0	0	0	27	480
1989 MAY	0	0	0	22	447
1989 JUN	0	0	0	54	320
1989 JUL	0	0	0	24	238
1989 AUG	0	0	0	17	193
1989 SEP	0	0	0	15	138
1989 OCT	0	0	0	37	360
1989 NOV	0	0	0	9	522
1989 DEC	0	0	0	7	429
1990 JAN	0	0	0	6	410
1990 FEB	0	0	0	3	414
1990 MAR	0	0	0	1	571
1990 APR	0	0	0	0	472
1990 MAY	0	0	0	0	481
1990 JUN	0	0	0	0	497
1990 JUL	0	0	0	0	357
1990 AUG	0	0	0	0	330
1990 SEP	0	0	0	0	287
1990 OCT	0	0	0	0	358
1990 NOV	0	0	0	0	374
1990 DEC	0	0	0	0	314
1991 JAN	0	0	0	0	414
1991 FEB	0	0	0	0	371
1991 MAR	0	0	0	0	450
1991 APR	0	0	0	0	506
1991 MAY	0	0	0	0	496
1991 JUN	0	0	0	0	407
1991 JUL	0	0	0	0	396
1991 AUG	0	0	0	0	367

Product Planning & Economics Staff
Marketing Information Center
Source: CATS
September 26, 1991

U.S. Vehicle Deliveries

	Citation	Pinto	Jeep Wrangler YJ CJ	Audi 5000	Suzuki Samurai
1983 SEP	5677	0	2780	1826	0
1983 OCT	6323	0	3083	2134	0
1983 NOV	5283	0	2946	3190	0
1983 DEC	6973	0	2624	3191	0
1984 JAN	6013	0	2559	3458	0
1984 FEB	5218	0	2868	3662	0
1984 MAR	15216	0	3419	4475	0
1984 APR	10051	0	3277	4716	0
1984 MAY	10182	0	3920	5082	0
1984 JUN	9153	0	3891	4938	0
1984 JUL	8985	0	3411	2586	0
1984 AUG	4560	0	3348	2677	0
1984 SEP	5429	0	3227	3660	0
1984 OCT	7257	0	3428	4368	0
1984 NOV	5085	0	3467	4469	0
1984 DEC	5025	0	2732	4009	0
1985 JAN	6338	0	2839	3312	161
1985 FEB	6163	0	2784	2841	87
1985 MAR	7077	0	2856	3778	165
1985 APR	6502	0	3174	4689	105
1985 MAY	5406	0	2796	5600	140
1985 JUN	2604	0	3046	4289	167
1985 JUL	2221	0	3981	4742	80
1985 AUG	2713	0	3058	3736	124
1985 SEP	3214	0	2788	2870	105
1985 OCT	647	0	3306	3967	75
1985 NOV	399	0	3426	4026	1039
1985 DEC	393	0	3602	4266	1607
1986 JAN	223	0	4050	3485	2865
1986 FEB	189	0	3291	3081	2741
1986 MAR	187	0	1982	4106	3706
1986 APR	174	0	1972	4028	2875
1986 MAY	124	0	2783	3767	4436
1986 JUN	82	0	3042	3194	3926
1986 JUL	46	0	2913	2950	4392
1986 AUG	0	0	2946	3082	3596
1986 SEP	0	0	2934	3764	3709
1986 OCT	0	0	2765	4317	4483
1986 NOV	0	0	2530	2347	4208
1986 DEC	0	0	4059	2359	6795
1987 JAN	0	0	1906	1417	5662
1987 FEB	0	0	2057	1360	6672
1987 MAR	0	0	2355	1726	8267
1987 APR	0	0	2751	4376	8341
1987 MAY	0	0	2746	4632	8000
1987 JUN	0	0	3318	6216	8150
1987 JUL	0	0	2551	739	7000
1987 AUG	0	0	0	603	7905
1987 SEP	0	0	0	1136	6077
1987 OCT	0	0	0	1413	5916
1987 NOV	0	0	0	1395	5082
1987 DEC	0	0	0	1015	5092

U.S. Vehicle Deliveries

	Citation	Pinto	Jeep Wrangler YJ CJ	Audi 5000	Suzuki Samurai
1979 MAY	30724	19552	5877	2831	0
1979 JUN	29894	17373	6551	2364	0
1979 JUL	28104	14940	5814	2710	0
1979 AUG	29779	12712	4915	3050	0
1979 SEP	28195	12740	5444	2364	0
1979 OCT	29895	13441	7412	2232	0
1979 NOV	28198	10673	6834	1586	0
1979 DEC	29884	10886	5668	1931	0
1980 JAN	32700	13733	5360	2173	0
1980 FEB	33317	13142	5146	2460	0
1980 MAR	39366	13193	4548	2781	0
1980 APR	33767	11878	3580	1944	0
1980 MAY	31657	13912	3418	1870	0
1980 JUN	29984	17529	4189	2211	0
1980 JUL	33606	11573	4346	2779	0
1980 AUG	28872	13460	3627	2403	0
1980 SEP	24674	16289	3315	2508	0
1980 OCT	31931	9281	3339	2623	0
1980 NOV	28356	5301	3474	1998	0
1980 DEC	25975	3176	2962	2208	0
1981 JAN	23075	2831	2301	2004	0
1981 FEB	29608	2506	2064	2007	0
1981 MAR	45041	1853	2975	2568	0
1981 APR	19487	959	2881	2493	0
1981 MAY	21159	542	2936	2812	0
1981 JUN	23414	348	3007	2497	0
1981 JUL	28020	998	3538	2673	0
1981 AUG	25218	0	2514	2570	0
1981 SEP	19739	0	2588	2313	0
1981 OCT	20924	0	1945	2243	0
1981 NOV	28553	0	2019	2549	0
1981 DEC	15946	0	1796	2695	0
1982 JAN	17757	0	1589	1788	0
1982 FEB	25740	0	1859	2009	0
1982 MAR	22984	0	2040	2313	0
1982 APR	11836	0	2334	2047	0
1982 MAY	16123	0	2915	2129	0
1982 JUN	10833	0	3613	2428	0
1982 JUL	12314	0	3137	1835	0
1982 AUG	13709	0	2368	2167	0
1982 SEP	12826	0	2335	2163	0
1982 OCT	12373	0	2685	1977	0
1982 NOV	18214	0	2572	2116	0
1982 DEC	12073	0	2271	2337	0
1983 JAN	9266	0	2287	1499	0
1983 FEB	7896	0	2425	1617	0
1983 MAR	8206	0	3454	2148	0
1983 APR	10507	0	3349	1919	0
1983 MAY	10701	0	3630	2103	0
1983 JUN	9969	0	3790	4523	0
1983 JUL	6387	0	3218	3126	0
1983 AUG	5191	0	2822	2826	0

U.S. Vehicle Deliveries

	Citation	Pinto	Jeep Wrangler YJ CJ	Audi 5000	Suzuki Samurai
1975 JAN	0	27283	0	0	0
1975 FEB	0	28664	0	0	0
1975 MAR	0	18604	0	0	0
1975 APR	0	17209	0	0	0
1975 MAY	0	17896	0	0	0
1975 JUN	0	22535	0	0	0
1975 JUL	0	31975	0	0	0
1975 AUG	0	24464	0	0	0
1975 SEP	0	20584	0	0	0
1975 OCT	0	29468	0	0	0
1975 NOV	0	23841	0	0	0
1975 DEC	0	20139	0	0	0
1976 JAN	0	19038	0	0	0
1976 FEB	0	19043	0	0	0
1976 MAR	0	19134	0	0	0
1976 APR	0	21468	0	0	0
1976 MAY	0	18957	0	0	0
1976 JUN	0	22225	0	0	0
1976 JUL	0	19654	0	0	0
1976 AUG	0	18754	0	0	0
1976 SEP	0	24162	0	0	0
1976 OCT	0	15715	0	0	0
1976 NOV	0	16171	0	0	0
1976 DEC	0	15215	0	0	0
1977 JAN	0	12637	0	0	0
1977 FEB	0	13240	0	0	0
1977 MAR	0	20016	0	0	0
1977 APR	0	24083	0	0	0
1977 MAY	0	20908	0	0	0
1977 JUN	0	22885	0	0	0
1977 JUL	0	16746	0	0	0
1977 AUG	0	16718	0	0	0
1977 SEP	0	19220	0	614	0
1977 OCT	0	19696	0	1196	0
1977 NOV	0	18034	0	1508	0
1977 DEC	0	16592	0	1589	0
1978 JAN	0	14111	4632	1250	0
1978 FEB	0	13454	6174	1454	0
1978 MAR	0	17123	6327	1917	0
1978 APR	0	16303	6657	1767	0
1978 MAY	0	16483	6559	1689	0
1978 JUN	0	13589	7287	1455	0
1978 JUL	0	11002	6309	1570	0
1978 AUG	0	15851	6264	1932	0
1978 SEP	0	12429	6589	1811	0
1978 OCT	0	12799	7928	1870	0
1978 NOV	0	12214	7857	1726	0
1978 DEC	0	12522	6713	1290	0
1979 JAN	5	13952	6890	2288	0
1979 FEB	13	18244	7033	2191	0
1979 MAR	120	23014	6634	2678	0
1979 APR	23630	20181	5806	2301	0

Technical References

Behrin,E.; Bolger, J.; Hudson, C.L.; O'Connell, L.F.; Rubin, B.; Schwartz, M.V.; Waide, C.H.; and Walsh, W.J. Energy Storage Systems for Automobile Propulsion. 2 vols. Livermore, California: U.S. Department of Commerce National Technical Information Service.,. Vol. 1: Overview and Findings. University of California.; Vol. 2: Detailed Report. Lawerence Livermore Laboratory. 15 Dec 1977

Brookman, Michael J. "Handling Lithium Batteries at the Factory." Electronic Products. 15 Nov 1984, pp 79-82.

Budney, Peter A. and Andrew, Michael G. "Flow-by lead-acid improving the performance standard for EV battery systems." SAE Technical Paper Series. (1989).

Cummins, D., and Pangerl, S.F. "Preventing Large-Battery Explosions." Bureau of Mines Information Circular. Aug. 1980.

Delco Remy Training Chart Manual. Section F, "Freedom Batteries."

Earley, Mark W., ed. National Electric Code--1990 Handbook, The. 5th ed. National Fire Protection Association, Batterymarch Park, Quincy MA. 1990.

Electric Vehicle Development Corporation. "Information Network Newsletter." vol.2. no 4. (April 1991): 1-4.

General Motors Advance Product Serviceability Committee. Serviceability Design Guidelines. 3rd ed. January, 1989.

Litai, D; Lanning, D.D.; and Rasmussen, N.C. "The Public Perception of Risk." Proceedings of Meeting of Society of Risk Analysis. June 1981, Waxh., D.C.

National Highway Traffic Safety Administration. General Estimates Systems 1989: A Review of Information on Police-Reported Traffic Crashes in the United States. National Center for Statistics and Analysis, Research and Development. Washington D.C.

National Highway Traffic Safety Administration. Fatal Accident Reporting System 1989: A review of Information on Fatal Traffic Crashes in the United States in 1989. National Center for Statistics and Analysis, Research and Development. Washington D.C.

Winburn, D.C. Practical Electrical Safety. New York, NY. Marcel Dekker, Inc. 1988.

Legal References

Albers, W. A. "Role of Product Defects in Accident Causation." Warren, Michigan. 9 January 1986.

Byington, S. John. "Risk Assessment: Legal Judgements and Products Liability, or the Nexus between Science and the Law." The Science of the Total Environment. vol. 99. (1990), 245-253.

"Current Report." Occupational Safety and Health Reporter. 2Oct. 199, pp. 491-492.

Jackson, Betsy D. "Defective Motor Vehicle Recalls: Untangling costs and benefits." Governance. Spring 1985, pp 44-47.

Risk Assessment

Albaugh, Larry R., and Hulbert, David A. "Risk Analysis of an Automated Assembly line Operation." Hercules Aerospace Div., Hercules Inc., Allegany Ballistics Lab., Cumberland, MD. (1979).

Drake, Alvin W. "A First Look at Fault Trees".

El-Kady, M.A., and Vainberg, M. Y. "Risk Assessment of Grounding Hazards due to step and touch potentials near Transmission Line Structures." IEEE Transactions on Power Apparatus and Systems. Vol PAS-102, No. 9. Sep 1983, 3080-3087

Garber, Nicholas J., and Joshua, Sarath C. "A Causal Analysis of Large Vehicle Accidents through fault tree analysis."

Haasl, David F.; Roberts, Norman H.; Vesely, William E.; and Goldberg, Francine F. Fault Tree Handbook. U.S.Nuclear Regulatory Commission. NUREG-0492. January 1981.

Hertz, David and Thomas, Howard. "Decision and Risk Analysis in a New Product and Facilities Planning Problem." Sloan Management Review. vol. 24 no. 2, winter 1983, 17-31.

Kenarangui, Rasuol. "Event-Tree Analysis by Fuzzy Probability". IEEE Transactions on Reliability. vol 40. no 1. April 1991.

Lewis, E.E. Introduction to Reliability Engineering. ch. 10. J. Wiley, 1987.

Maurer, R.H. and Uy O.Manuel. "Fault-Tree Safety Analysis of a Large $Li/SOCl_2$ Spacecraft Battery." 1986 Goddard Space Flight Center Battery Workshop (Greenbelt, MD Nov. 18-19, 1986) Nasa Conference Publication 2486 (Washington D.C.: NASA, 1987) , 93-119.

Rasmussen, Norman C. "Nuclear Power Reactor Safety." Lecture Notes 1988.

Schwing, Richard. "Probability Risk Assessments and Stopping Rules in Safety Design: A Thought Starter." 18 September 1985.

Schwing, Richard. General Motors Research Labs, Warren, MI. Presentation around the theme of Health/Safety Decisions, 24 June 1991.

Schwing, Richard. General Motors Research Labs, Warren, MI. Interview, July 1991.

Slattery, Chuck. "Electric Vehicle High Voltage Issues." 20 May 1991,

Tusa, Wayne. "Risk Assessment: Engineering Tool." Civil Engineering, Vol. 56, No. 2 (February 1986): 59-61.

Electric Shock

Dalziel, C. F. "Electric Shock Hazard", IEEE Spectrum, February 1972.

Dalziel, D.F. "The Threshold of Perception Currents." AIEE Transactions on Power Apparatus and Systems. August 1954.

Erskine, J. F. "Electrical Accidents." Practitioner. vol 22. no. 1332. (June 1979), 777-81.

Gallagher, J.P. and Talbert, O.R. "Motor Neuron Syndrome after Electric Shock." Acta Neurologica Scandinavice. vol. 83. no. 2. February 1991, 79-82.

Geddes, L.A., and Baker, L.E. "Principles of Applied Biomedical Instrumentation" third edition, copyright 1989 by John Wiley & Sons, Inc.

International Electrotechnical Commission (IEC). "Effects of Current Passing Through the Human Body." IEC Publication 479, Part 1, 1984, Part 2, 1987

Jaffe, Richard; Fejgin, Moshe; Aderet, Noah Ben. "Fetal Death in Early Pregnancy due to Electric Current." Acta Obstet Gynecol Scand vol. 65, (1986) 283.

James, T.N.; Riddick, L.; Embry,J. H. "Cardiac abnormalities demonstrated postmortem in four cases of Accidental Electrocution, and their potential significance relative to nonfatal electrical injuries of the Heart." American Heart Journal. vol. 120, no. 1, 1990, 143-157.

Karl, Richard C.; Williams, Donald B.; "Intestinal Injury Associated with Low-voltage Electrocution". The Journal of Trauma. vol. 21, no. 3, March 1981.

Lown, B.and Graboys, T.B. "Sudden Death: An Ancient Problem Newly Perceived." Cardiovascular Medicine. vol. 2, no. 3, (1977), 219-38.

O'Flanagan, P.H., "Fracture due to Shock from Domestic Electricity Supply." Injury Feb. 1975, vol. 6, no. 3, 244-5.

Mazor, M.; Leiberman, J.R. "Abortion Caused by Electrical Current". Archives of Gynecology and Obstetrics. vol. 241, no.1, 1987, 71-72.

Rajam, K. H.; Reddy, D.R.; Sathyanarayana, K.; Madhusudhan Rao, D. "Fracture of Vertebral Bodies due to Accidental Electric Shock. " Indian Medical Association, Journal. vol. 66, no. 2, 16 Jan 1976, 35.

Sances, A.; Jr., Larson; S. J., Myklebust; J. Cusick, J. F. "Electrical Injuries." Surgery, Gynecology and Obstetrics, vol. 149, no. 1, July 1979, 97-108.

Shen, Z. Y.; Chang, Z. D.; Wang, N. Z. "Electrical Injury of wrist: Classification and Treatment--clinical analysis of 90 cases." Burns, vol. 16, no. 6, 1990, 449-456.

Skoog, T. "Electrical Injuries." Journal of Trauma. vol. 10, no. 10, October 1970, 816-830.

Stueland, Dean T.; Stamas, Peter, Jr.; Welter, Timothy M.; Cleveland, David A. "Bilateral Humeral Fractures from Electrically induced Muscular Spasm." The Journal of Emergency Medicine. vol. 7, January, 1989, 457-459.

Williams, Donald B; Karl, Richard C. "Intestinal Injury associated with Low-voltage Electrocution." Journal of Trauma. vol. 21, no.3, March 1981, 246-250.

Index

R

S

T

U

W