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FIRE SAFETY IN TRANSIT SYSTEMS FAULT TREE ANALYSIS

William T. Hathaway
Arthur L. Flores
Stephanie H. Markos
Marilyn K. Goldberg
Ira M. Dinkes

PROJECT MEMORANDUM

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U.S. DEPARTMENT OF TRANSPORTATION
RESEARCH AND SPECIAL PROGRAMS ADMINISTRATION
Transportation Systems Center
Cambridge MA 02142

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1. INTRODUCTION

This Project Memorandum presents a series of fault tree logic diagrams which have been developed as the initial task in a project to identify and evaluate prospective fire safety countermeasures applicable to transit vehicles. Figure 1-0 presents an overview of the project and each of its five tasks. A detailed discussion of the project methodology and project results with countermeasures identified for implementation in transit vehicles will be presented in the final report to be published at a later date. The purpose of this document is to present fault trees which illustrate the sequences of events which may lead to a transit-fire related casualty. A description of the basis for their development and an explanation of their intended use are included as well as information on basic fault tree construction and symbol terminology.

Fault tree analysis was chosen as the principal tool for identifying countermeasures because it is a systematic method of analyzing the complex series of events which occur during a fire. All of these events including human events, and material and environmental factors may be presented in a systematic manner by using a fault tree. Each event or sequence of events can then be examined to identify appropriate countermeasures and to evaluate the effect of potential countermeasures in minimizing or eliminating a fire threat. Fault tree diagrams can also be used in the following manner:

- As an educational tool to fully explain fire ignition, fire propagation and occupant evacuation.
- As an aid in developing vehicle procurement specifications.
- As an aid or checklist for the vehicle designer.
- As an aid in developing vehicle preventive maintenance, repair and operational practices.
- As an aid in developing emergency response and evacuation procedures.

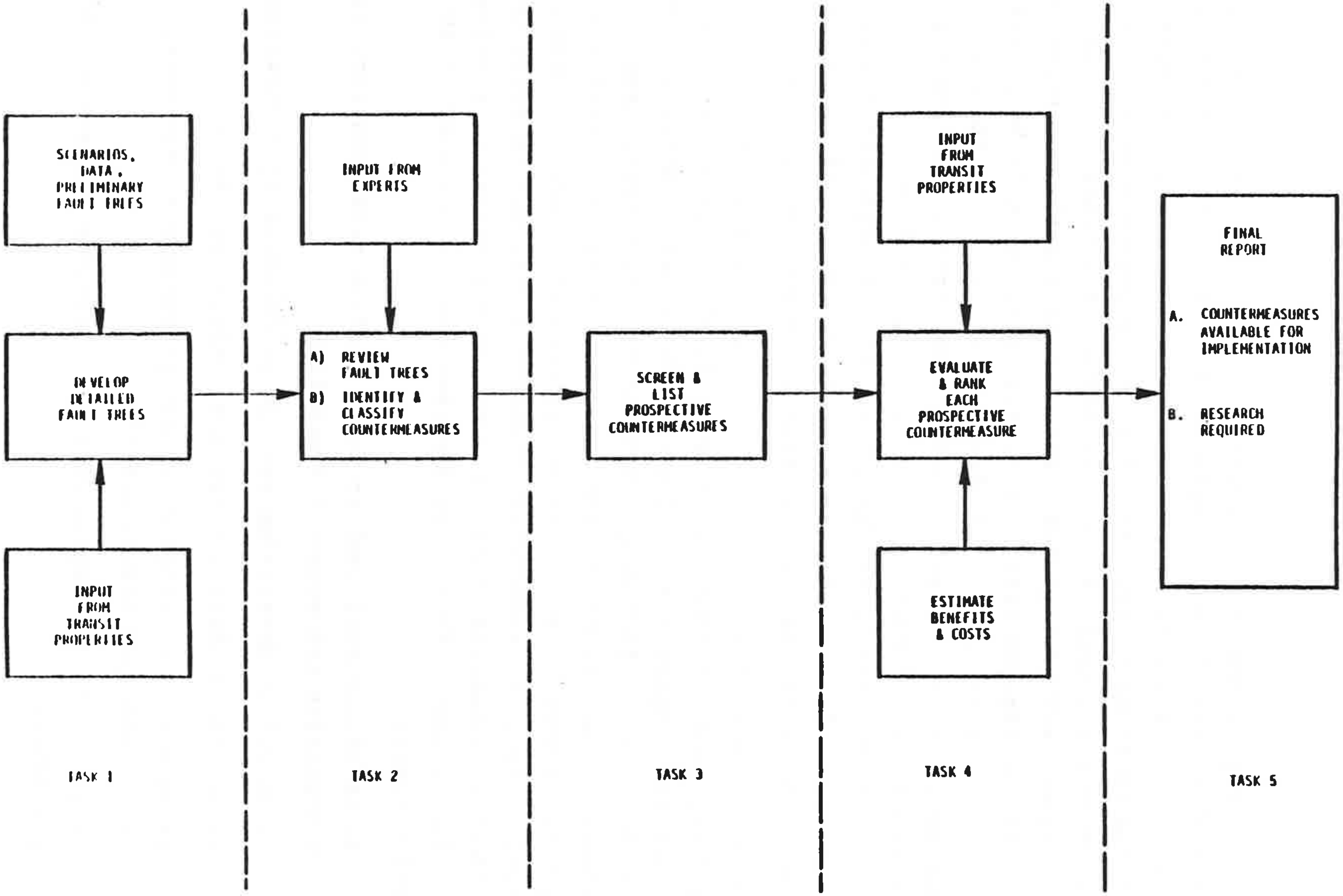

FIGURE 1-0. FIRE SAFETY COUNTERMEASURES FLOW CHART

A previous UMTA-sponsored TSC study identified the fire threat in transit vehicles in both a quantitative and qualitative manner. The results of this study are presented in the report "Identification of the Fire Threat in Urban Transit Vehicles."[1] It presents data on ignition sources and frequency of fire-and-smoke incident occurrence for rail rapid transit (RRT) vehicles and transit buses. Scenarios and preliminary fault trees which supplemented these data provided a better understanding of fire propagation and the human involvement with the fire events. This previous effort has served as the foundation for the development of the fault trees contained herein.

The following sections contain a discussion of fault tree construction and present the fault trees developed to depict fire incidents occurring in a rail rapid transit vehicle or bus, fire/smoke suppression or containment and the evacuation of individuals from these vehicles.

2. FAULT TREE DEVELOPMENT METHODOLOGY

2.1 BACKGROUND

A fault tree is a graphical representation of the relationship between certain specific events and an ultimate undesired event. Fault tree analysis is a technique first developed by aerospace safety engineers to identify and evaluate the potential causes of system failures (e.g., undesired events) and to develop methods of controlling and/or eliminating such failures.

A typical fault tree diagram is constructed as follows. A particular undesired event is selected. This head or undesired event is the event whose occurrence must be minimized or prevented. Primary events, and their interactions and causes, leading to the undesired head event are then examined and broken down into secondary events and causes. This reverse reasoning process continues until there is either insufficient information or an event is not considered significant enough for further analysis. A more extensive explanation of fault tree diagram construction is presented in Section 2.2.

Fault trees may have quantitative or qualitative applications, or both. Quantitative trees are used to calculate specific probabilities of events. Qualitative trees provide overall pictorial diagrams of complex sequences of events and causes. These sequences can then be analyzed to identify specific areas where corrective action (e.g., component redesign) could be employed to prevent the undesired event from occurring. The fault trees presented in this Project Memorandum are of a qualitative nature and will serve as the basis for the identification of fire safety countermeasures applicable to transit vehicles.

Qualitative fault trees were chosen for several reasons. The most notable advantage is that a high level of detail can be generated for use in understanding the number of events and causes leading to a particular undesired event (defined in this analysis as a transit-fire related casualty). This detail can be generated because the sequences of potential events are not restricted to those which can actually be documented. (Historical data concerning transit fires are usually quite limited.) Thus, many more possible combinations of events and their causes leading to the undesired event can be examined. Moreover, this high level of detail permits the consideration of many countermeasures which could reduce the occurrence of events leading to the undesired transit-fire related casualty.

Another positive factor is the pictorial quality of the fault tree diagram which illustrates the logical progression of events from a low order cause to the high order undesired event.

2.2 PROCEDURE FOR FAULT TREE CONSTRUCTION

The following discussion is intended to provide the reader with sufficient knowledge to understand the fault tree diagrams presented in the following sections. For a more extensive discussion of fault tree analysis, the reader is referred to the literature[2, 3, 4, 5].

The basic premise of fault tree logic is that events are caused by the occurrence of other events. These events and their interaction are represented by particular symbols which can be arranged in various combinations. Figure 2-0 illustrates the symbols used in the construction of the fault tree diagrams contained in this document. A brief description of these symbols and usage will assist in comprehending the logical relationships indicated. Figure 2-0 should be referred to throughout the reading of the following descriptive material.

Symbols known as "logic gates" are used to illustrate the manner in which incidents at one level of the fault tree combine to produce the next (higher) logical event. The two gates used in this representation are the "OR" gate and the "AND" gate. The "OR" gate, as shown in Figure 2-0, is equivalent to the situation where <u>any</u> of the input events (below the gate) may lead to the output event (above the gate). For example, the occurrence of "B"

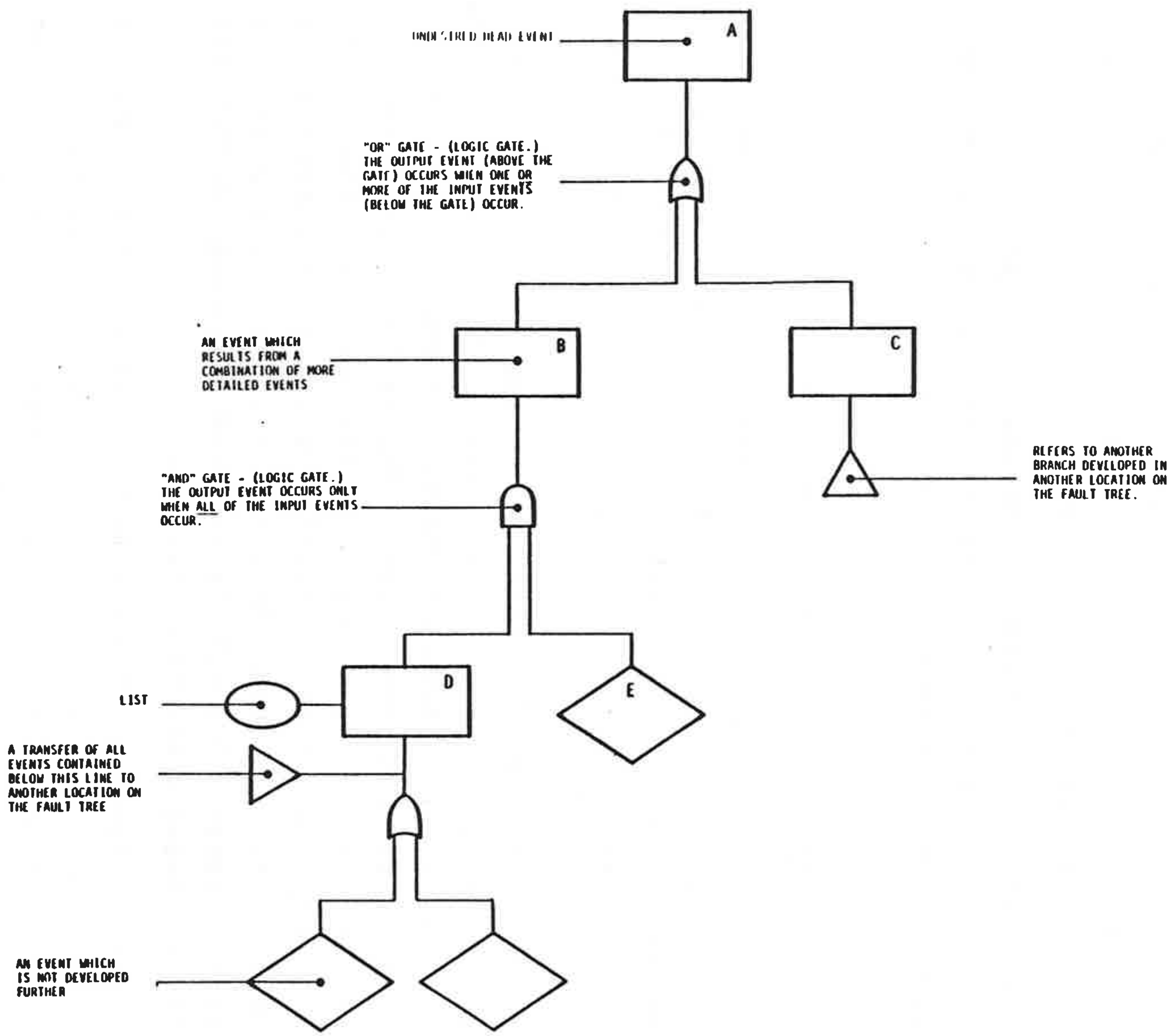

FIGURE 2-0. SYMBOLS USED IN FAULT TREE CONSTRUCTION

or "C" or both may result in "A". More than one input event may occur, but only one is necessary for the output event (A) to occur. The "AND" gate represents a situation where all of the listed input events must occur to produce the output condition. For example, both "D" and "E" must occur before "B" results; these two conditions must occur simultaneously.

Other symbols used include rectangles, diamonds and triangles. Rectangles describe output events, i.e., events which are analyzed further to determine how they occurred. As such, a rectangle is used to depict the head (undesired) event at the top of a branch and it is also used throughout the tree to indicate other events which are developed in more detail. The rectangle is the only event symbol which has both a gate and input event symbols below it; therefore it cannot be used as the lowest symbol on a fault tree branch. Rectangles may also represent inputs to another output event. In fact, the rectangle may represent an input (cause) event on one level and an output (result) event on another level simultaneously.

Diamond shaped symbols represent undeveloped events which are not broken down further because they are not considered significant or because of lack of information. As such, fault tree branches are terminated with diamonds when the information needed to explain the event is not available or is nonexistent or the event is considered trivial for the purposes of a particular analysis.

A triangle signifies the transfer of a particular line of reasoning to another location within the fault tree. Essentially, this allows for a condensation of the fault tree by eliminating the need for repeating a series of events that have been described in another fault tree branch. It should be noted that there is always more than one transfer triangle. Where the triangle is connected horizontally to a rectangle, or to the vertical line connecting a rectangle to a logic gate, everything below the rectangle (the particular branch) is transferred to another branch of the fault tree diagram. The title of the event in the rectangle above the horizontal line triangle need not be the title of the event to which the transferred information branch attaches and applies. Rectangles with triangles attached by a vertical line (below the rectangle) indicate the point of attachment for the information branch which was initially developed in another branch. Transfer triangles are labeled in two ways. Triangles identified by a letter only refer to major branches developed elsewhere in the fault tree diagram. Within these major branches, smaller series of events are often developed which may be transferred both within a major branch or to other major branches. These smaller series of events are labeled by both a letter and number according to the branch in which they first appear.

One additional symbol, the oval connected by a horizontal line to a rectangle, represents a list of items that are too numerous to include directly on the fault tree. For the purposes of this report, the lists refer to combustible materials located or used in different areas of the transit vehicles.

The fault tree diagram presented in Figure 2-1 is the overview in which the head or ultimate undesired event is "Fire Related Transit Casualty Occurs". Two primary (input) events leading to this top undesired (output) event are "Fire/Smoke Conditions Are Present in Area" and "Individual Fails To Evacuate Area". The occurrence of both of these major events is necessary for the transit fire related casualty to occur.

Each of these primary events is analyzed and branches of secondary events are developed. "Fire/Smoke Conditions Are Present in Area" results from both "Fire/Smoke Incident Occurs" and "Fire/Smoke Is Not Suppressed or Contained". The event, "Individual Fails To Evacuate the Area" (most specifically the vehicle), occurs because either "Individual Fails To Remove Self" or "Individual Is Not Rescued". The "area" could also include elevated, underground or at-grade stations and right-of-way. In addition, the underground right-of-way can be divided into the tunnel and the tube (underwater passage). However, these other locations are not developed in this analysis. Each of the events shown in this overview is developed more extensively in the following sections. Moving from left to right on this overview, the fault tree diagrams for "Fire/Smoke Occurs in Occupant Compartment of RRT Car" are presented in Section 3, the fault tree diagrams for "Fire/Smoke Occurs in Occupant Compartment of Bus" are treated in Section 4, the fault tree diagrams for "Fire/Smoke Is Not Suppressed or Contained" are treated in Section 5, and the fault tree diagrams for "Individual Fails To Evacuate Area" are treated in Section 6.

When reviewing the fault tree diagrams there are several important considerations which should be noted. First, the occurrence of any one event does not necessarily mean that the head event, (a fire or casualty) will occur. The fault tree is a tool which allows the reader to see combinations or sequences of events that many times are unrelated to each other or several independent events which must occur for the head event to occur. Second, there are several unspecified factors or conditions which may influence the probability of occurrence of an event or alter the intensity of an event. Some of these factors or conditions are the presence of wind currents or rain, the occurrence of vibration, a component or part that is worn in a particular or unusual manner, the presence of sufficient combustible material to propagate the fire, etc. Where possible, factors or conditions such as these have been incorporated in the fault tree diagrams. Third, within the fault trees there are branches where the probability of occurrence of the head event is unknown; however, there are other branches where the available historical statistical data have provided a rough estimate of the probability of occurrence of the head event. Nonetheless, whether the head event in the branch has a low, moderate or high probability of occurrence, it must be considered as having the potential of occurring and cannot be ignored; it must be addressed.

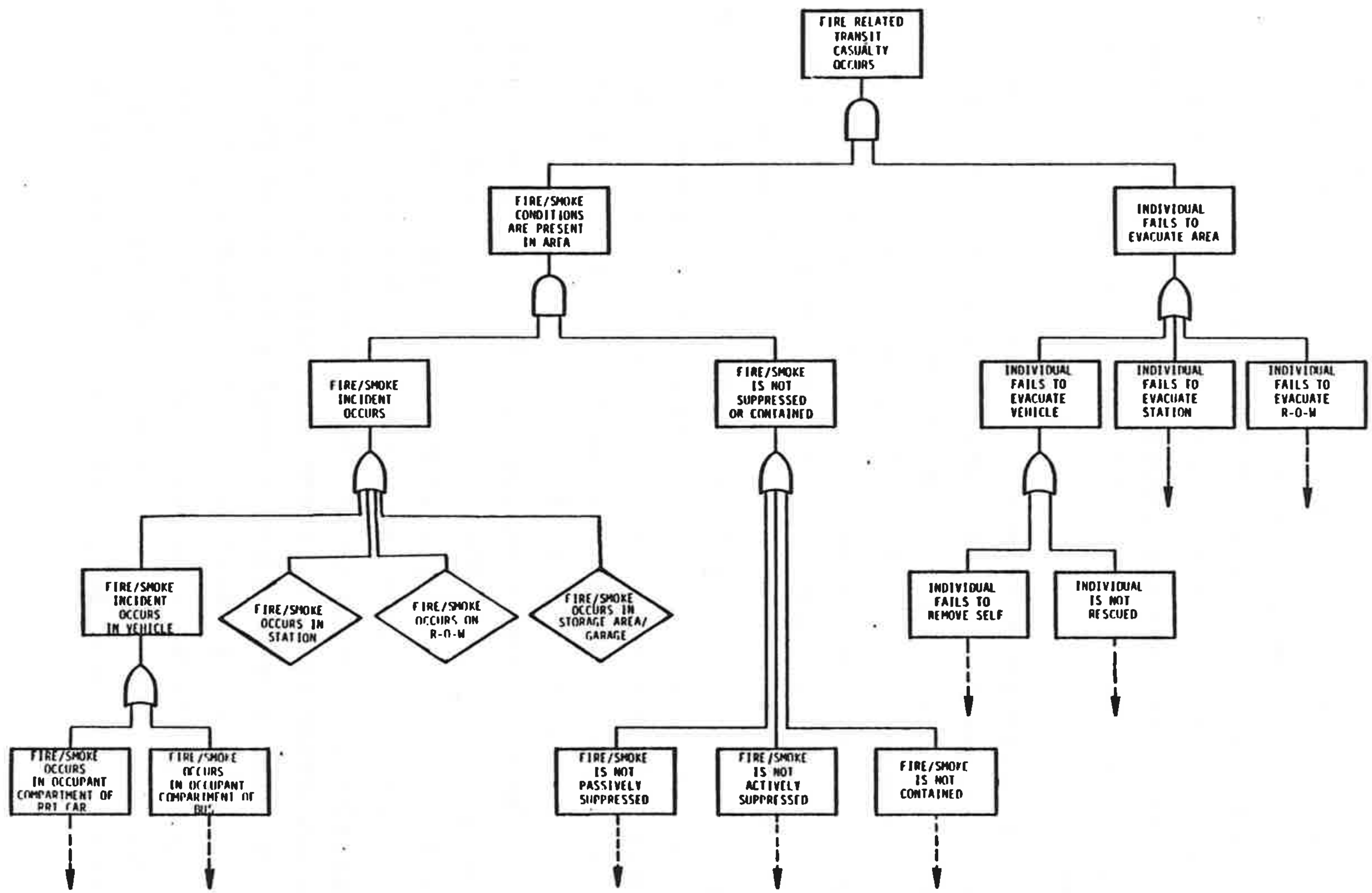

FIGURE 2-1. OVERVIEW: FIRE RELATED TRANSIT CASUALTY OCCURS

3. RAIL RAPID TRANSIT (RRT) CAR FIRE/SMOKE INCIDENT

3.1 BACKGROUND

In the development of fault tree diagrams representing a rail rapid transit (RRT) car fire incident, an effort was made to incorporate into the fault tree diagrams the many possible variations which exist in transit car design and operation.

Each transit property has RRT cars built to its own specifications. As such, transit cars built at the same time by the same manufacturer may differ since each property may specify the structure, equipment, materials and operational procedures for its particular transit cars. For this reason, the fault trees contain many variations in design and operations which are not directly applicable to any particular vehicle or transit property.

To account for the differences in the current RRT car fleet (approximately 10,000 cars), the fault tree diagrams have been developed in as generalized and nonspecific way as possible without sacrificing the accuracy needed to describe the ignition and propagation of the fire. Every effort has been made to identify all possible ignition sources on the RRT car.

The technical data used in the construction of the fault tree diagrams were obtained from several sources. Statistical and historical data, although limited, provided an indication of the frequency of fire occurrence, location of ignition, and components of the RRT car involved. This information was obtained from published accident reports, transit property reports, newspaper clippings, transit property personnel and TSC staff. Because the information did not usually contain the detailed causative data necessary for fault tree analysis, it was essential to study the construction of the RRT car in order to determine potential as well as known fire hazards. Additional technical information was obtained from a review of vehicle construction specifications and maintenance manuals, and discussions with transit property staff and other technical people. This information was integrated with the historical and statistical data and then used in developing the fault tree diagram.

3.2 FAULT TREE DIAGRAMS

Figure 3-0 is an overview fault tree for the head event, "Fire/Smoke Occurs in Occupant Compartment of RRT Car". This event was chosen because the occurrence of a fire within the occupant compartment itself represents one of the most potentially serious safety hazards to passengers because of heat, smoke and toxic gases within the confined passenger space.

This primary event, "Fire/Smoke Occurs in Occupant Compartment of RRT Car", results from the occurrence of either of the two secondary events: "Fire/Smoke Originates within Occupant Compartment" or "Fire/Smoke Penetrates from Outside Occupant Compartment". In turn, these two events are developed further. The fire may originate in four interior areas of the occupant compartment. These areas are indicated on the overview as: "Fire/Smoke Occurs on/under/or back of Seats", "Fire/Smoke Occurs on Floor", "Fire/Smoke Occurs at Wall" and "Fire/Smoke Occurs at Ceiling". These four major events are developed in Figures 3-1 through 3-4 and their subnumbers.

Four major events which lead to the occurrence of the event, "Fire/Smoke Penetrates from Outside Occupant Compartment" are: "Fire/Smoke Penetrates from Crew Compartment", "Fire/Smoke Penetrates from under RRT Car", "Fire/Smoke Penetrates thru Roof of RRT Car" and "Fire/Smoke Penetrates thru Side of RRT Car". These four events are illustrated in Figures 3-5 through 3-8 and their subnumbers. These major events have been developed down to the level where further information is either unavailable or considered insignificant (bottom event or diamond).

Table 3-1 provides a key to the lists of combustible materials used or located in the various areas of the RRT car.

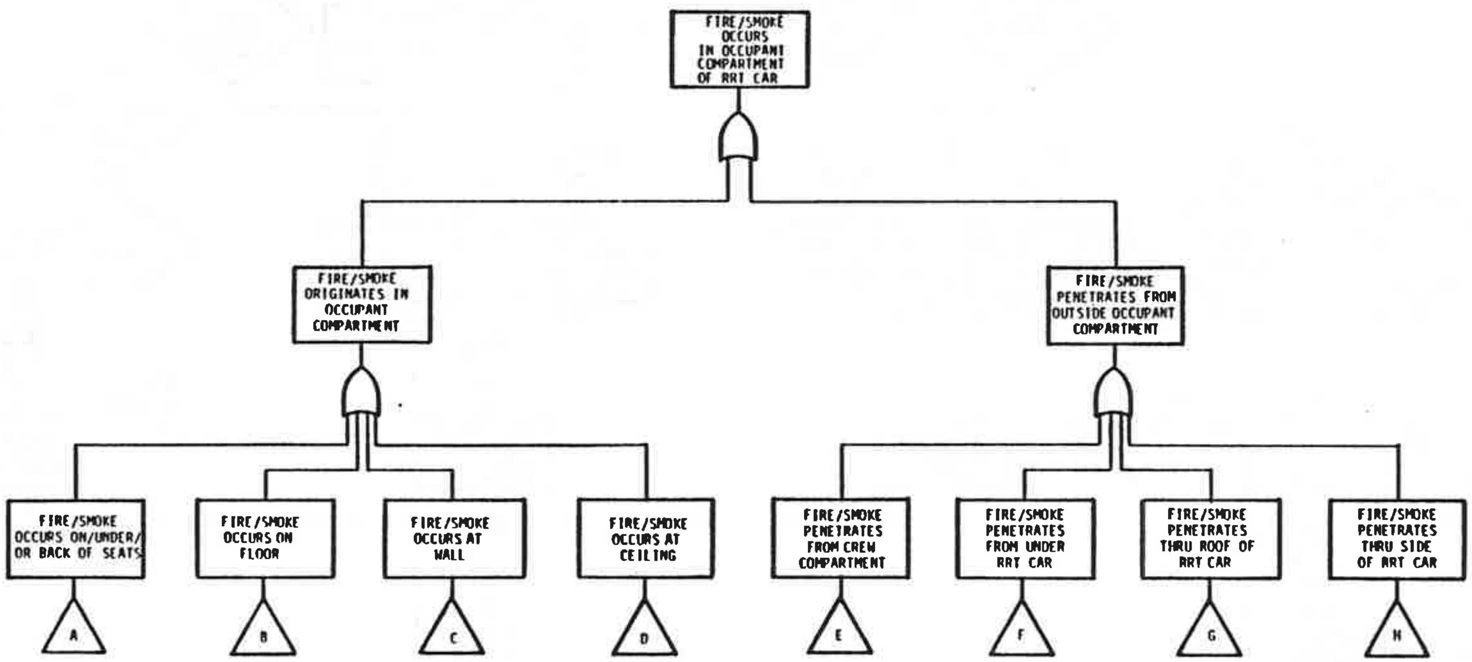

FIGURE 3-0. OVERVIEW: FIRE/SMOKE OCCURS IN OCCUPANT COMPARTMENT OF RRT CAR

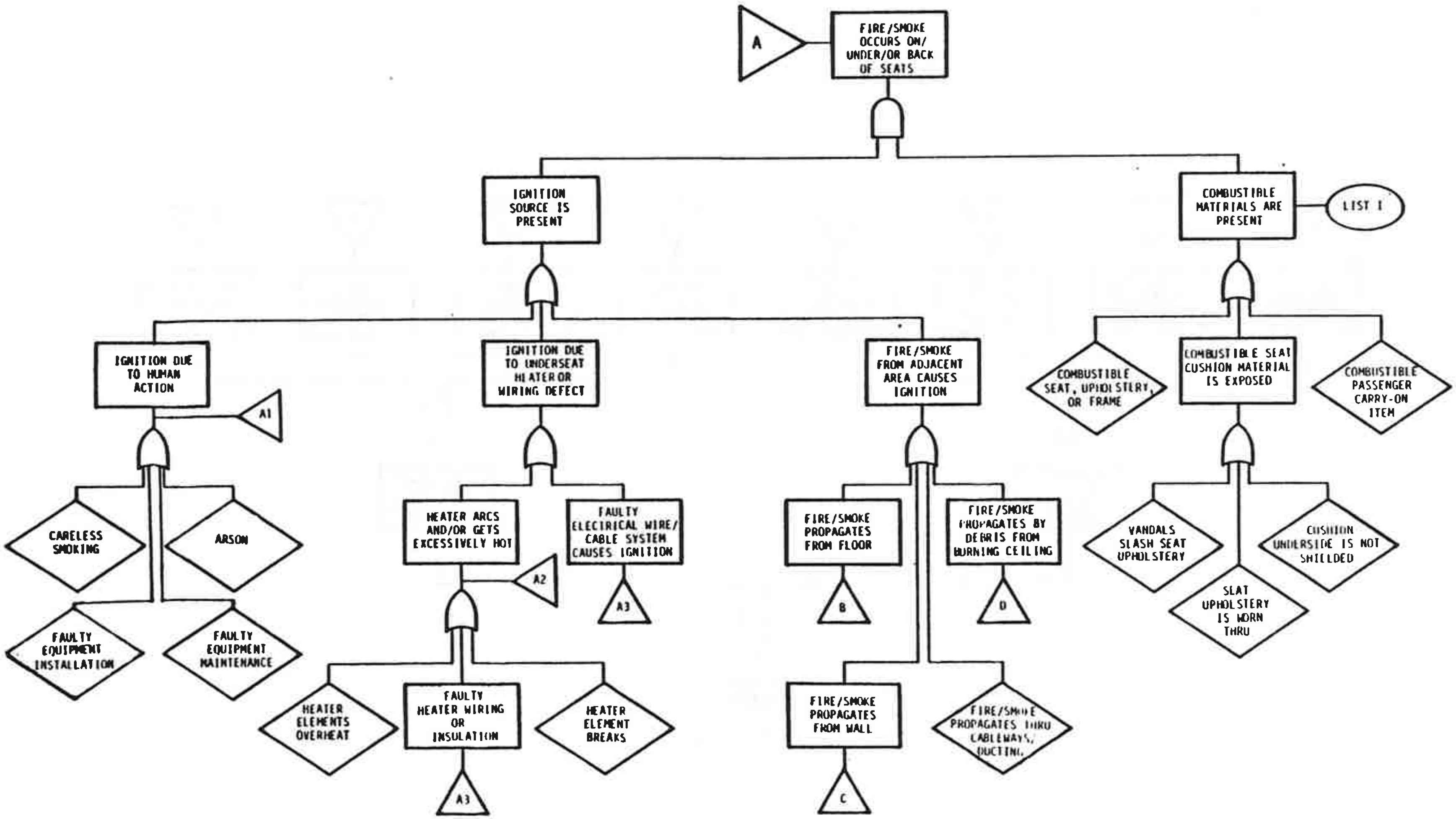

FIGURE 3-1. A: FIRE/SMOKE OCCURS ON/UNDER/OR BACK OF SEATS

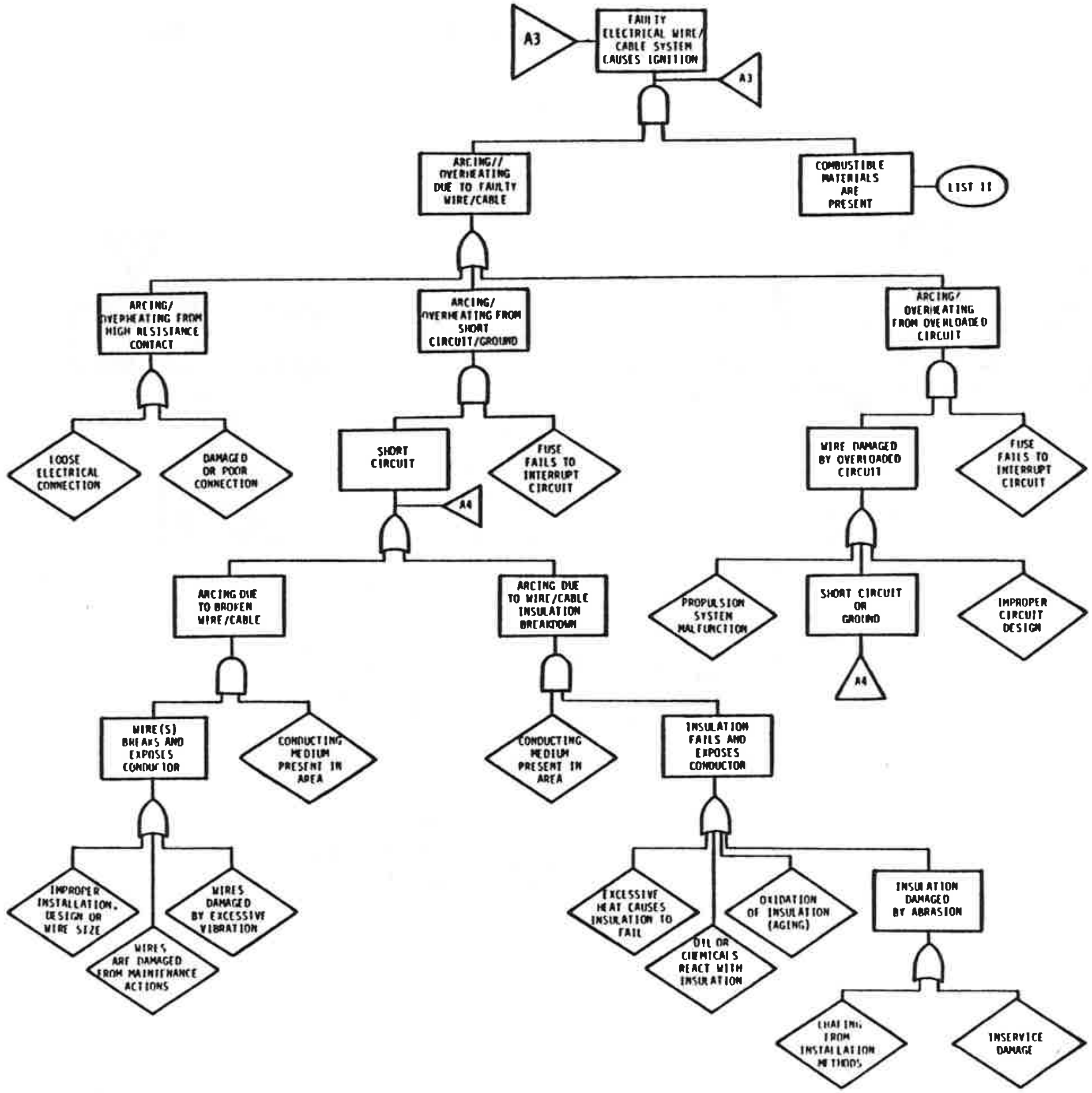

FIGURE 3-1-1. A3: FAULTY ELECTRICAL WIRE/CABLE SYSTEM CAUSES IGNITION

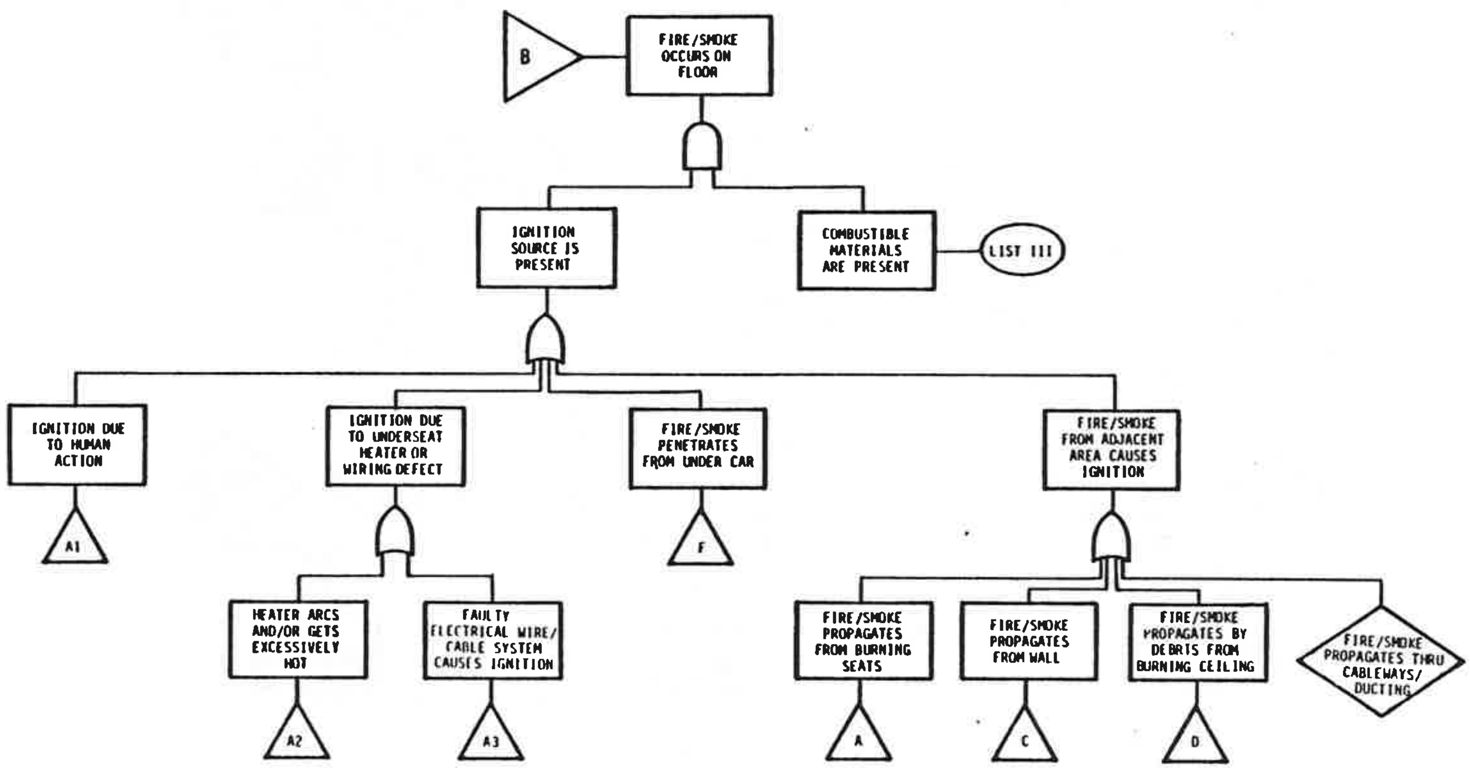

FIGURE 3-2. B: FIRE/SMOKE OCCURS ON FLOOR

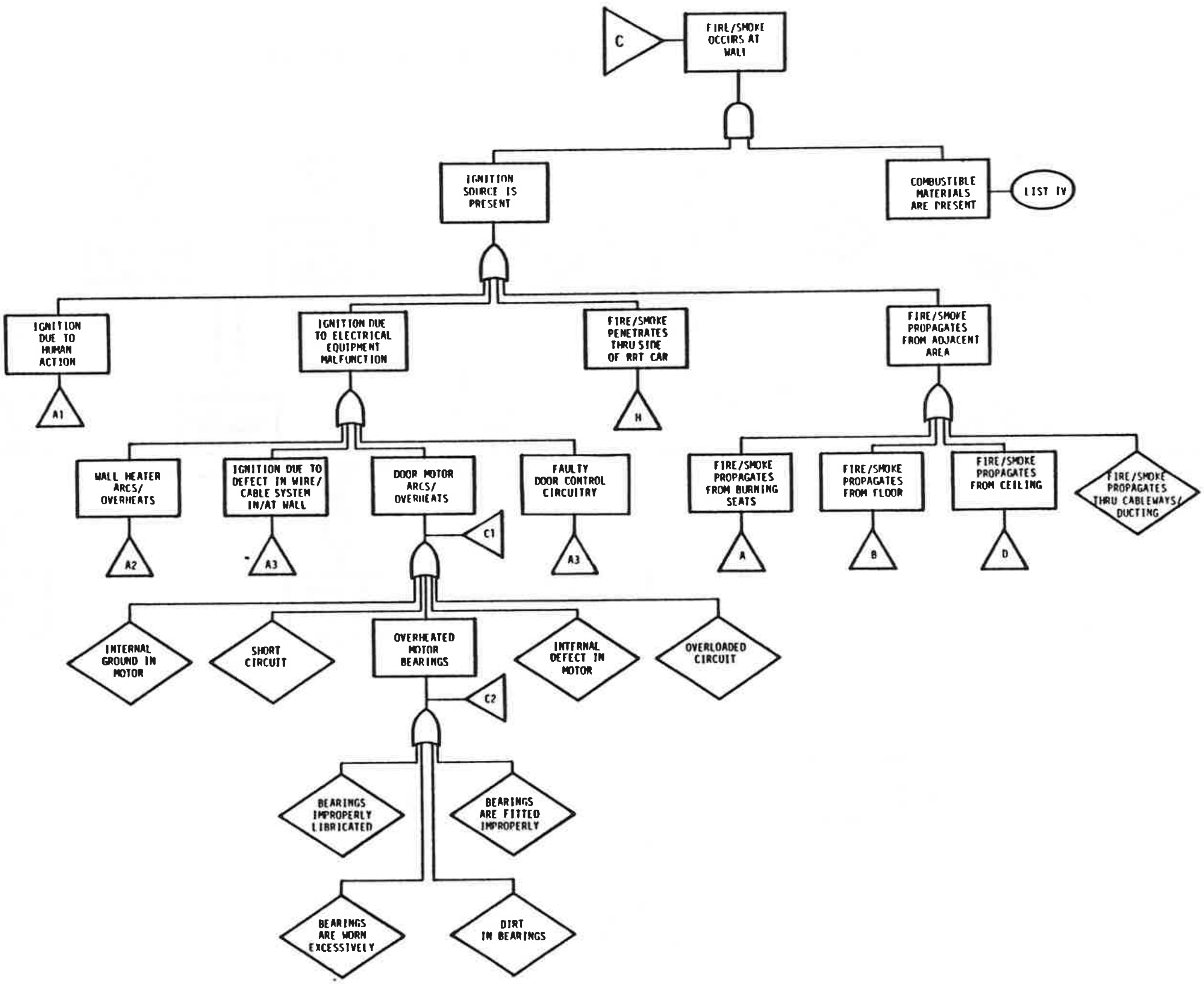

FIGURE 3-3. C: FIRE/SMOKE OCCURS AT WALL

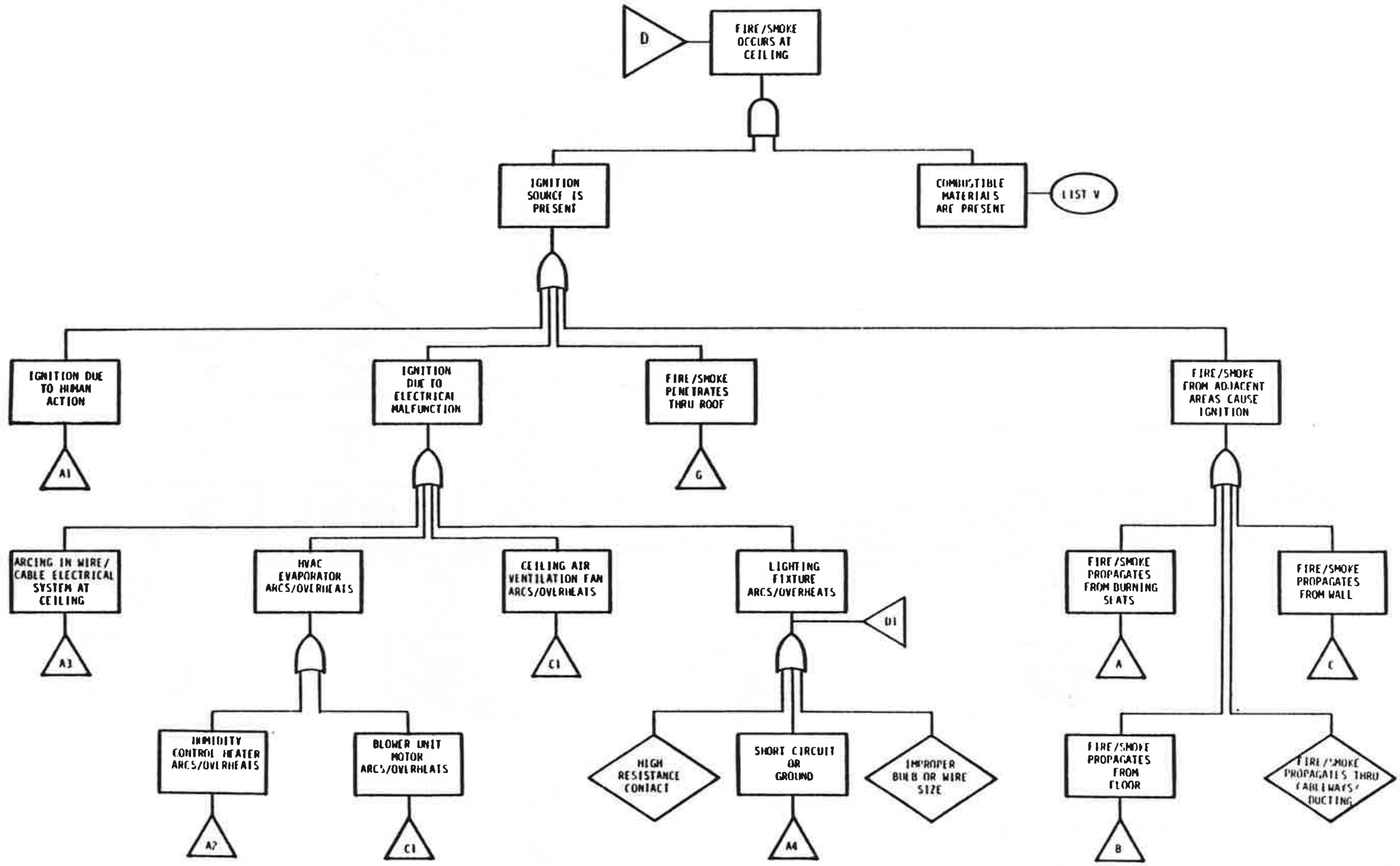

FIGURE 3-4. D: FIRE/SMOKE OCCURS AT CEILING

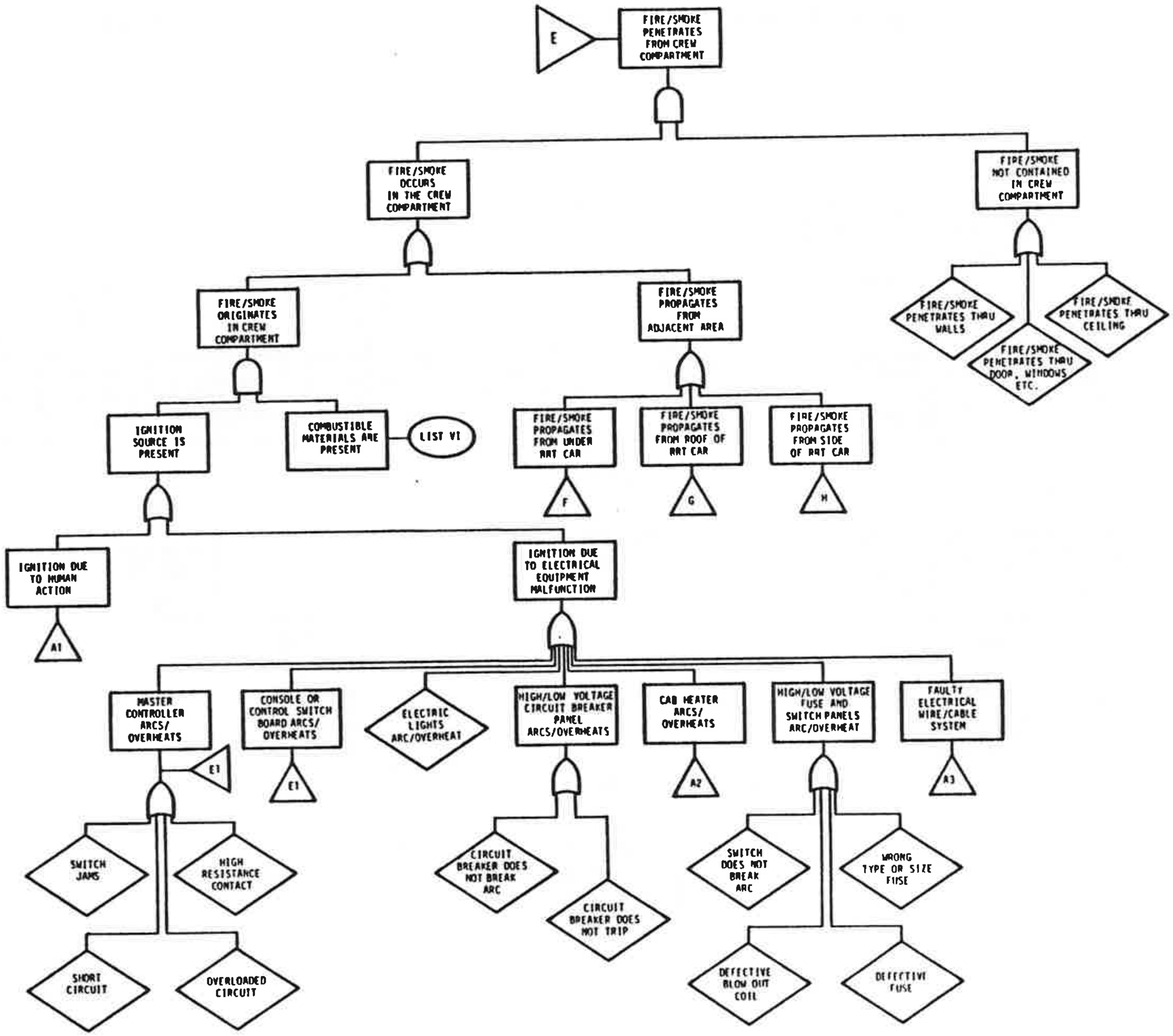

FIGURE 3-5. E: FIRE/SMOKE PENETRATES FROM CREW COMPARTMENT

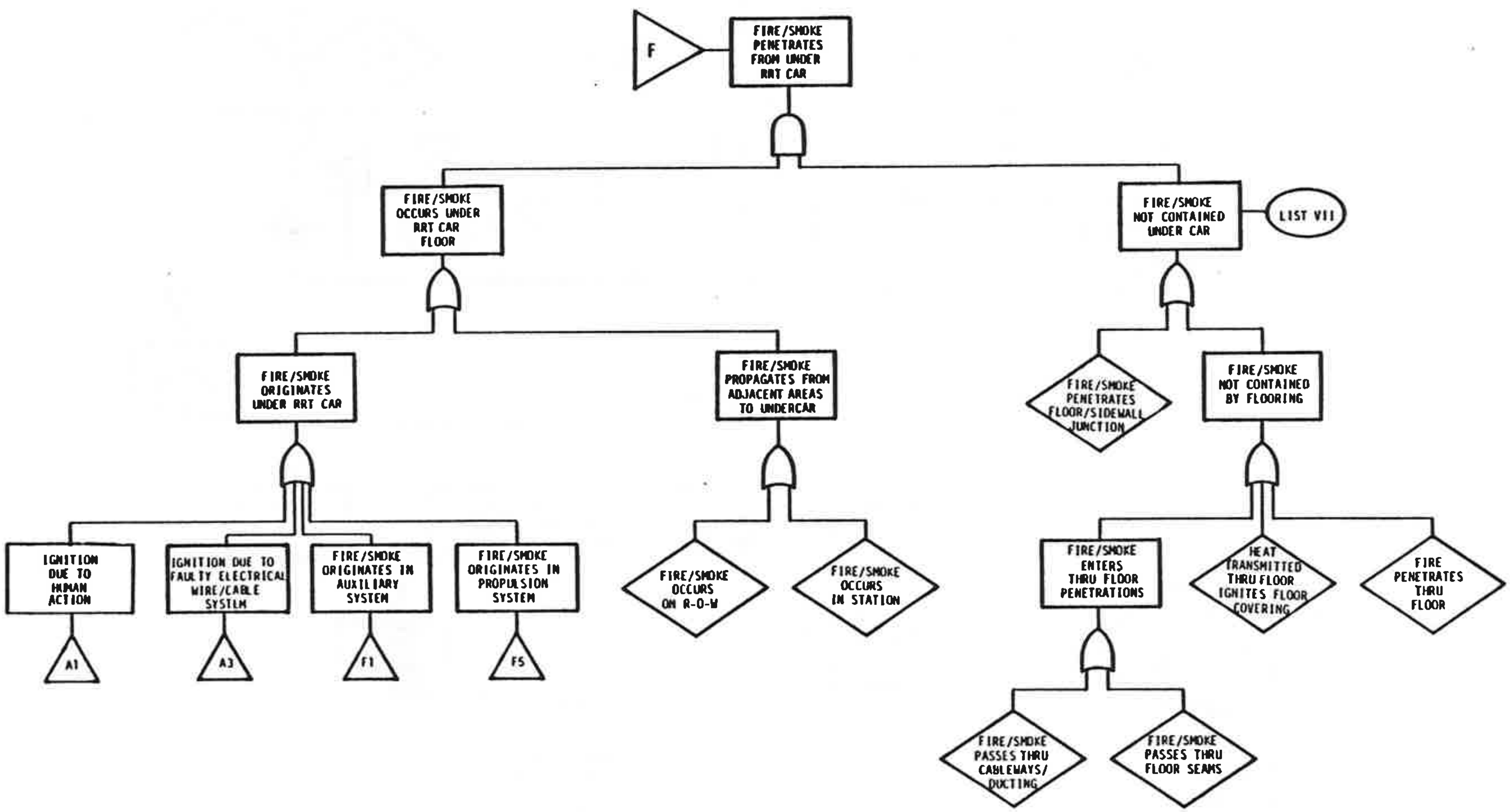

FIGURE 3-6. F: FIRE/SMOKE PENETRATES FROM UNDER RRT CAR

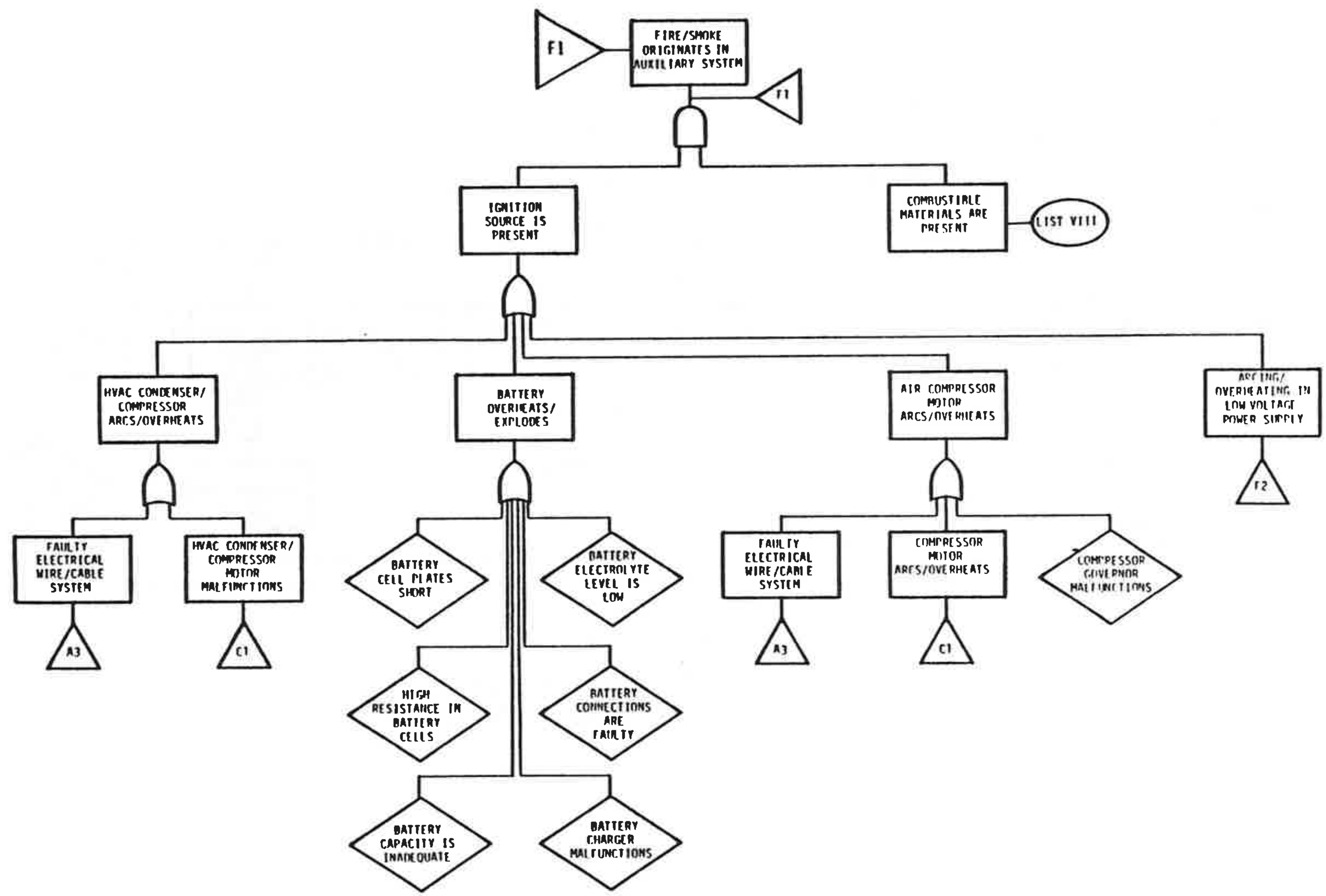

FIGURE 3-6-1. F1: FIRE/SMOKE ORIGINATES IN AUXILIARY SYSTEM

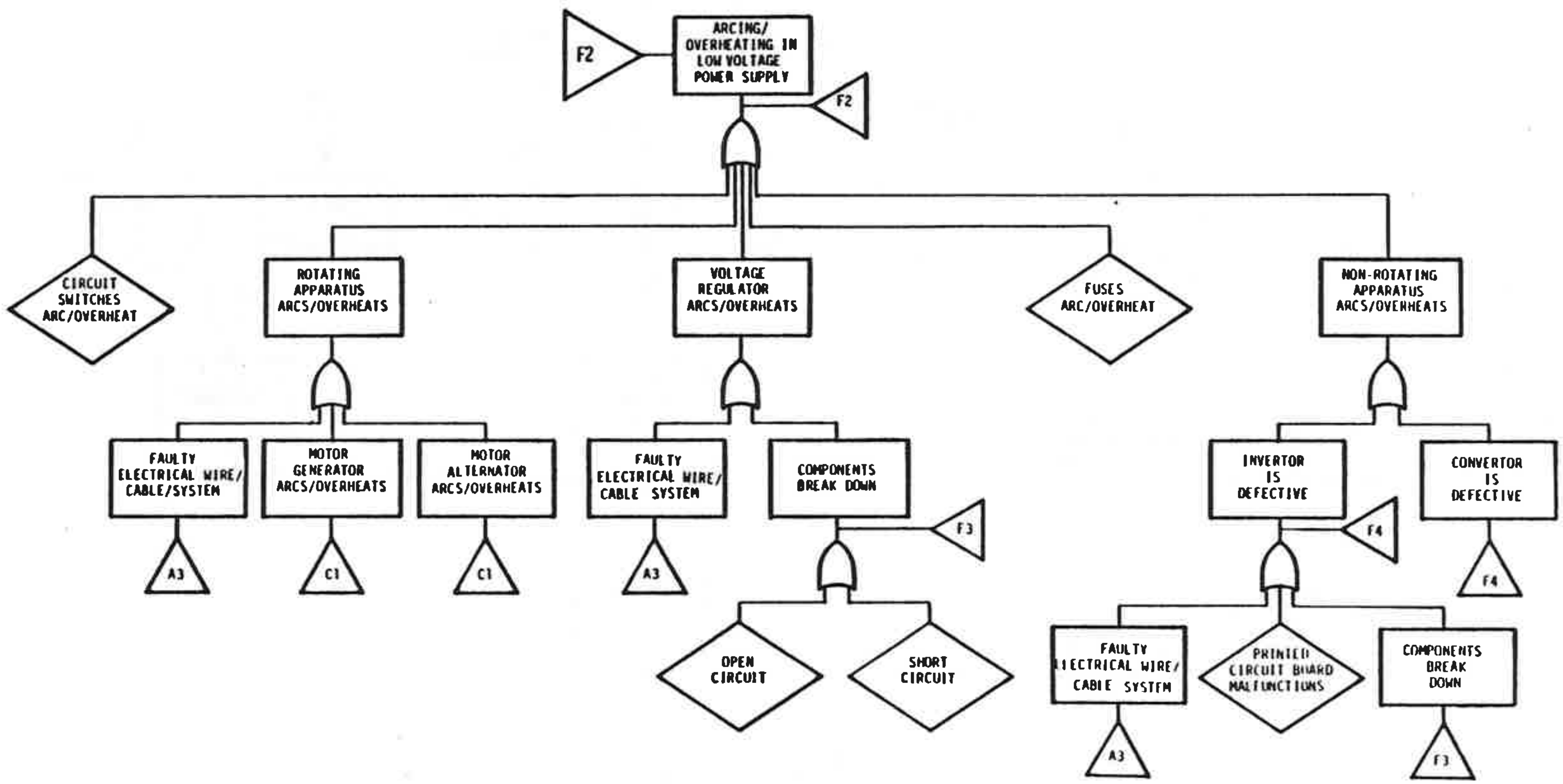

FIGURE 3-6-2. F2: ARCING/OVERHEATING IN LOW VOLTAGE POWER SUPPLY

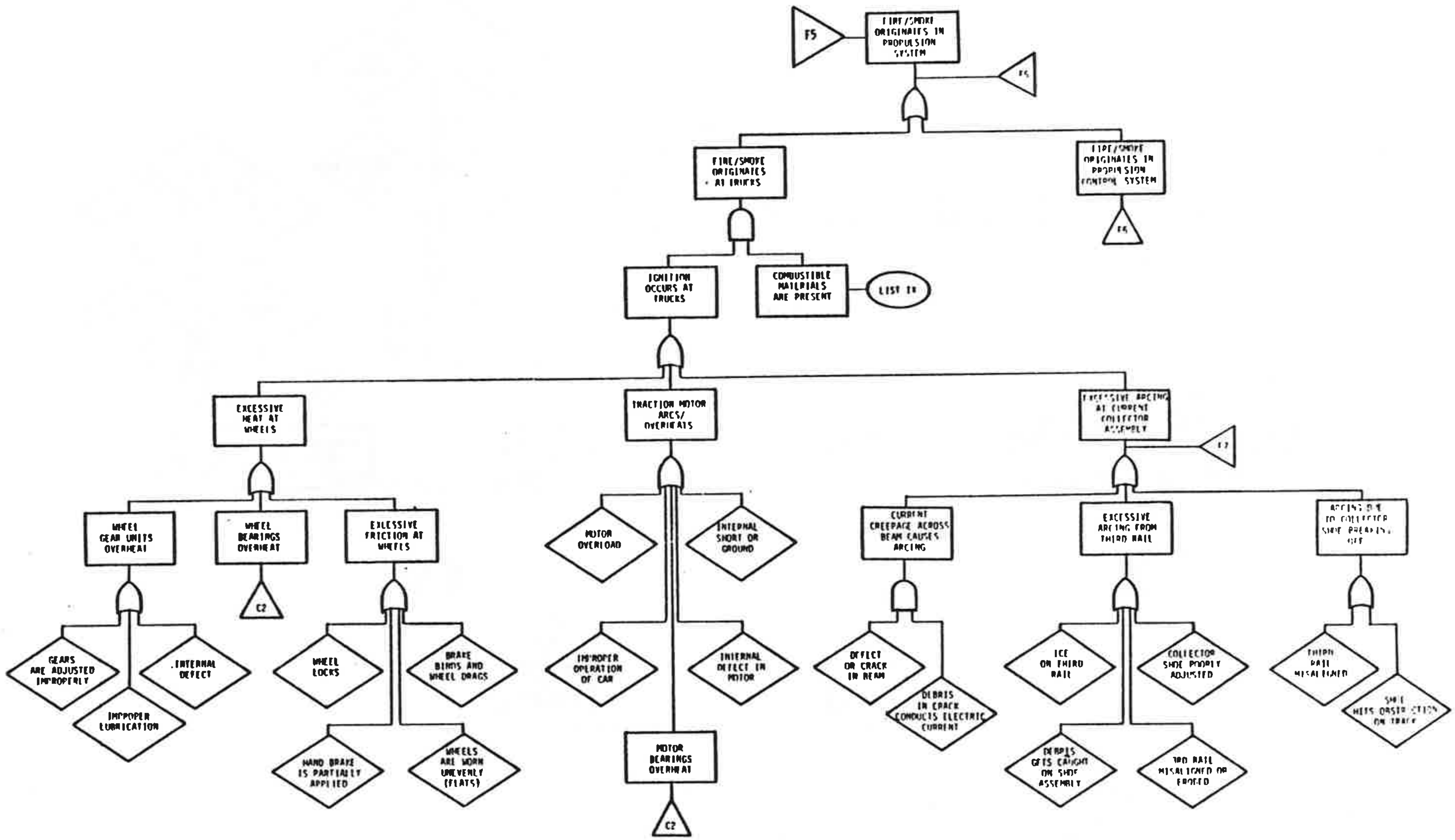

FIGURE 3-6-3. F5: FIRE/SMOKE ORIGINATES IN PROPULSION SYSTEM

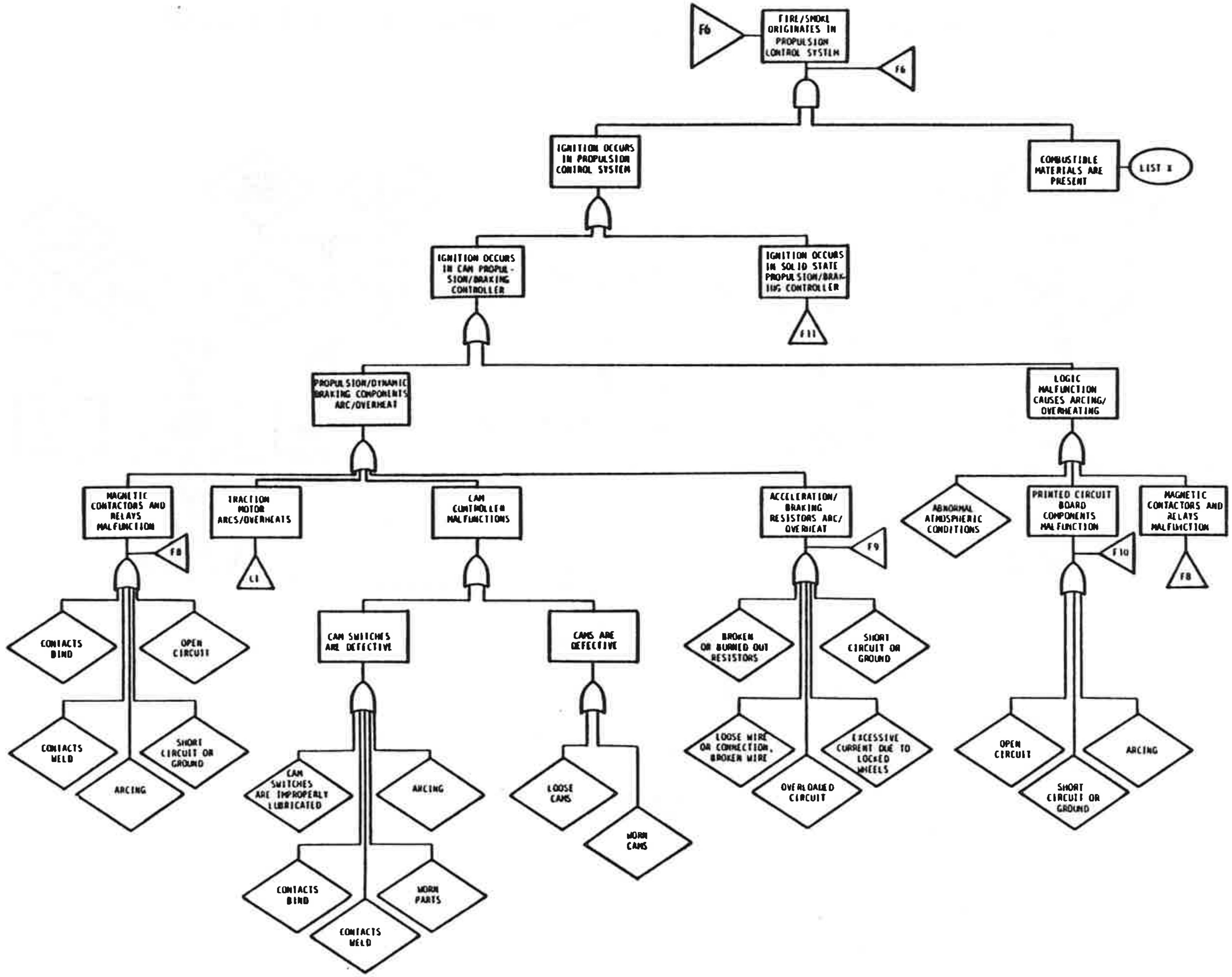

FIGURE 3-6-4. F6: FIRE/SMOKE ORIGINATES IN PROPULSION CONTROL SYSTEM

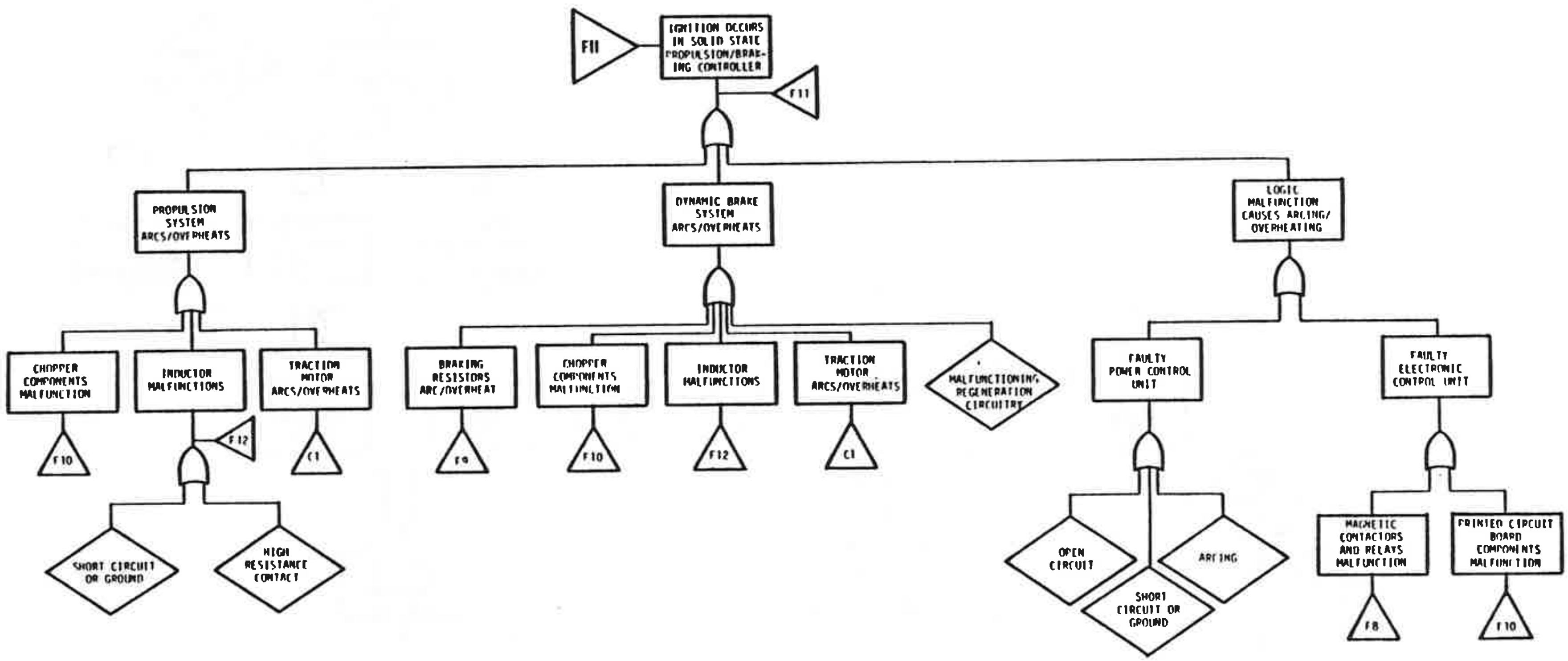

FIGURE 3-6-5. F11: IGNITION OCCURS IN SOLID STATE PROPULSION/BRAKING CONTROLLER

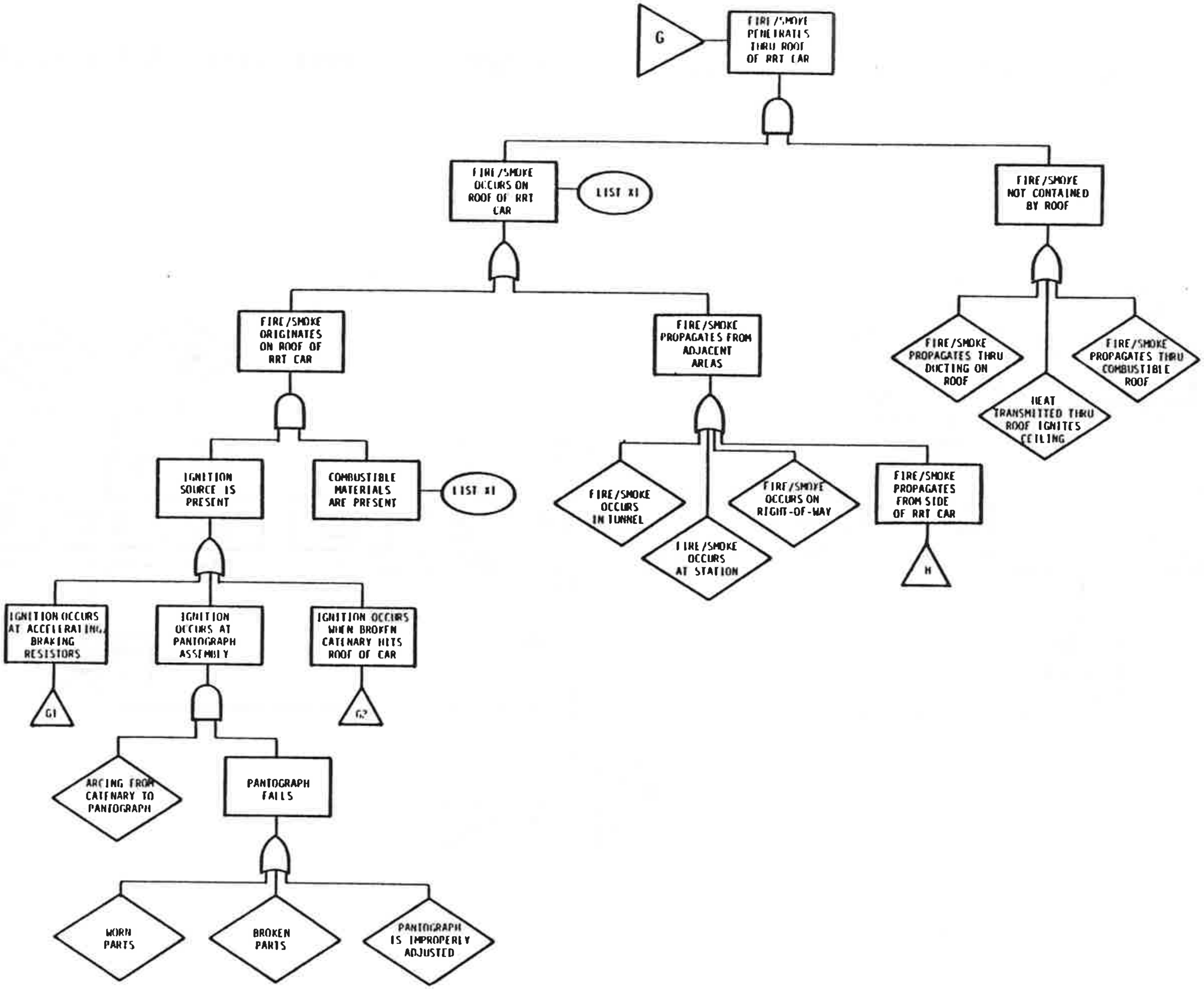

FIGURE 3-7. G: FIRE/SMOKE PENETRATES THRU ROOF OF RRT CAR

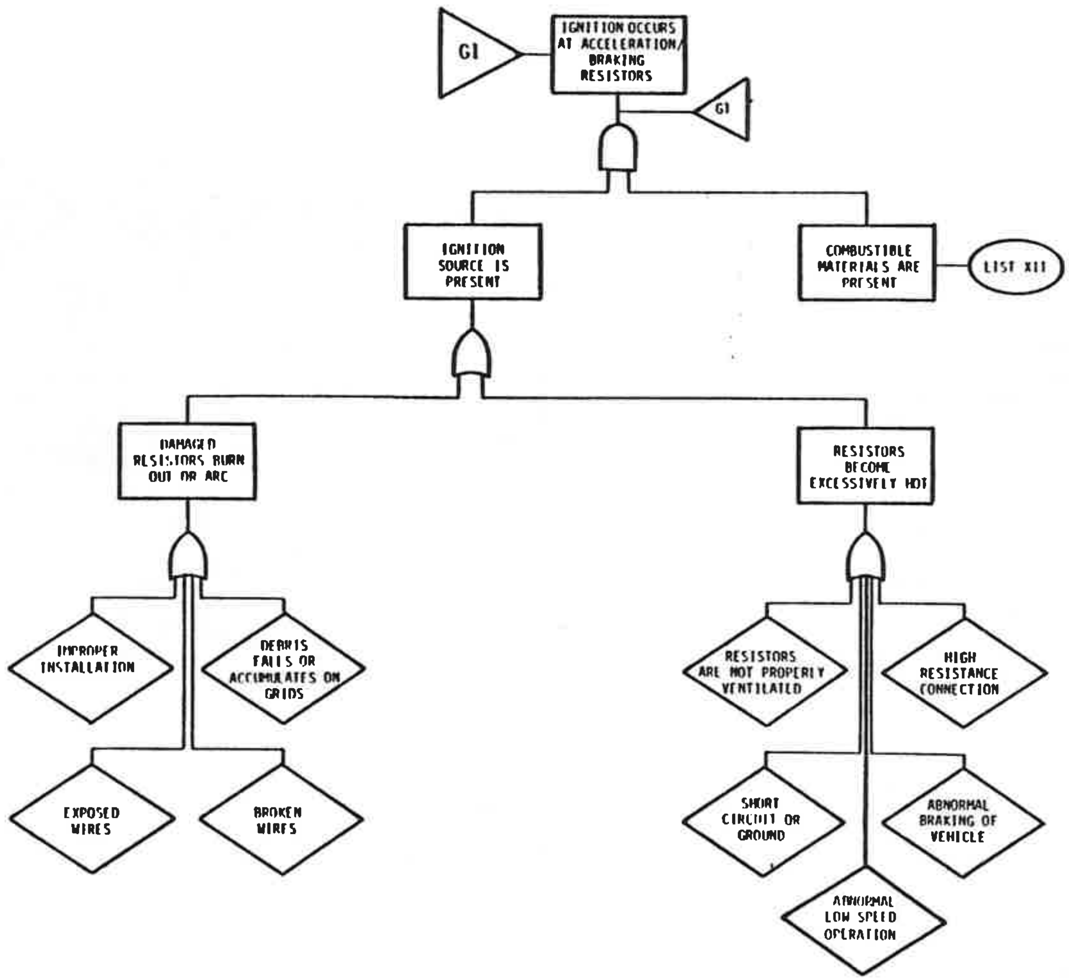

FIGURE 3-7-1. G1: IGNITION OCCURS AT ACCELERATION/BRAKING RESISTORS

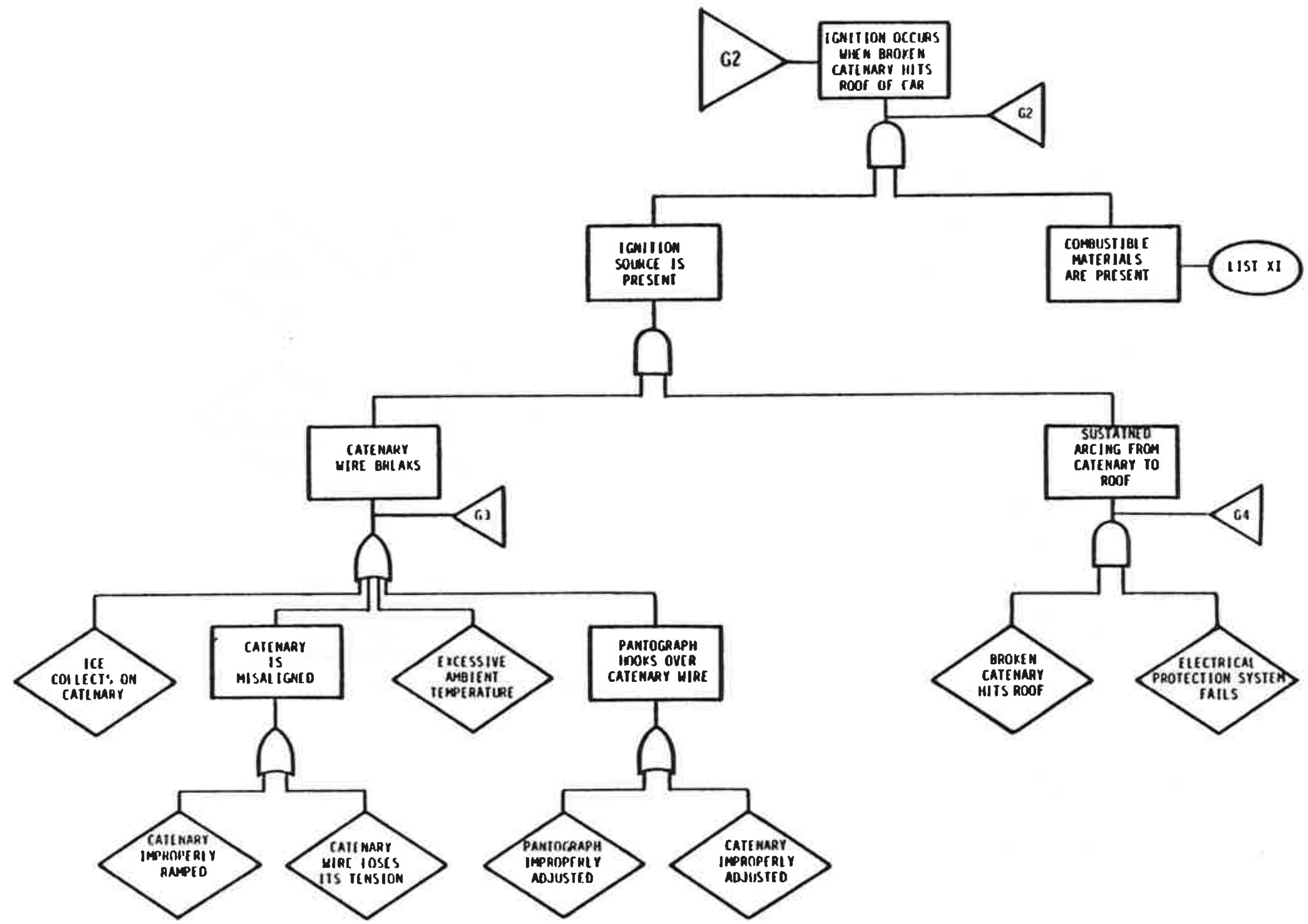

FIGURE 3-7-2. G2: IGNITION OCCURS WHEN BROKEN CATENARY HITS ROOF OF CAR

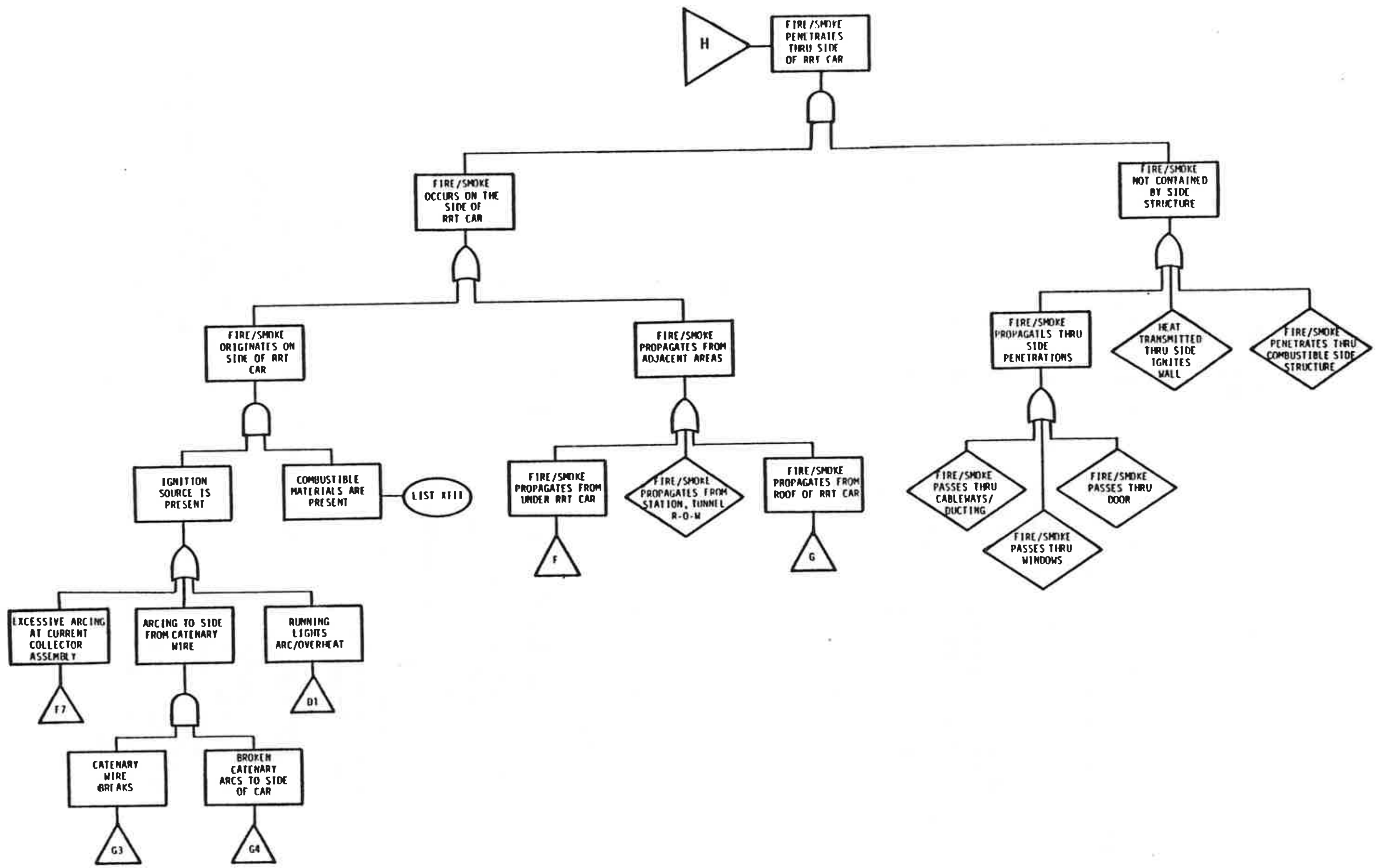

FIGURE 3-8. H: FIRE/SMOKE PENETRATES THRU SIDE OF RRT CAR

TABLE 3-1. KEY TO RRT CAR FAULT TREE COMBUSTIBLE MATERIALS LISTS

The following lists define the various types of combustible materials according to the list numbers indicated on the branches of the RRT car fault tree diagrams.

List I Combustible Materials Located on, in, or under Seats:

- Seat cushion materials
- Cushion support materials
- Cushion coverings
- Upholstery materials
- Wires and wire insulation for underseat heaters
- Seat frames (wood, plastic)
- Molded seats
- Trash or debris
- Occupant carry-ons
- Door engine lubricant and seals
- Coatings
- Adhesives

List II Combustible Materials in Electrical Wire/Cable System:*

- Wire
- Wire insulation
- Aluminum conductor cable
- Cable insulation
- Cable and wire holders, ties, grommets
- Accumulated dirt
- Debris

List III Combustible Materials Located on the Floor:

- Floor tiles (rubber, vinyl, vinyl-asbestos, etc.)
- Carpeting
- Carpet padding
- Carpet or tile adhesive
- Trash or debris
- Occupant carry-ons
- Wind screens
- Seat frame

List IV Combustible Materials Located at or in Walls:

- Wall panels
- Door panels
- Plastic windows
- Light diffusers
- Window frames
- Window and door gaskets
- HVAC ducting
- Electrical wire/cable system - see List II
- Thermal insulation
- Wood or plastic supports
- Signs and advertisements
- Wall liners
- Wind screens

TABLE 3-1. KEY TO RRT CAR FAULT TREE COMBUSTIBLE MATERIALS LISTS (CONT.)

List V — Combustible Materials Located at or in Ceiling:

- Ceiling panels
- Light diffusers
- Thermal insulation
- Acoustical insulation
- HVAC ducting
- Electrical wire/cable system - see List II

List VI — Combustible Materials Used in Crew Compartment Equipment:

- Control board panels
- Switches and fuses
- Electrical wires
- Electrical wire insulation
- Plastic connectors
- Circuit board components**
- Ladder
- Contact shoe lifting stick
- Log or instruction book

List VII — Combustible Materials Used in Structural Flooring:

- Plymetal flooring (aluminum)
- Plymetal flooring core materials (wood, plastic)
- Wood, plywood
- Thermal insulation
- Acoustical insulation
- Paint
- Sealer

List VIII — Combustible Materials Located in the Auxiliary System:

- Air hoses
- Battery casing
- Connectors
- Electrical wire/cable system - see List II
- Lubricant
- Gaskets
- Escaping hydrogen gas from battery
- Oil on battery electrolyte
- Debris
- Undercoating
- Paint

List IX — Combustible Materials Located at Trucks:

- Composition brake shoe
- Current collector shoe beam
- Gaskets, connectors, seals
- Accumulated grease and dirt
- Motor insulation materials
- Motor armature and windings
- Debris
- Air-cushion bolsters of rubber or neoprene
- Rubber door gaskets at the ends of and over trucks
- Electrical wire/cable system - see List II
- Metal dust
- Undercoating (Petroleum Base)

TABLE 3-1. KEY TO RRT CAR FAULT TREE COMBUSTIBLE MATERIALS LISTS (CONT.)

List X — Combustible Materials Located in Cam/Solid State Propulsion Controllers:

- Electrical wire/cable system - see List II
- Circuit board components**
- Connectors
- Motor insulation materials
- Motor armature and windings
- Accumulated grease and dirt

List XI — Combustible Materials Located in Structural Roofing:

- Electrical wire/cable system - see List II
- Aluminum outer shell
- Wood or plastic supports
- HVAC ducting
- Coatings
- Thermal insulation
- Acoustical insulation
- Pantograph mount
- Aluminum outer shell of car
- Debris

List XII — Combustible Materials Located at Acceleration/Braking Resistors on Roof:

- Electrical wire/cable system - see List II
- Aluminum outer shell of car
- Leaves and tree branches
- Debris

List XIII — Combustible Materials Used in Side Structure of Car:

- Aluminum outer shell
- Plastic windows
- Window and door gaskets
- Wood or plastic supports
- HVAC ducting
- Thermal insulation
- Acoustical insulation
- Electrical wire/cable system - see List II
- Paint

*Wire and cable insulation usually provides the initial support for electrical fires. Since wires and cables extend to all vehicle locations; fire propagation, which results from an electrical fire, is dependent upon the initial location of the ignition.

**Components - resistors, transistors, diodes, rectifiers, capacitors.

4. BUS FIRE/SMOKE INCIDENT

4.1 BACKGROUND

In the development of the fault tree diagrams representing a bus fire incident, an effort was made to incorporate into the fault tree diagrams the many possible differences which exist in transit bus design and operations.

Each transit property has buses built to its own specifications. As such, transit buses built at the same time by the same manufacturer may differ since each property may specify the structure, equipment, materials and operational procedures for its particular buses. For this reason, the fault trees contain many variations in design and operations, which are not directly applicable to any particular vehicle or transit property.

To account for the differences in the current bus fleet (approximately 53,000, including gas, diesel and electric propulsion vehicles), the fault tree diagrams have been developed in as generalized and nonspecific way as possible without sacrificing the accuracy needed to describe the ignition and propagation of the fire. Every effort has been made to identify all possible ignition sources on the transit bus. Included in the bus fault tree is the trackless trolley with its unique trolley pole.

The technical data used in the construction of the fault tree diagrams were obtained from several sources. Statistical and historical data, although limited, provided an indication of the frequency of fire occurrence, location of ignition, and components of the bus vehicle involved. This information was obtained from published accident reports, transit property reports, newspaper clippings, transit property personnel and TSC technical staff. Because the information did not usually contain the detailed causative data necessary for fault tree analysis, it was essential to study the construction of bus vehicles in order to determine potential, as well as known fire hazards. Additional technical information was obtained from a review of vehicle construction specifications and maintenance manuals, and discussions with transit property staff and other technical people. This information was integrated with the historical and statistical data and then used in developing the fault tree diagrams.

4.2 FAULT TREE DIAGRAMS

Figure 4-0 is an overview fault tree for the head event "Fire/Smoke Occurs in Occupant Compartment of Bus".

This undesired event was chosen because the occurrence of a fire within the occupant compartment itself represents one of the most potentially serious safety hazards to passengers, because of heat, smoke and toxic gases within the confined passenger space.

The primary event, "Fire/Smoke Occurs in Occupant Compartment of Bus", results from the occurrence of either of two secondary events: "Fire/Smoke Originates within Occupant Compartment" or "Fire/Smoke Penetrates from Outside Occupant Compartment". In turn, these two events are developed further. The fire may originate in five interior areas of the occupant compartment. These areas are indicated on the overview as: "Fire/Smoke Occurs on/under/or back of Seats", "Fire/Smoke Occurs on Floor", "Fire/Smoke Occurs at Wall", "Fire/Smoke Occurs at Ceiling", and "Fire/Smoke Occurs at Instrument Panel/Dashboard". These five major events are developed in Figures 4-1 through 4-5 and their subnumbers. Four major events which could lead to the occurrence of the event, "Fire/Smoke Penetrates from Outside Occupant Compartment", are: "Fire/Smoke Penetrates from Engine Compartment", "Fire/Smoke Penetrates from under Bus", "Fire/Smoke Penetrates thru Roof of Bus" and "Fire/Smoke Penetrates from Side of Bus". These four events are illustrated in Figures 4-6 through 4-9 and their subnumbers. These major events have been developed down to the level where further information either is unavailable or considered insignificant (bottom event or diamond).

Table 4-1 provides a key to the lists of combustible materials used or located in the various areas of the vehicle.

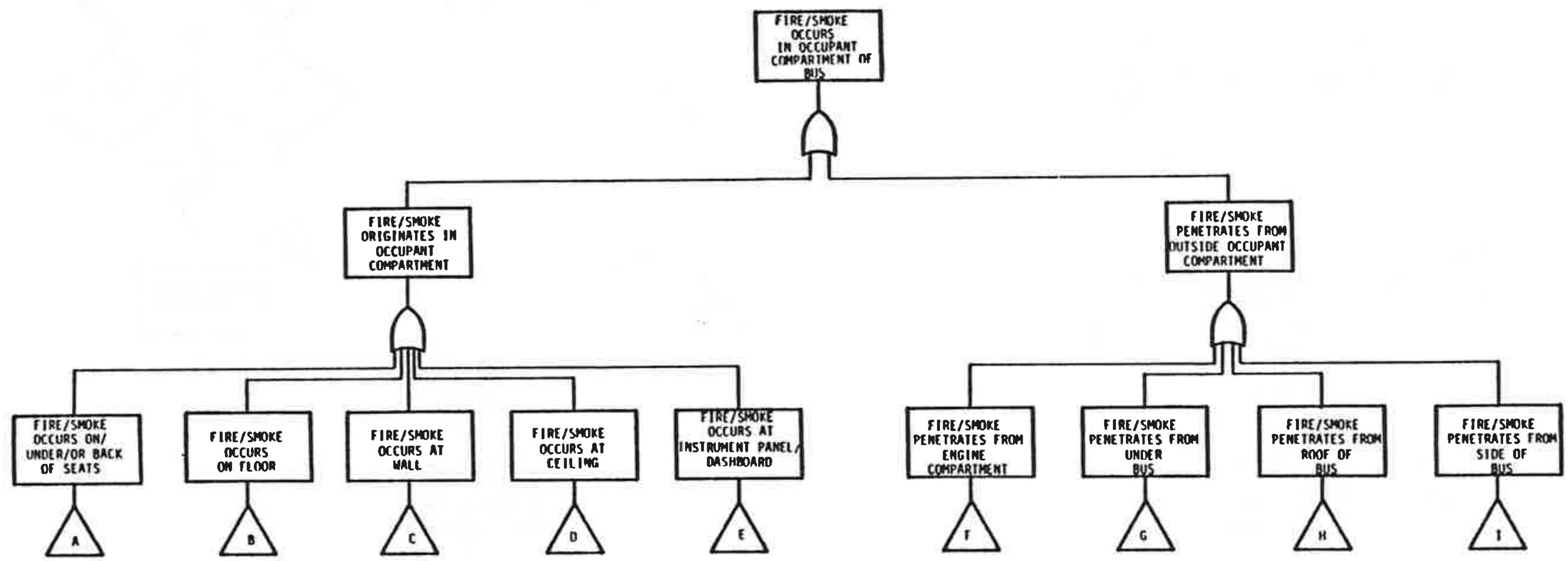

FIGURE 4-0. OVERVIEW: FIRE/SMOKE OCCURS IN OCCUPANT COMPARTMENT OF BUS

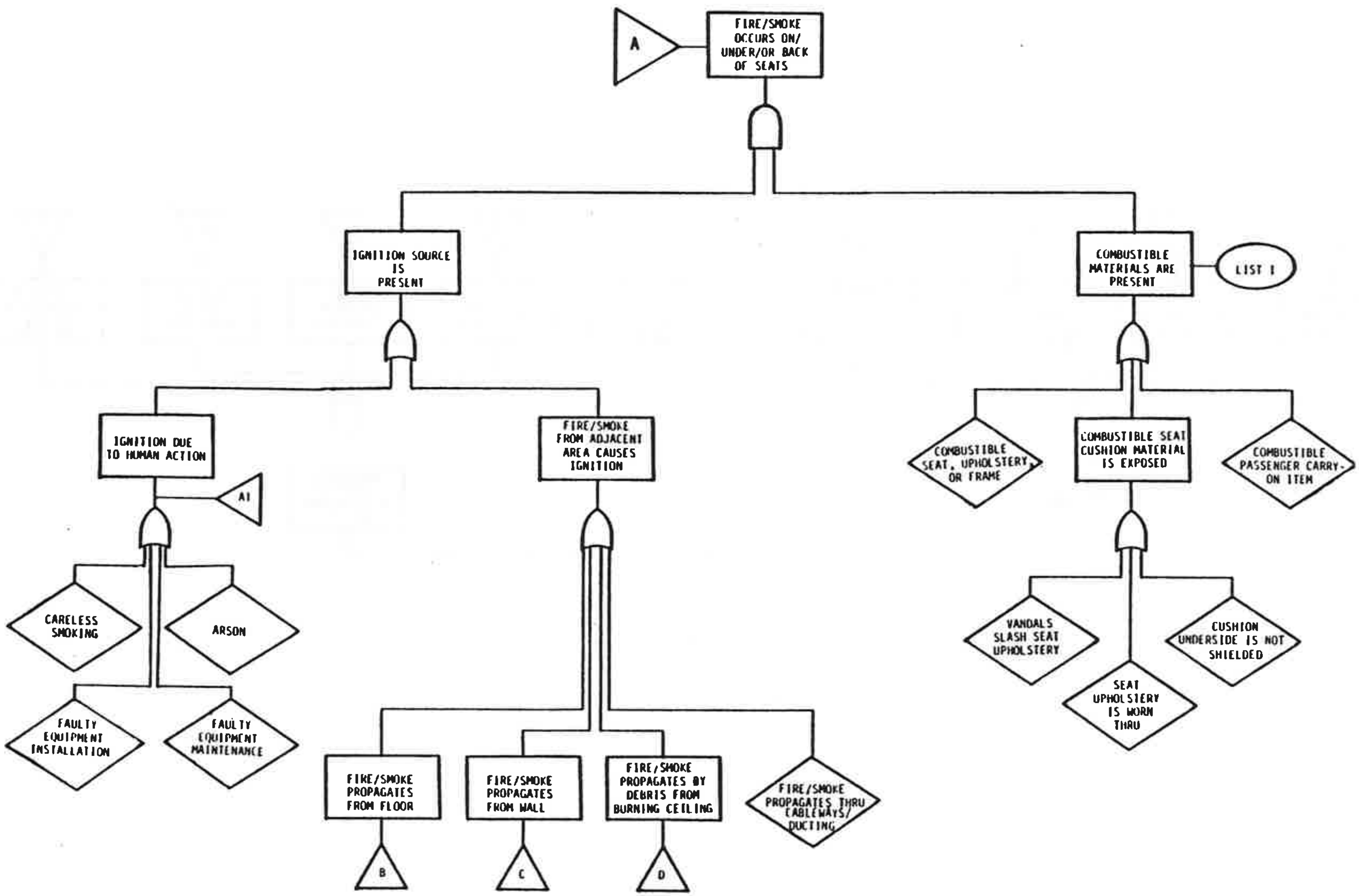

FIGURE 4-1. A: FIRE/SMOKE OCCURS ON/UNDER/OR BACK OF SEATS

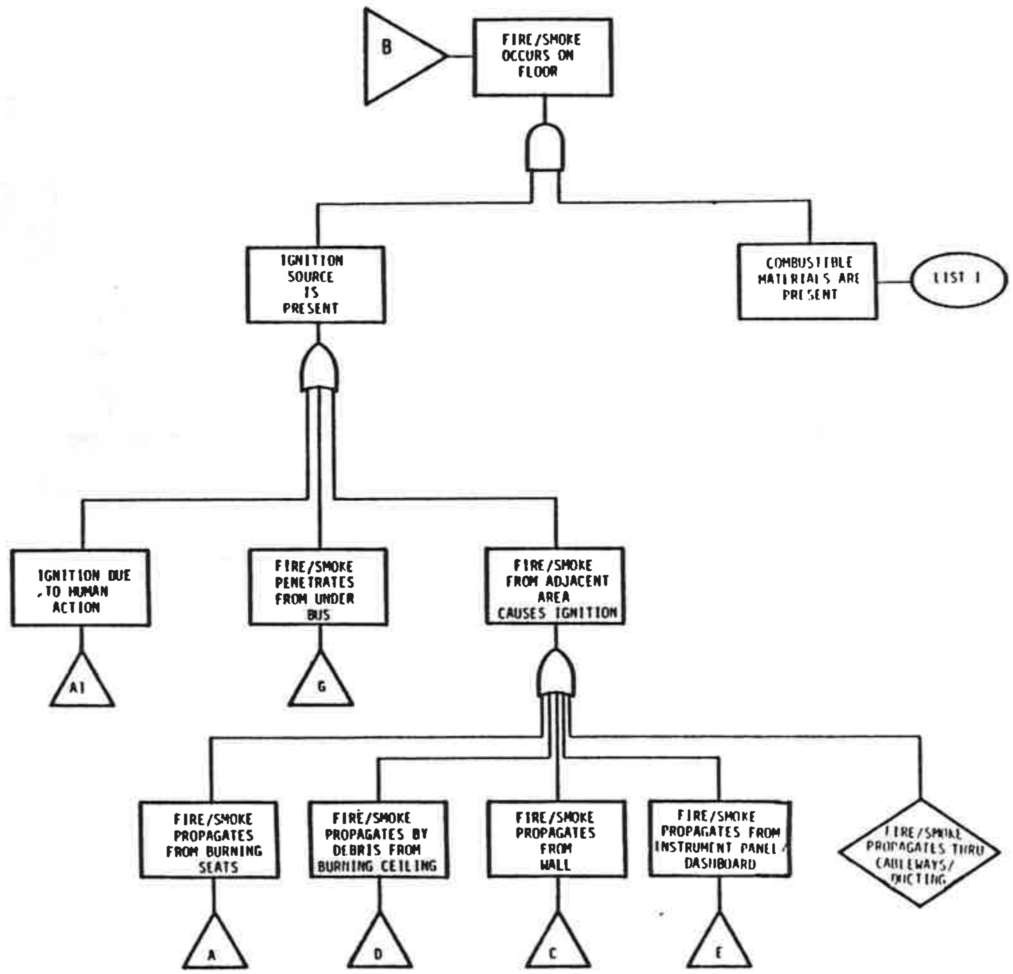

FIGURE 4-2. B: FIRE/SMOKE OCCURS ON FLOOR

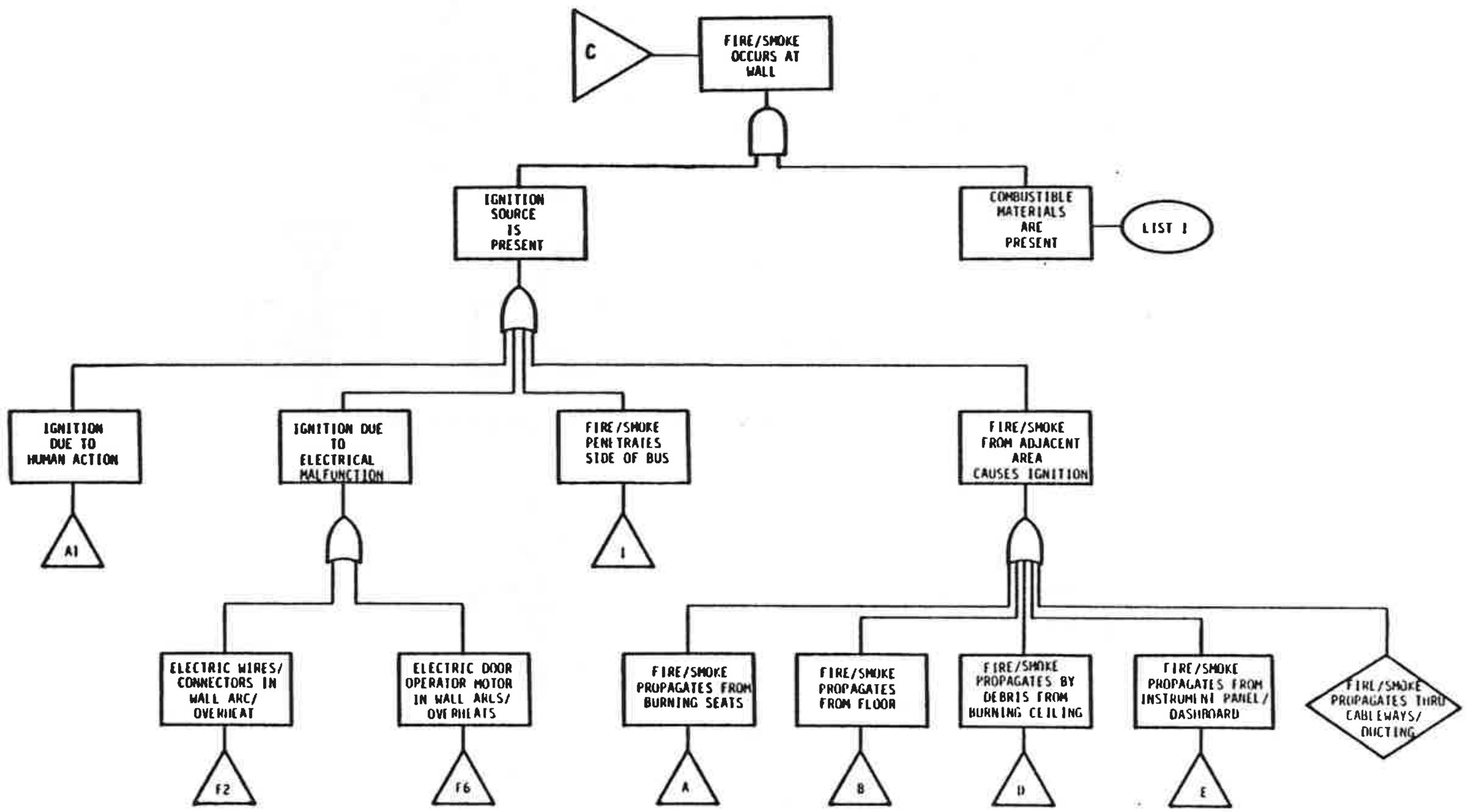

FIGURE 4-3. C: FIRE/SMOKE OCCURS AT WALL

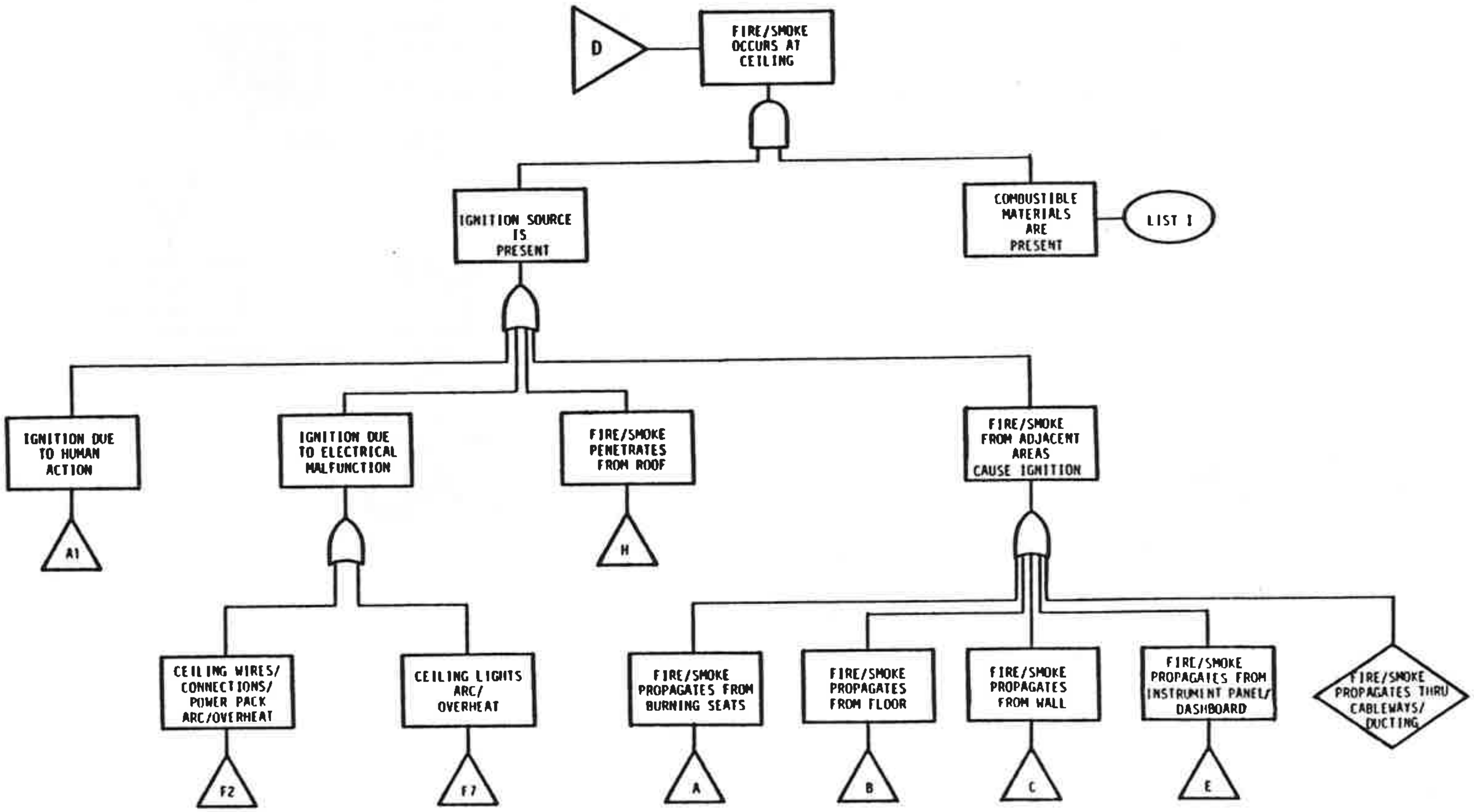

FIGURE 4-4. D: FIRE/SMOKE OCCURS AT CEILING

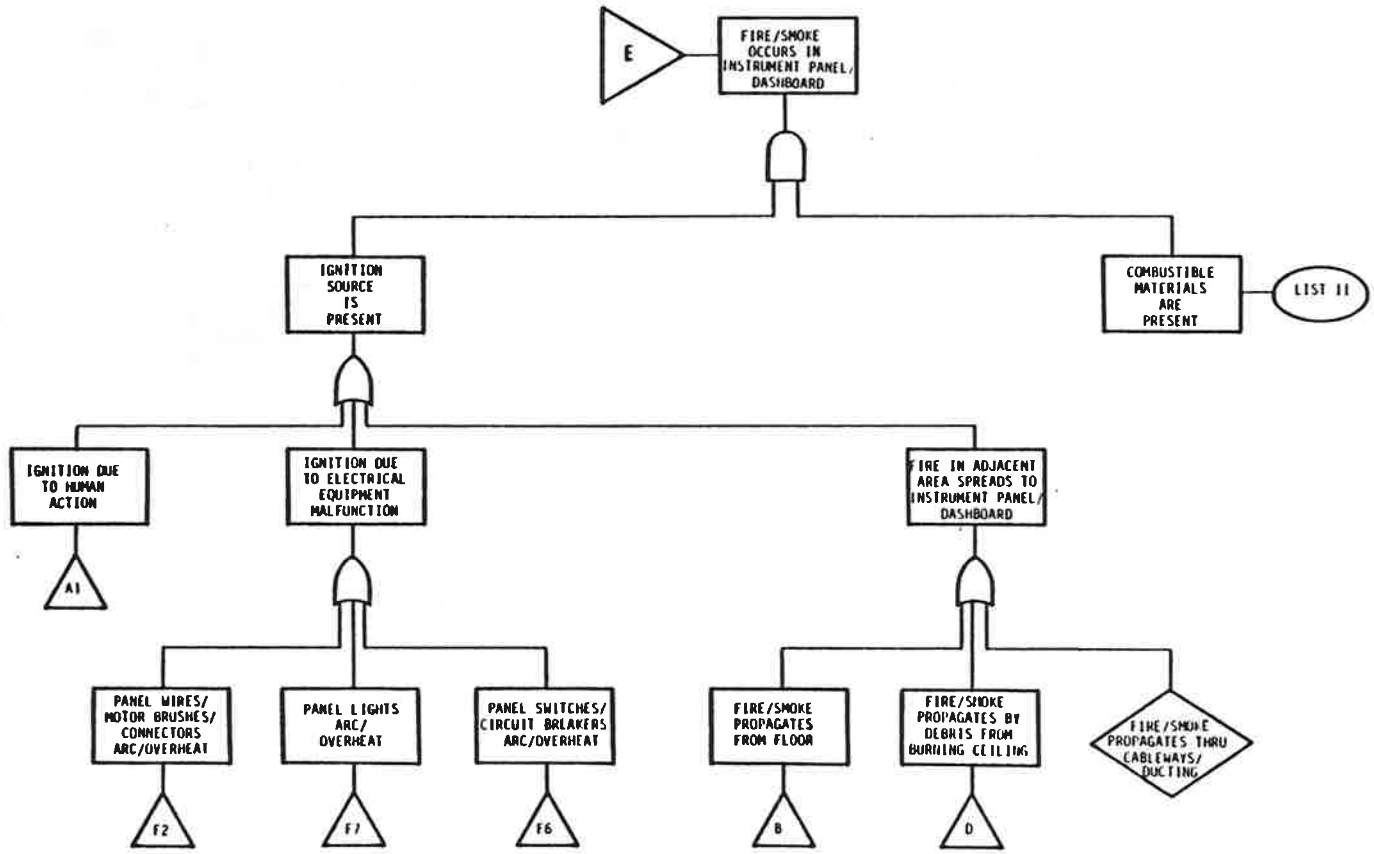

FIGURE 4-5. E: FIRE/SMOKE OCCURS IN INSTRUMENT PANEL/DASHBOARD

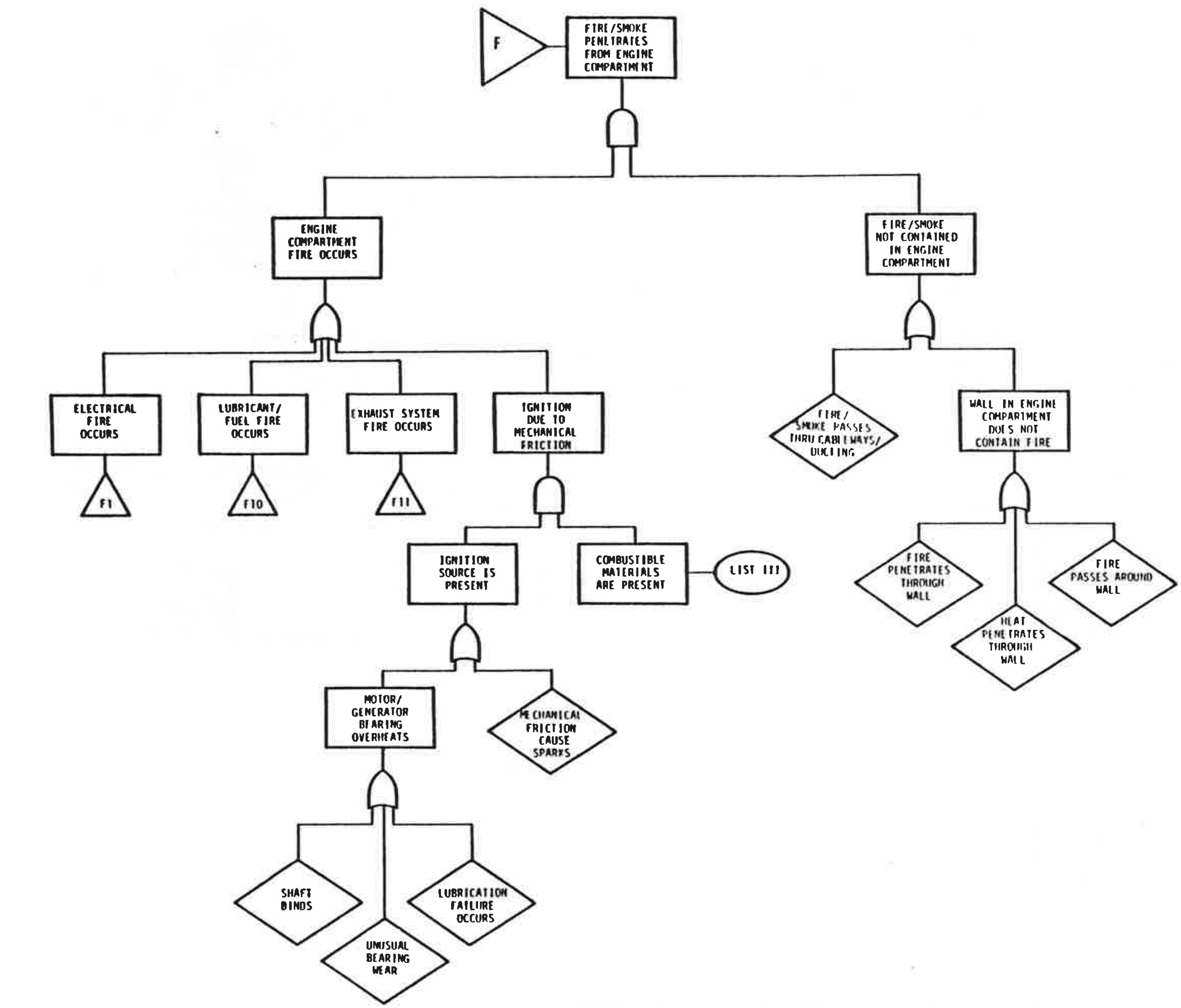

FIGURE 4-6. F: FIRE/SMOKE PENETRATES FROM ENGINE COMPARTMENT

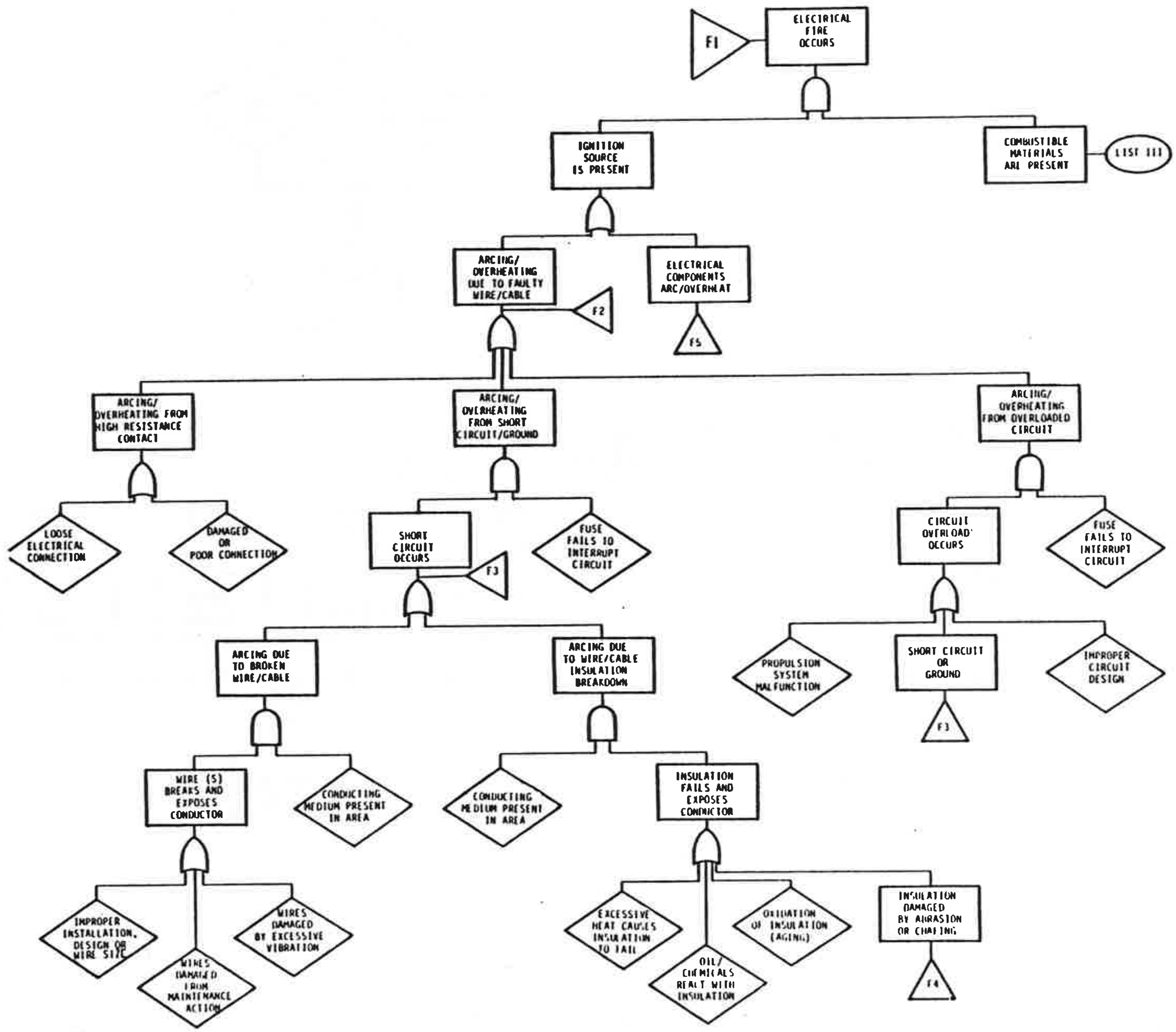

FIGURE 4-6-1. F1: ELECTRICAL FIRE OCCURS

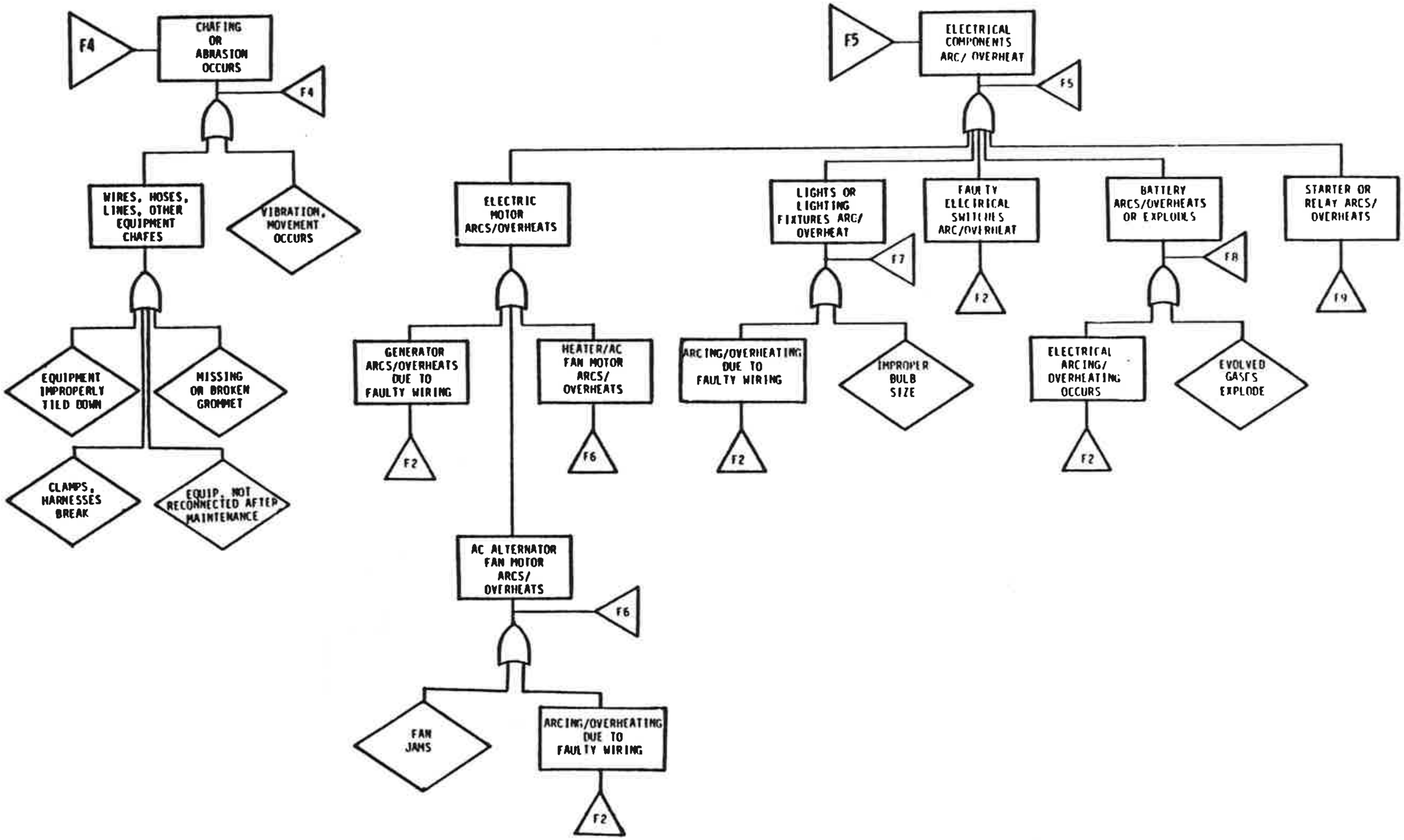

FIGURE 4-6-2. F4: CHAFING OR ABRASION OCCURS
F5: ELECTRICAL COMPONENTS ARC/OVERHEAT

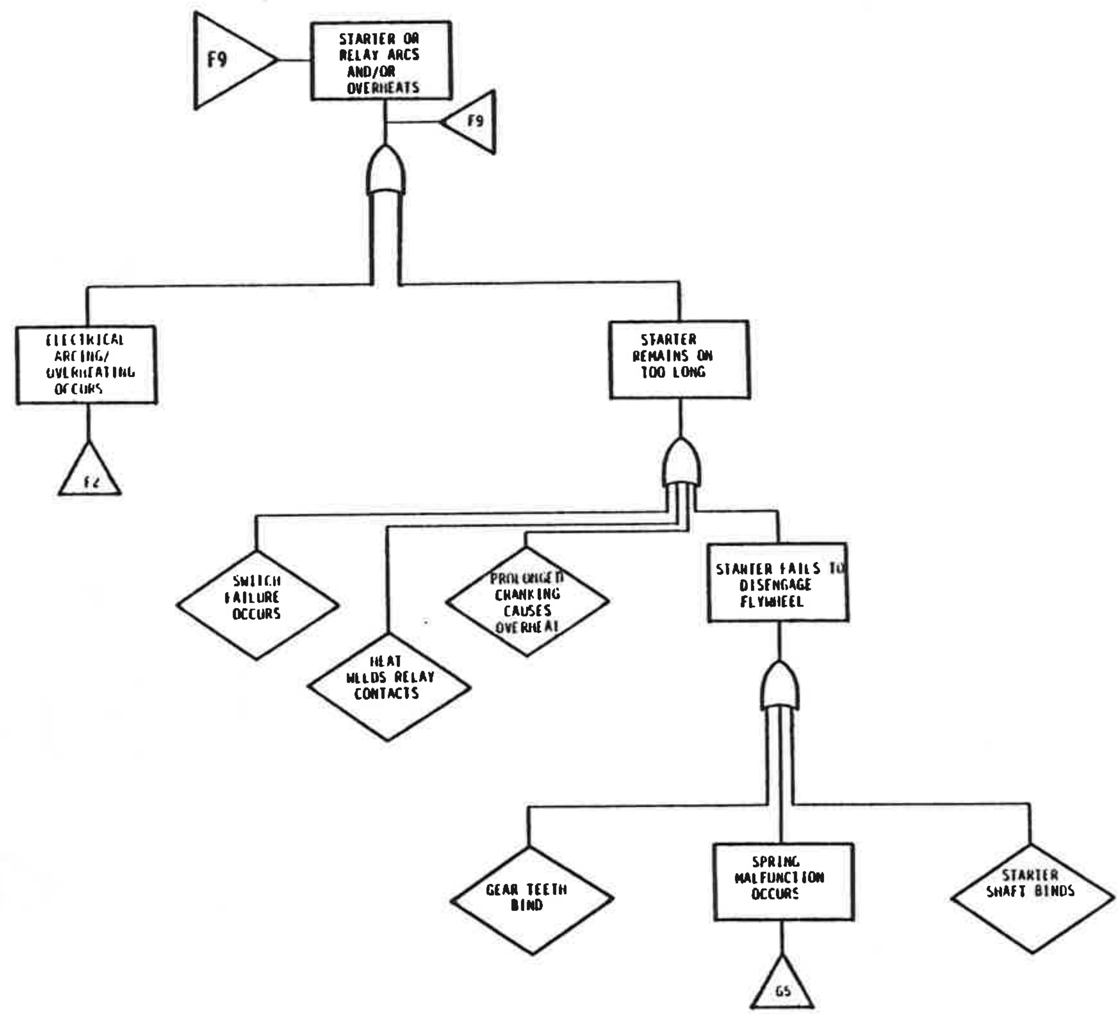

FIGURE 4-6-3. F9: STARTER OR RELAY ARCS AND/OR OVERHEATS

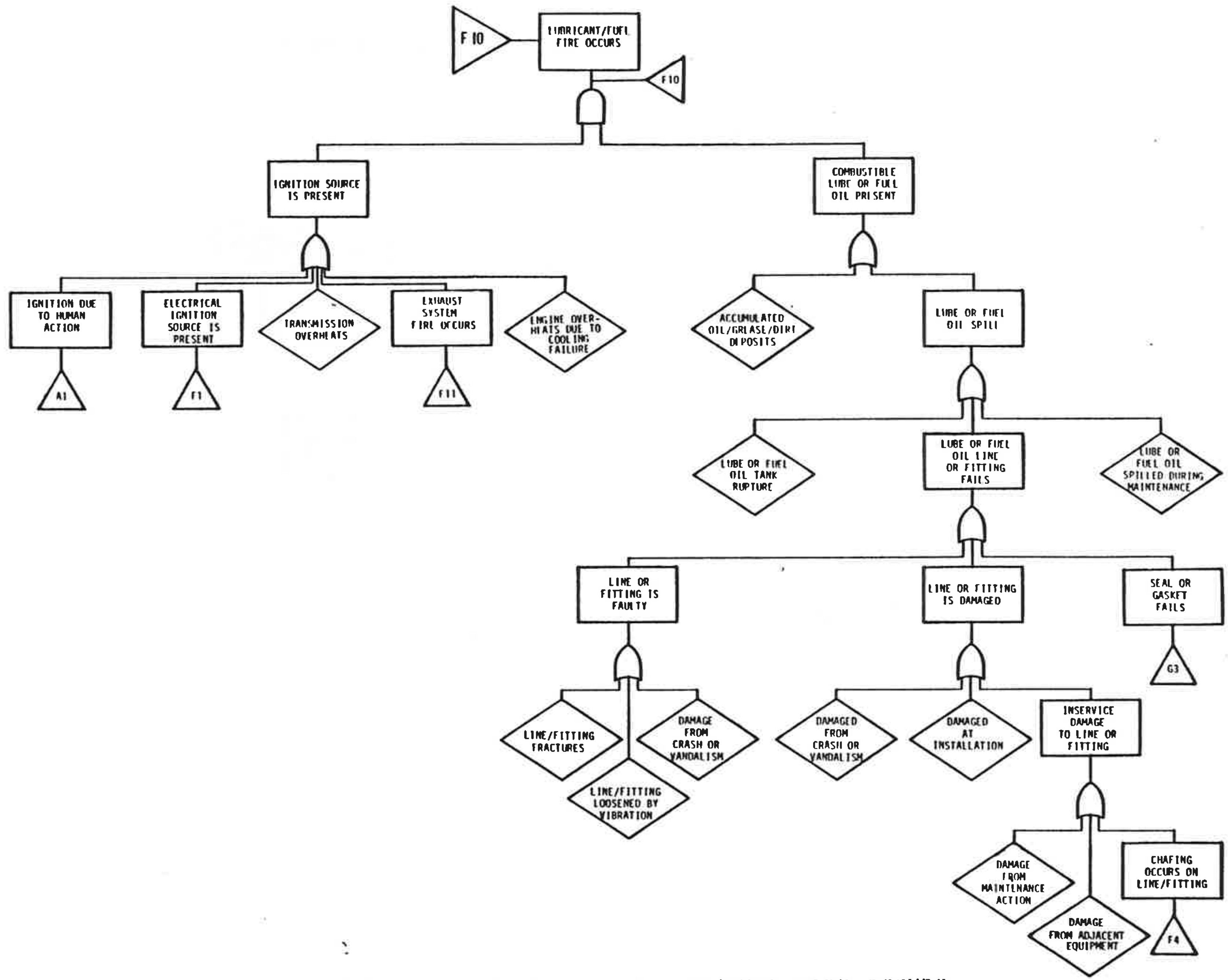

FIGURE 4-6-4. F10: LUBRICANT/FUEL FIRE OCCURS

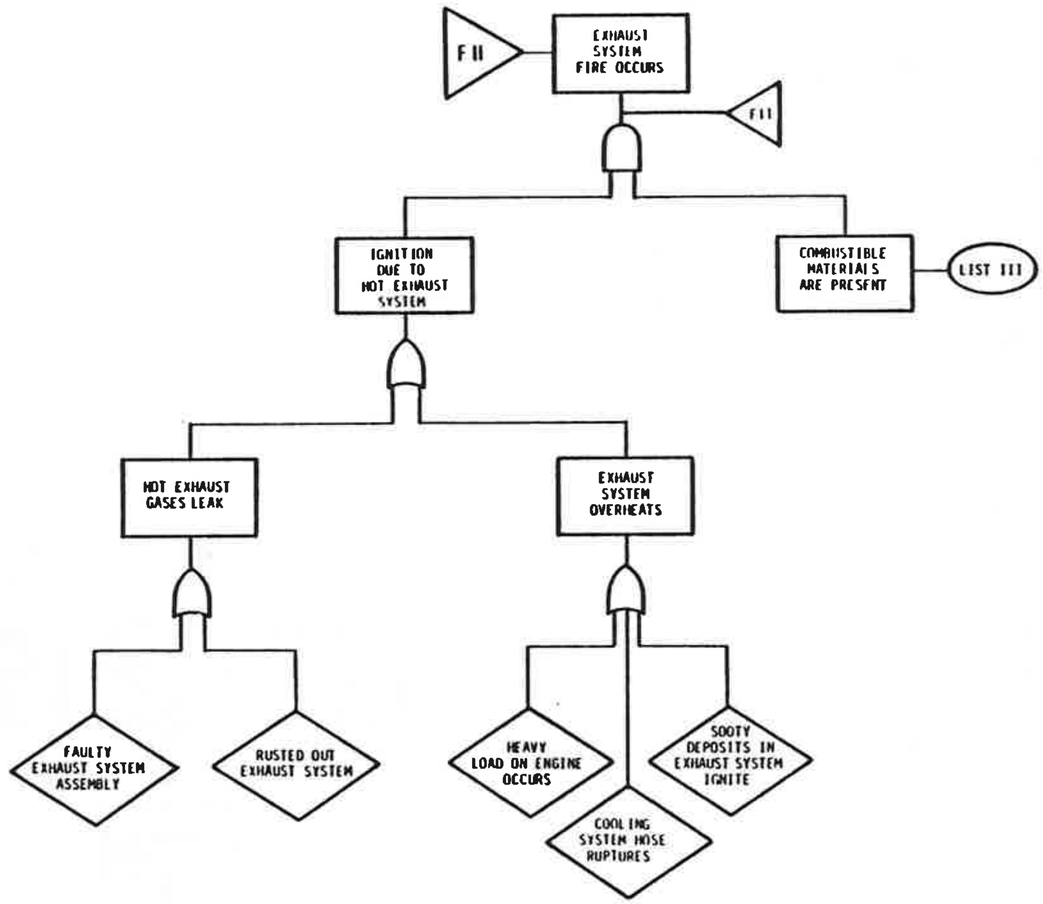

FIGURE 4-6-5. F11: EXHAUST SYSTEM FIRE OCCURS

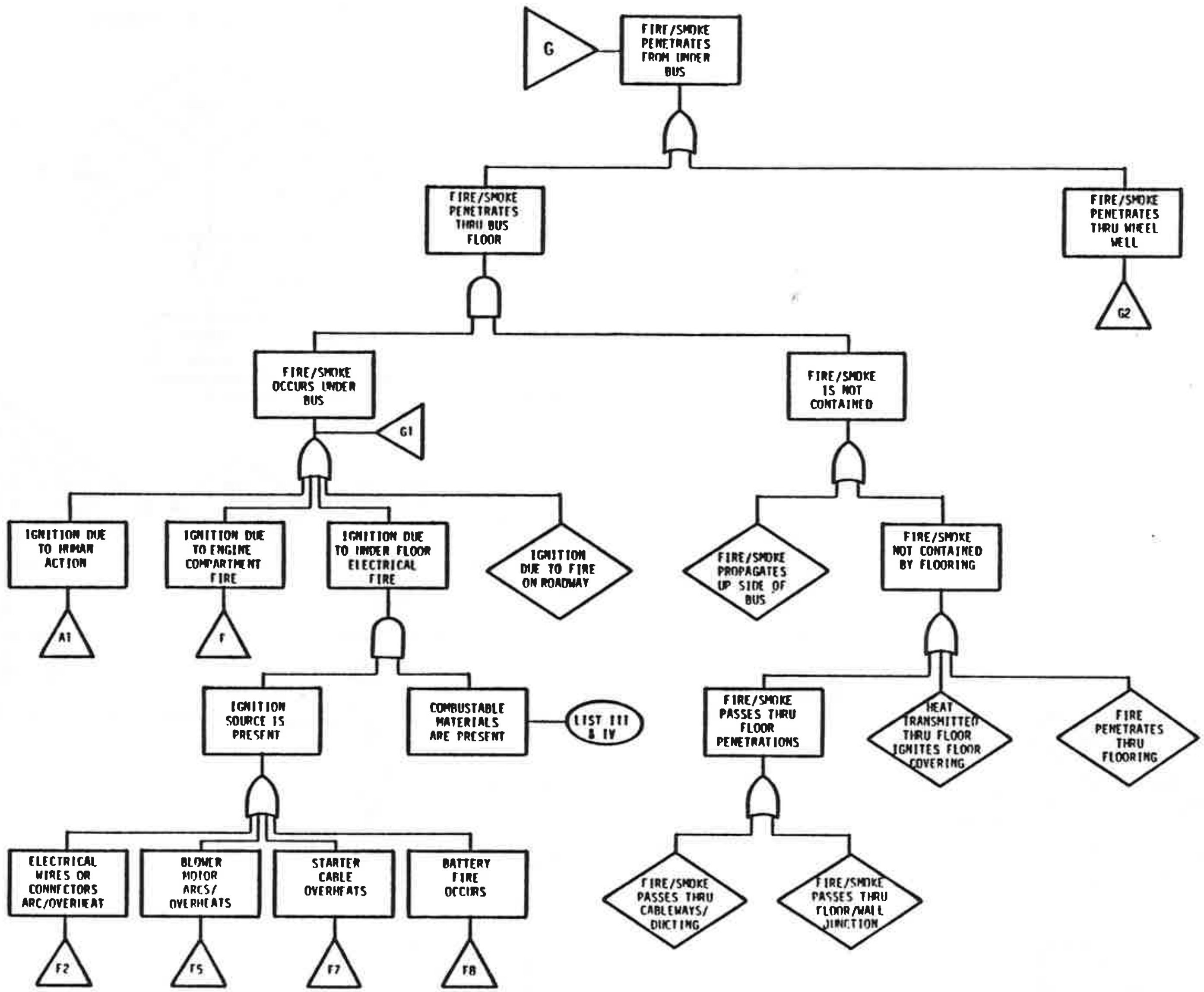

FIGURE 4-7. G: FIRE/SMOKE PENETRATES FROM UNDER BUS

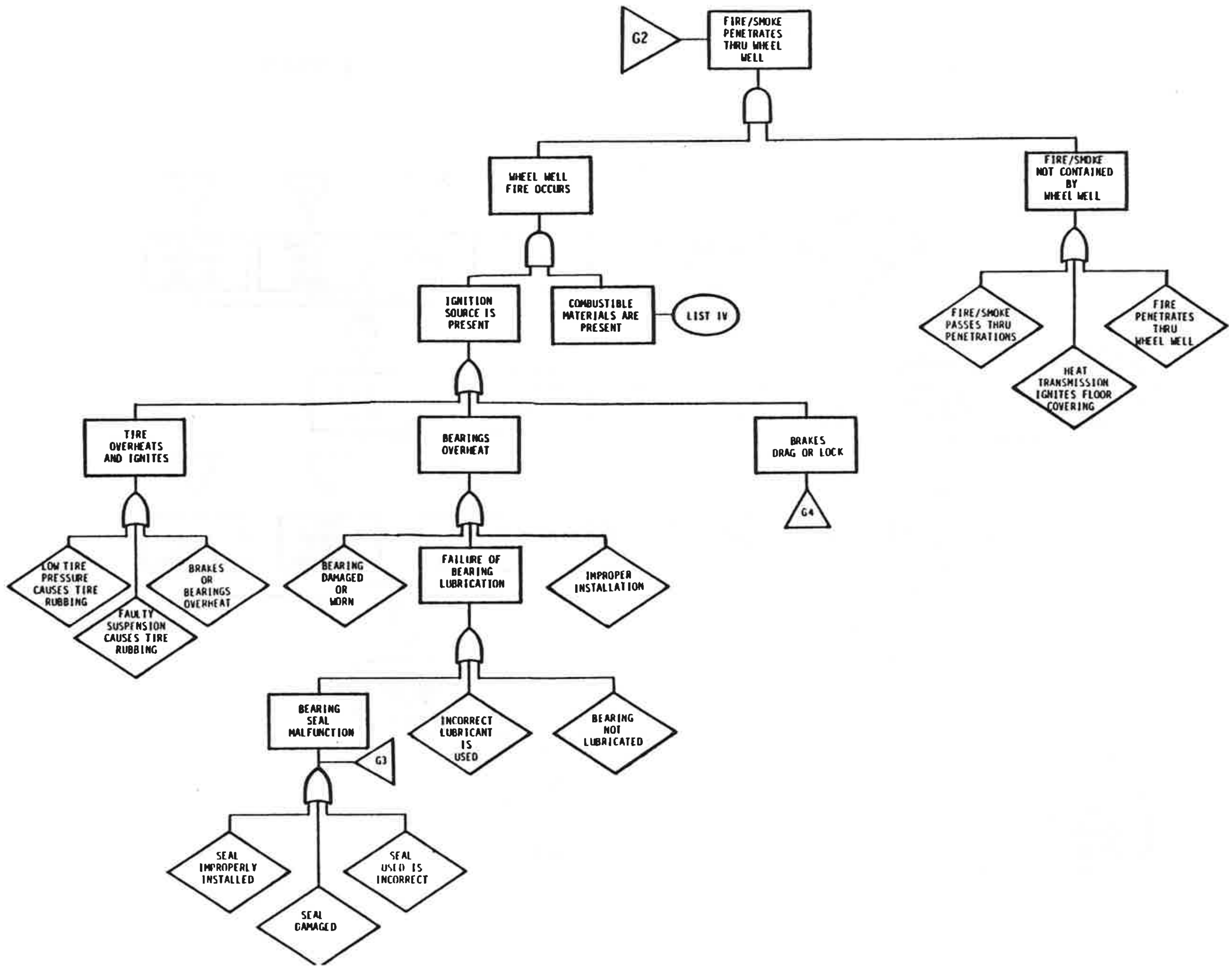

FIGURE 4-7-1. G2: FIRE/SMOKE PENETRATES THRU WHEEL WELL

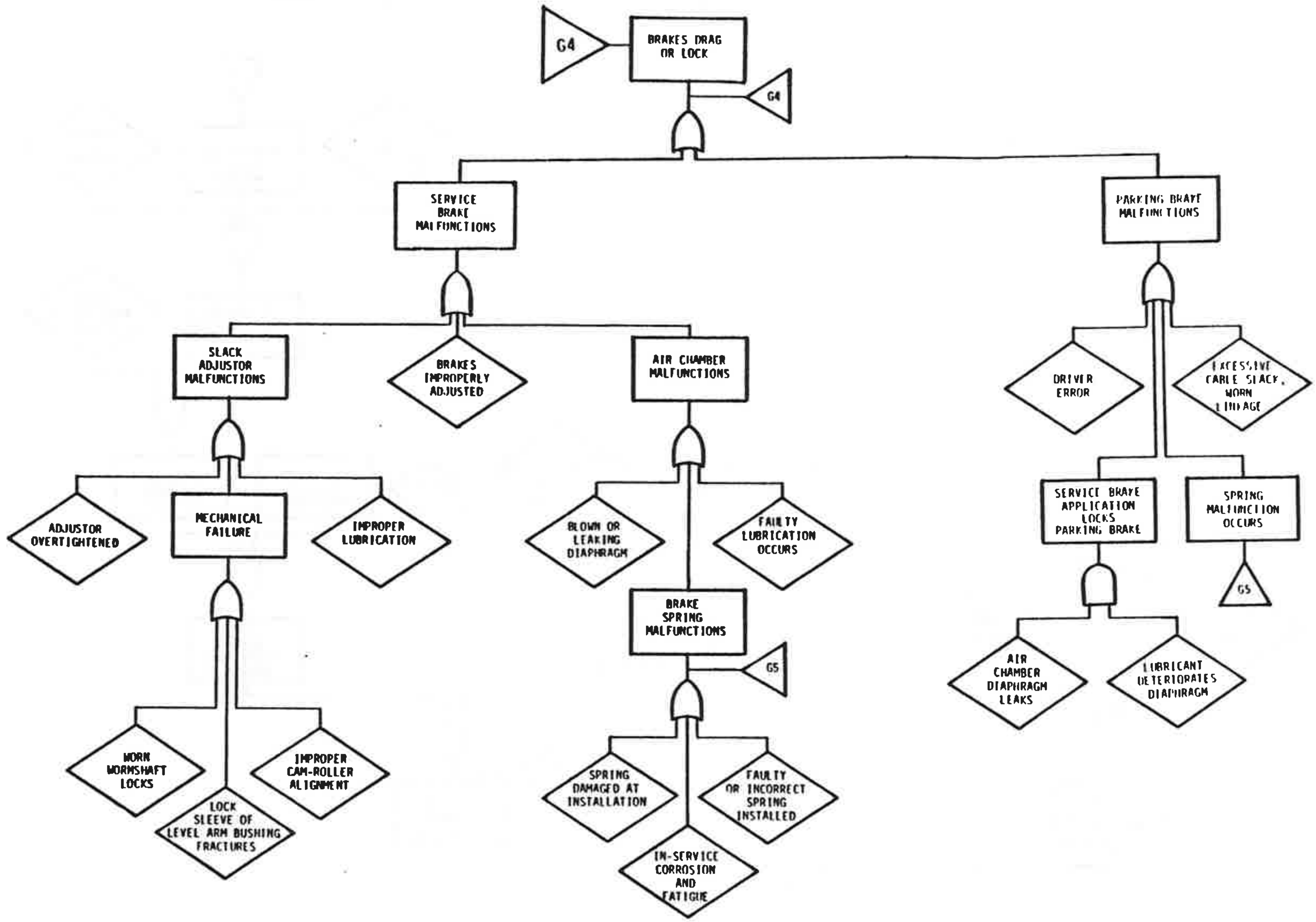

FIGURE 4-7-2. G4: BRAKES DRAG OR LOCK

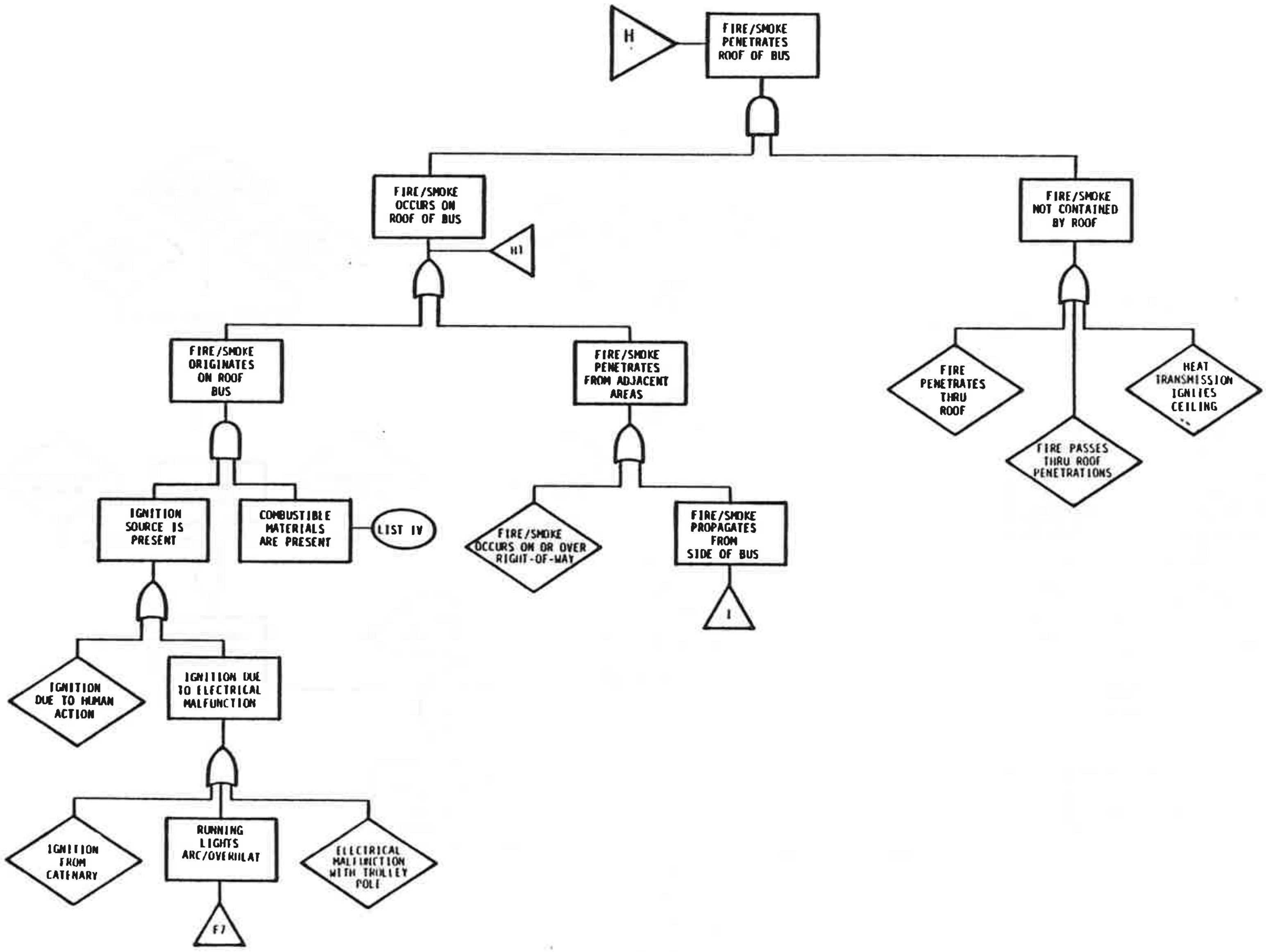

FIGURE 4-8. H: FIRE/SMOKE PENETRATES ROOF OF BUS

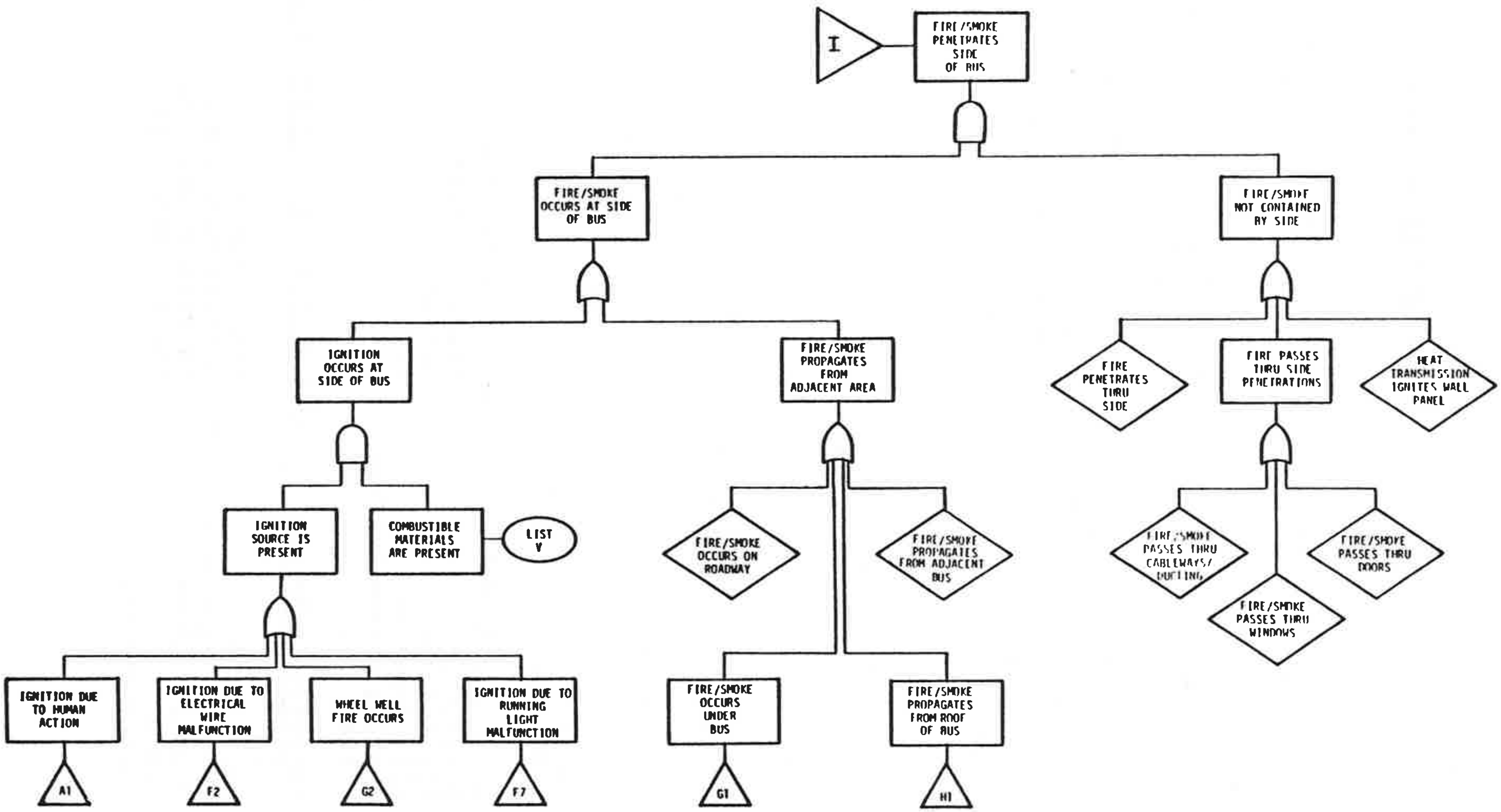

FIGURE 4-9. I: FIRE/SMOKE PENETRATES SIDE OF BUS

TABLE 4-1. KEY TO BUS FAULT TREE COMBUSTIBLE MATERIALS LISTS

The following lists define the various types of combustible materials according to the list numbers indicated on the branches of the bus fault tree diagrams.

List I Combustible Materials Located in Occupant Compartment:

- Passenger carry-on
- Seat cover
- Seat cushion
- Seat frame (plastic)
- Wall/ceiling panel
- Thermal and acoustic insulation
- Windows (plastic)
- Window gasket
- Door seal
- Trash left on board
- Carpet/carpet pad
- Other floor covering
- Wood floor
- Ducting
- Advertising signs
- Light diffuser
- Electrical insulation
- Grommets

List II Combustible Materials Located in Instrument Panel:

- Transfers stuffed in panel
- Plastic panel cover
- Electrical insulation
- Flares (emergency)

List III Combustible Materials Located in Engine Compartment/ Electrical Components:

- Oily deposits
- Rags, trash left by workers
- Hoses
- Electrical insulation
- Leaking lubricants/fuel
- Sooty exhaust deposits
- Plastic clamps/ties/parts
- Gaskets/grommets
- Thermal/acoustic insulation

List IV Combustible Materials Located in Wheel Well:

- Plastic grease cap
- Plastic wheel well
- Oily deposits
- Bearing grease/bearing lube seal
- Brake lubricant
- Air hose
- Tire

List V Combustible Materials Located in Exterior (side/front/ rear):

- Door seals
- Plastic light lens
- Plastic window
- Signs
- Rubber bumpers
- Window gasket
- Spilled fuel lubricant
- Oily/sooty deposits
- Trolley pole rope

5. SUPPRESSION/CONTAINMENT OF FIRE/SMOKE INCIDENT

5.1 BACKGROUND

Although all possible fire sources may never be eliminated, the swift suppression and/or containment of a transit fire is a key factor in the reduction of potential casualities.

The types of suppression/containment systems which may be present vary according to transit property because of differing policies and procedures, environmental conditions, etc. The fault tree diagrams presented in the following illustrations are general in nature and as such do not represent the suppression/containment systems of any particular transit property. However, during the development of the diagrams, an attempt was made to incorporate many of the possible variations in suppression/containment design and operation.

The technical data used in the development of the fault tree diagrams were obtained from several sources. Among the most important were the detailed descriptions of major fire incidents contained in government and transit property investigative reports. These reports provided insights into methods of extinguishment used, communication difficulties, coordination problems and equipment failures, as well as their interaction during actual fire situations. Other sources were regulations promulgated by DOT modal administrations and guidelines published by the American Public Transit Association (APTA)[7] and National Fire Protection Administration (NFPA)[8].

5.2 FAULT TREE DIAGRAMS

Figure 5-0 illustrates the overview fault tree for the undesirable head event, "Fire/Smoke Is Not Suppressed or Contained". This event was chosen because the failure to adequately suppress or contain a transit fire incident can result in hazardous conditions which in turn could lead to a fire-related casualty.

The event, "Fire/Smoke Is Not Suppressed or Contained", results from one of three primary events: "Fire/Smoke Is Not Passively Suppressed", "Fire/Smoke Is Not Actively Suppressed", or "Fire/Smoke Is Not Contained". Passive is defined as automatic, Active as requiring some form of human action, and Contained as confining the fire/smoke within a limited area.

Either one or all of the three secondary events: "Passive Suppression System Does Not Exist", "Passive Suppression System Does Not Respond", or "Passive Suppression System Is Inadequate", may result in the undesired event, "Fire/Smoke Is Not Passively Suppressed". The further development of this branch is presented in Figure 5-1.

The undesired event, "Fire/Smoke Is Not Actively Suppressed", may be caused by either one or all of the following three events: "Active Suppression System Does Not Exist", "Individual Does Not Take Suppressive Action", or "Individual Suppressive Action Is Ineffective". The two latter events are illustrated in Figures 5-2 and 5-3 and their subnumbers.

Either one of two events: "Fire Is Not Contained" or "Smoke Is Not Contained", may lead to "Fire/Smoke Is Not Contained". These events are presented in Figure 5-4.

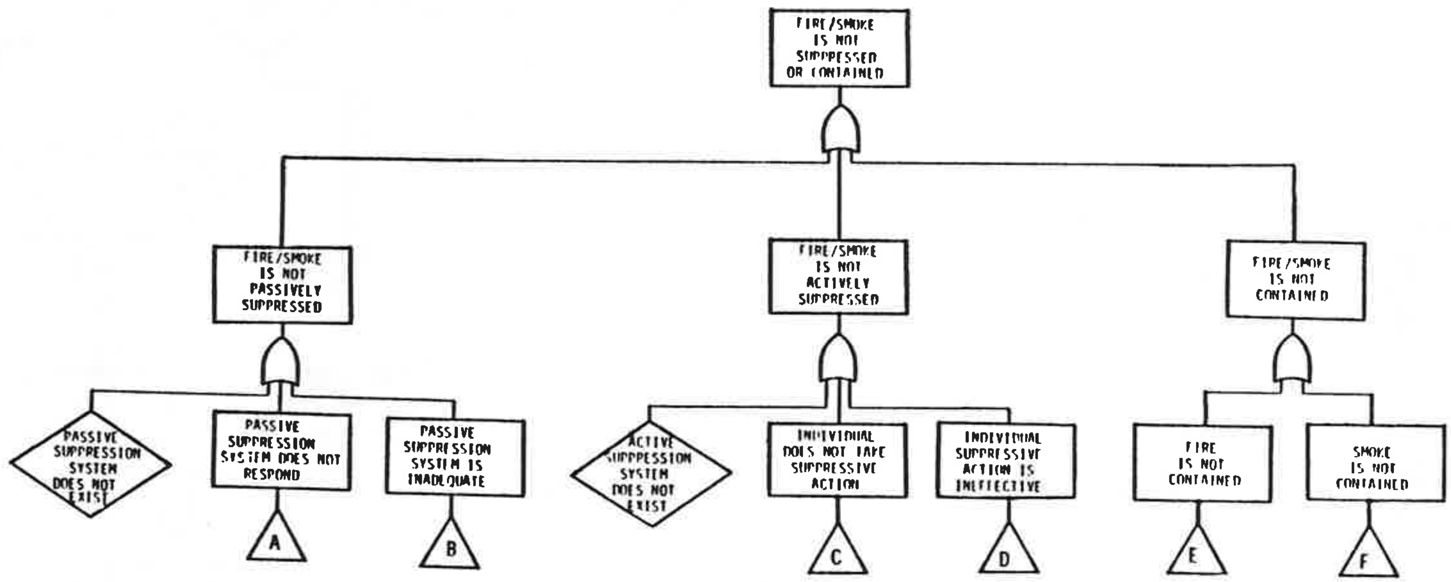

FIGURE 5-0. OVERVIEW: FIRE/SMOKE IS NOT SUPPRESSED OR CONTAINED

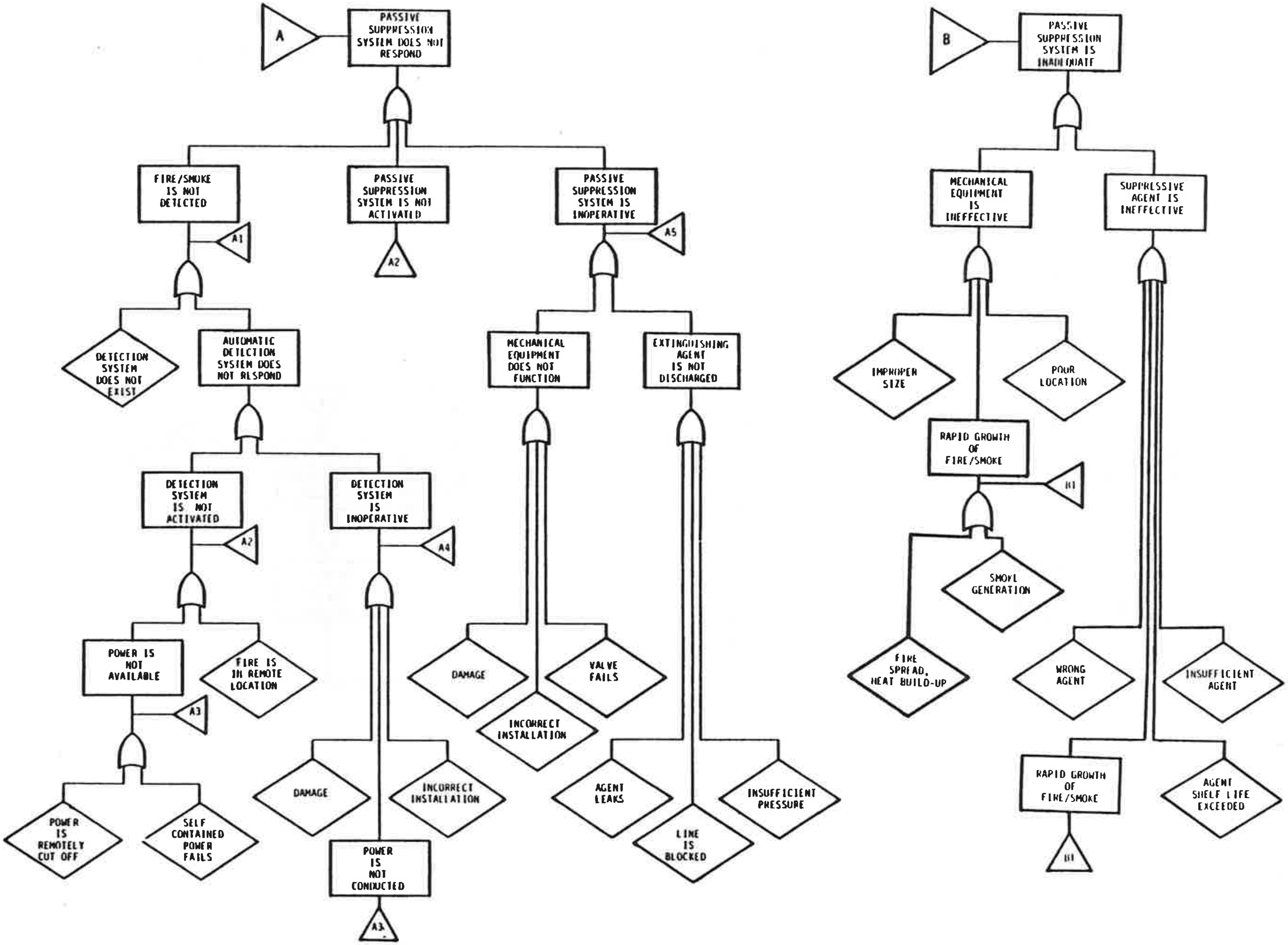

FIGURE 5-1. A: PASSIVE SUPPRESSION SYSTEM DOES NOT RESPOND
B: PASSIVE SUPPRESSION SYSTEM IS INADEQUATE

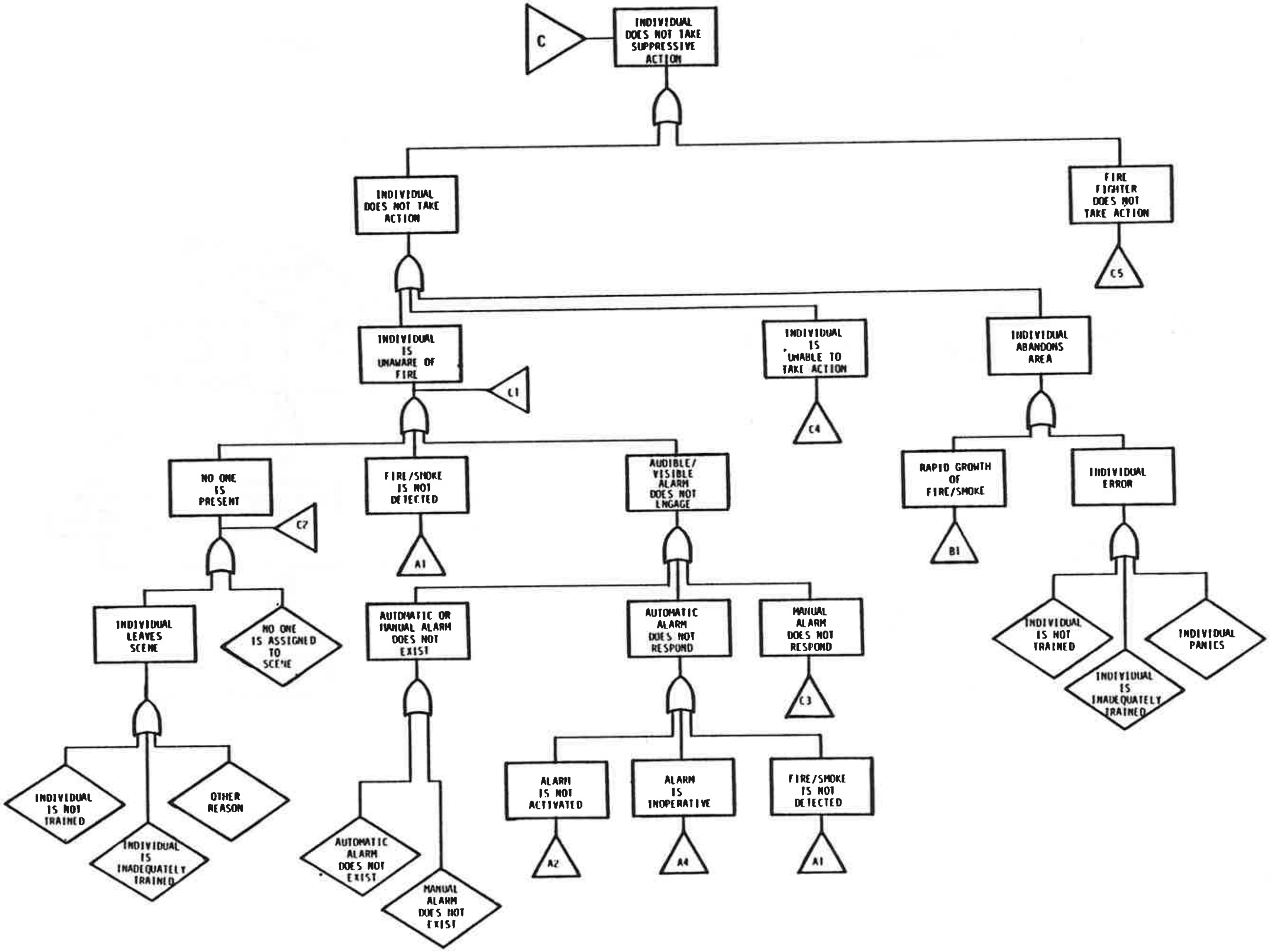

FIGURE 5-2. C: INDIVIDUAL DOES NOT TAKE SUPPRESSIVE ACTION

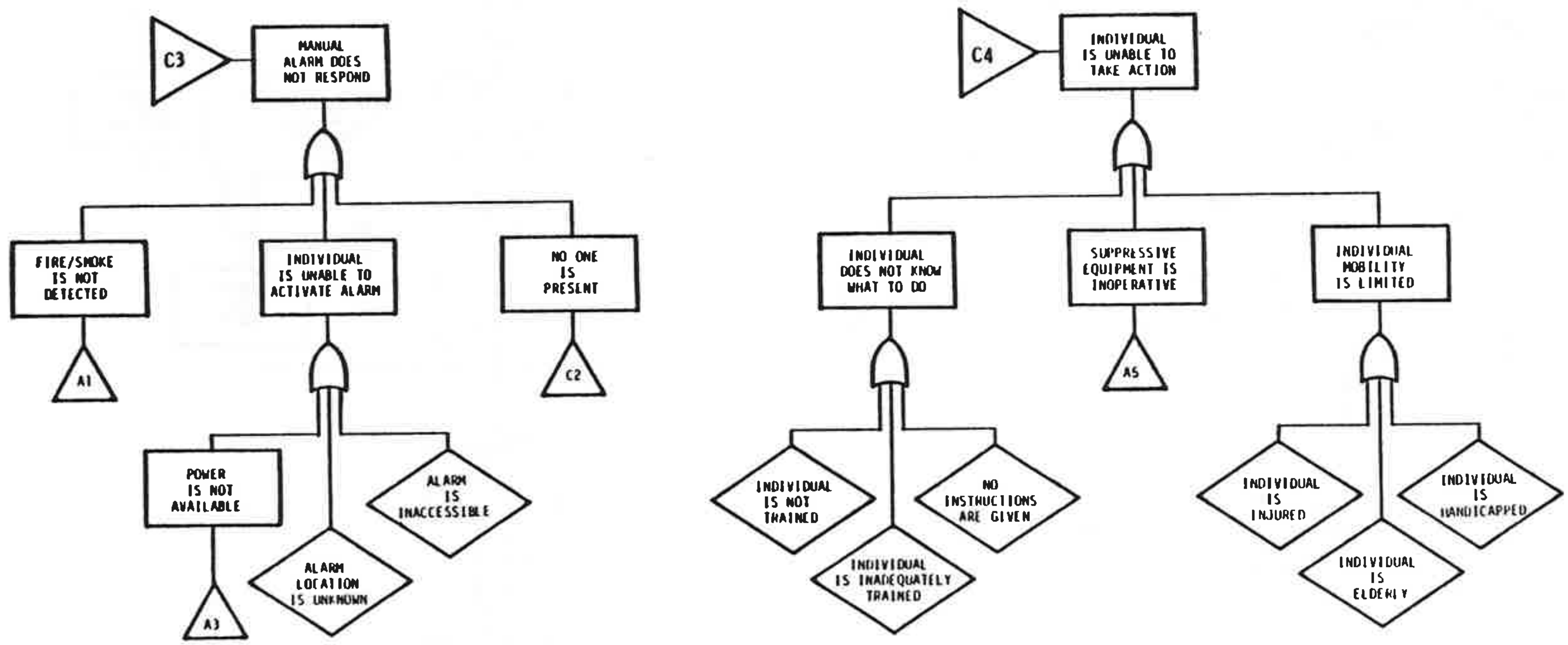

FIGURE 5-2-1. C3: MANUAL ALARM DOES NOT RESPOND
C4: INDIVIDUAL IS UNABLE TO TAKE ACTION

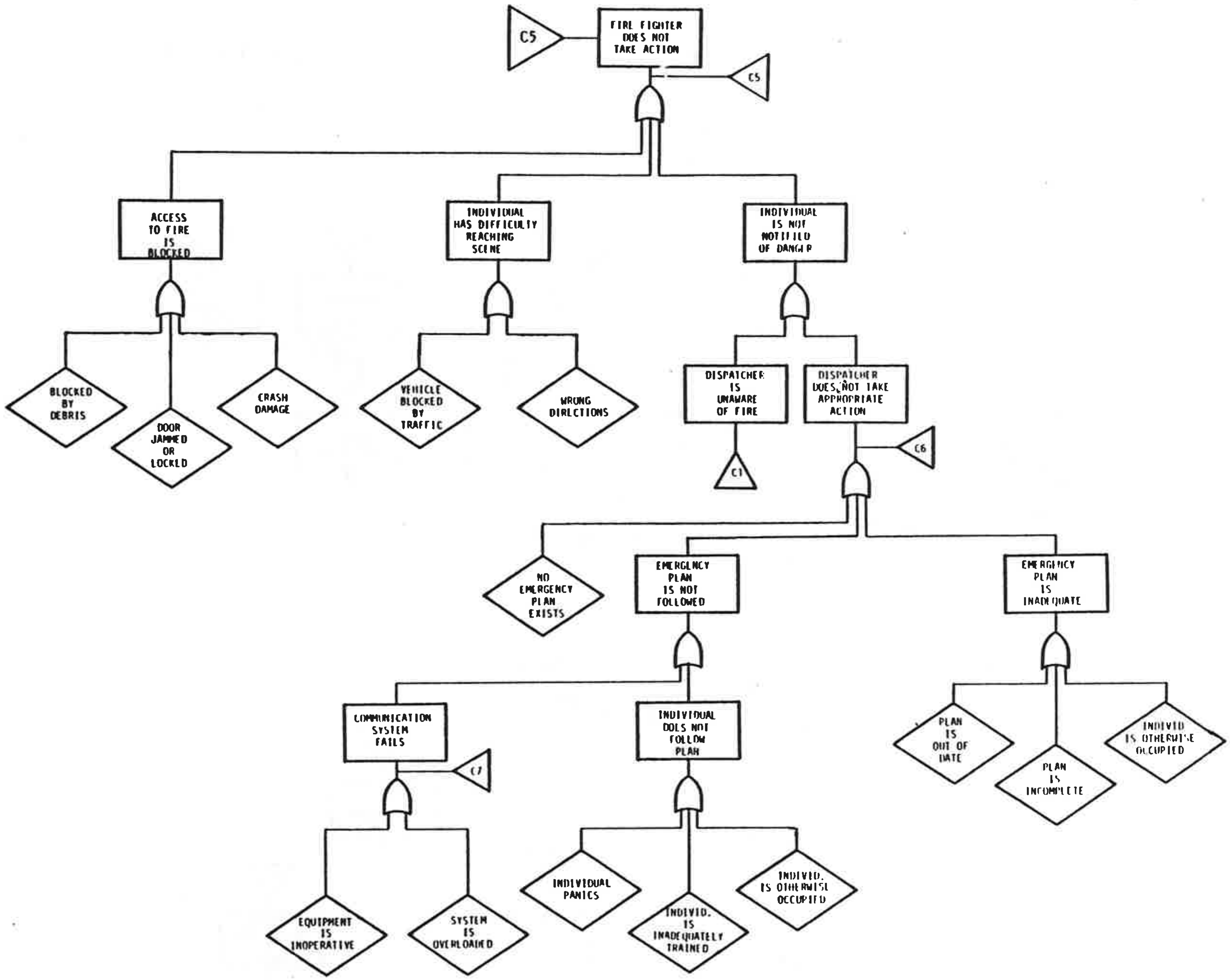

FIGURE 5-2-2. C5: FIREFIGHTER DOES NOT TAKE ACTION

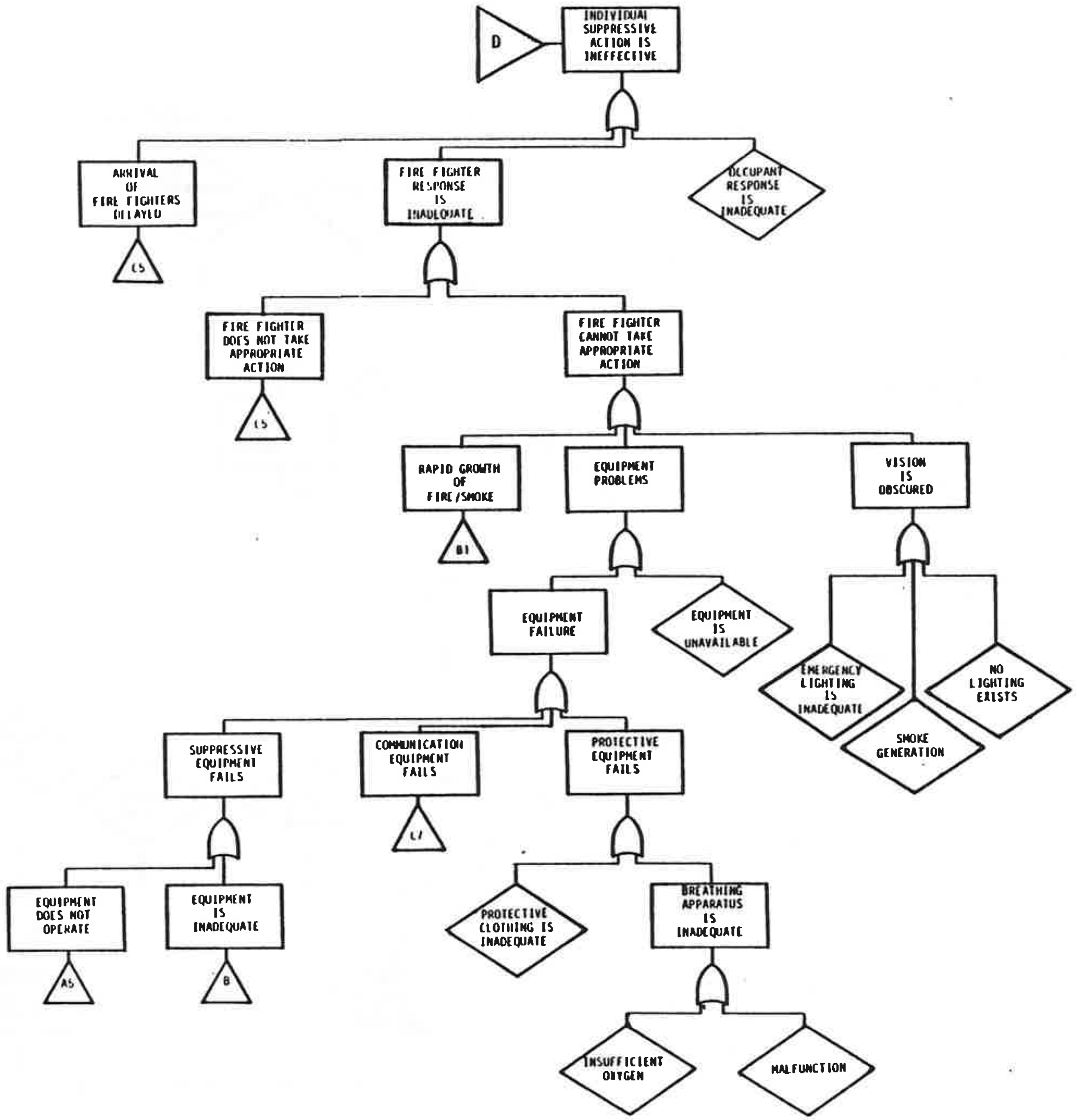

FIGURE 5-3. D: INDIVIDUAL SUPPRESSIVE ACTION IS INEFFECTIVE

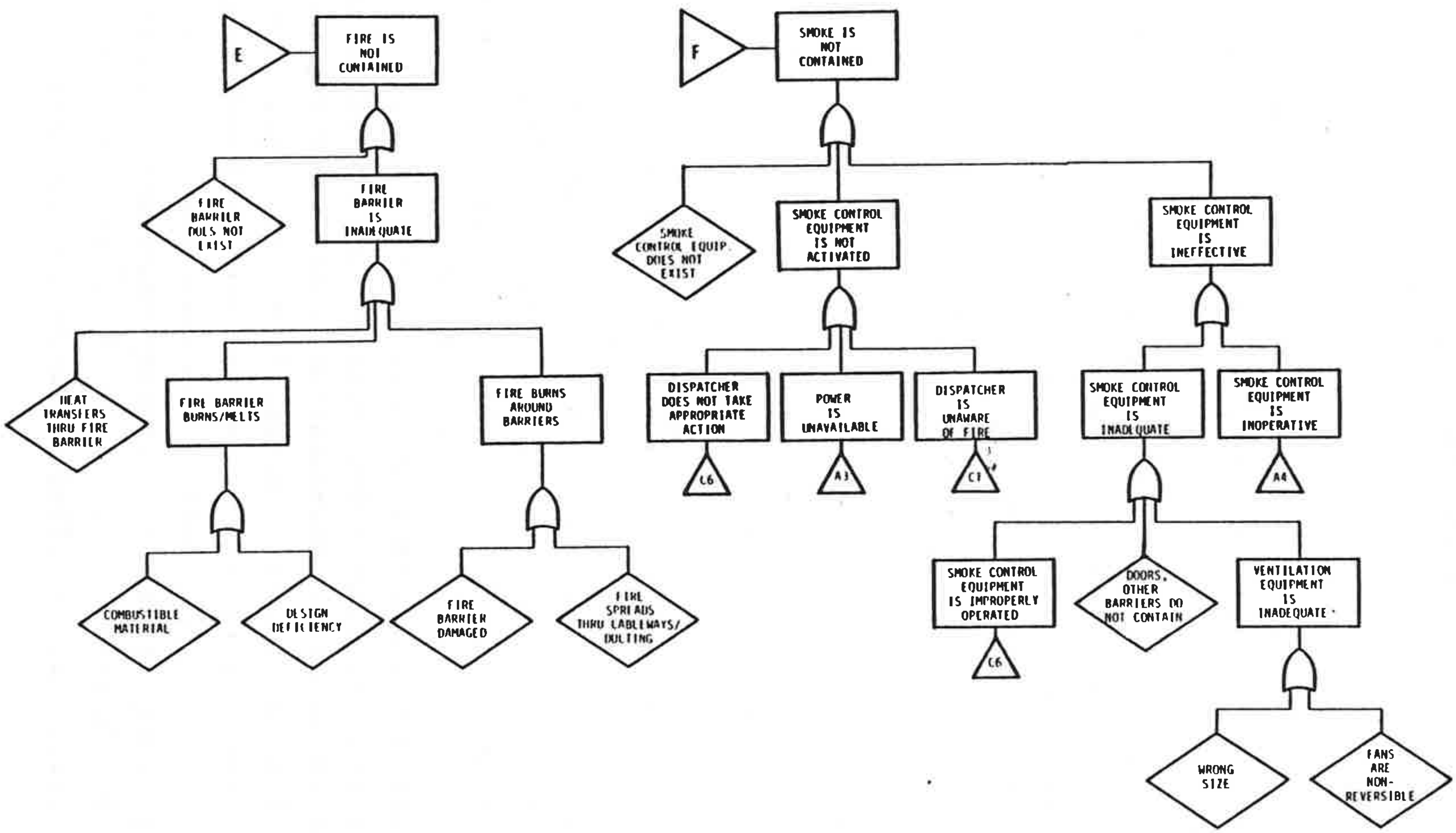

FIGURE 5-4. E: FIRE IS NOT CONTAINED
F: SMOKE IS NOT CONTAINED

6. EVACUATION OF INDIVIDUALS

6.1 BACKGROUND

In the event of a serious transit fire, a key priority to ensure passenger safety is the evacuation of passengers from the hazardous area.

Each transit property has developed emergency evacuation plans based on experience and environmental conditions. The type of rescue equipment and personnel required to evacuate individuals varies according to the location of the vehicle, i.e., is a subway tunnel or on an elevated platform. It should be noted that the evacuation of the individual from the vehicle is considered more important in this analysis than evacuation from the right-of-way or stations. The fault tree diagrams presented in the following figures reflect that primary focus. They are general in nature, but an attempt has been made to incorporate many of the possible variations among vehicles.

The technical data used in the development of the fault tree diagrams were derived from several sources. The evacuation of passengers has been addressed in various manners by many government and private groups. As a result, an extensive body of literature exists which proved quite valuable in the construction of these fault tree diagrams. The detailed descriptions of major fire situations, contained in government and transit property investigative reports, provided insights into procedures used, communication difficulties, coordination problems and the interaction of all of these factors in actual fire situations. The emergency plans of specific transit properties were reviewed and provided valuable information regarding how these properties perceive training of employees, and emergency provisions such as emergency exits. Publications of APTA[7] and NFPA,[8] in particular, offered general guidelines regarding equipment and emergency procedures.

6.2 FAULT TREE DIAGRAMS

Figure 6-0 illustrates the overview for the undesirable event, "Individual Fails to Evacuate Area". This event was chosen because the failure of an individual to evacuate the area containing fire/smoke conditions could result in injury or death. This head event results from the occurrence of either one or all of three primary events: "Individual Fails to Evacuate Vehicle", "Individual Fails to Evacuate R-O-W*", or "Individual Fails to Evacuate Station". The fault tree diagrams focus on evacuation from the vehicle. Therefore, although evacuation from the other areas is recognized as important, the branches dealing with this topic are not developed to the same degree as those dealing with the vehicle.

Two primary events leading to "Individual Fails to Evacuate Vehicle" are "Individual Fails To Remove Self" and "Individual Is Not Rescued".

The occurrence of either of the events: "Individual Fails To Take Timely Action" or "Egress Is Impossible", could lead to the event, "Individual Fails To Remove Self". These branches are further developed and shown in Figures 6-1 and 6-2 and their sub-numbers.

The occurrence of either of the events: "Assistance Is Unable To Remove Individual" or "Assistance Is Not Available", could result in the event, "Individual Is Not Rescued". These branches are presented in Figures 6-3 and 6-4.

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*Right-of-Way.

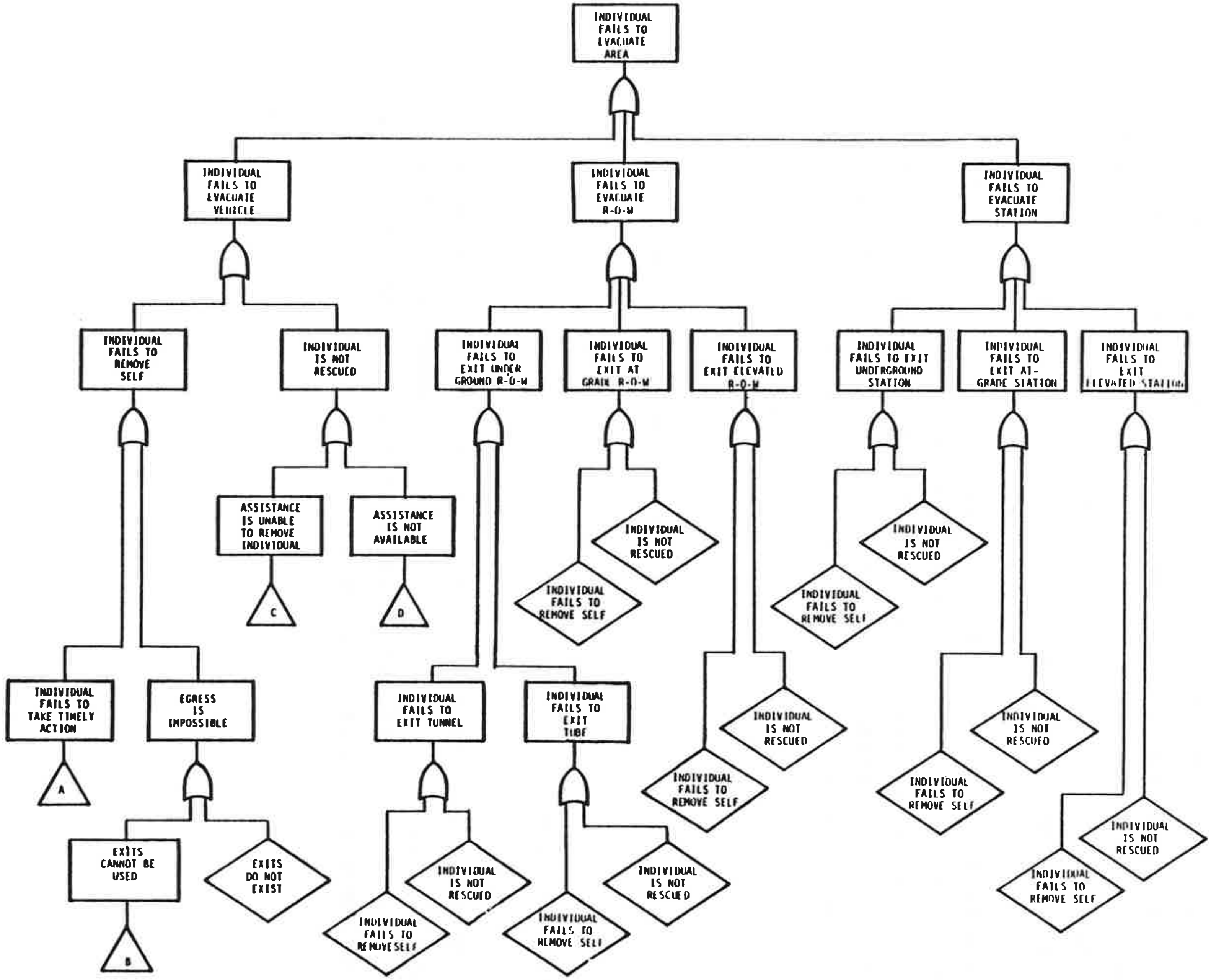

FIGURE 6-0. OVERVIEW: INDIVIDUAL FAILS TO EVACUATE AREA

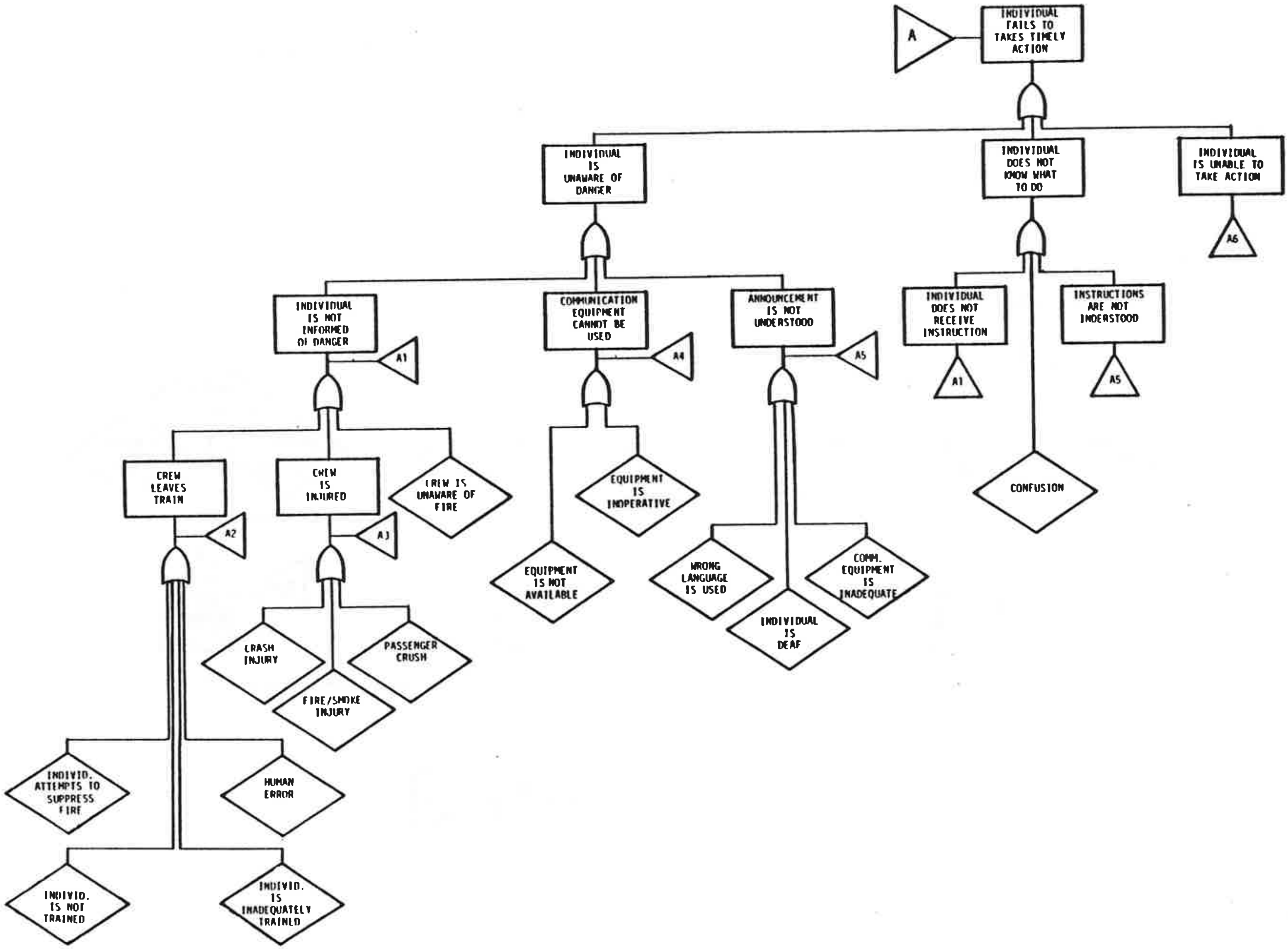

FIGURE 6-1. A: INDIVIDUAL FAILS TO TAKE TIMELY ACTION

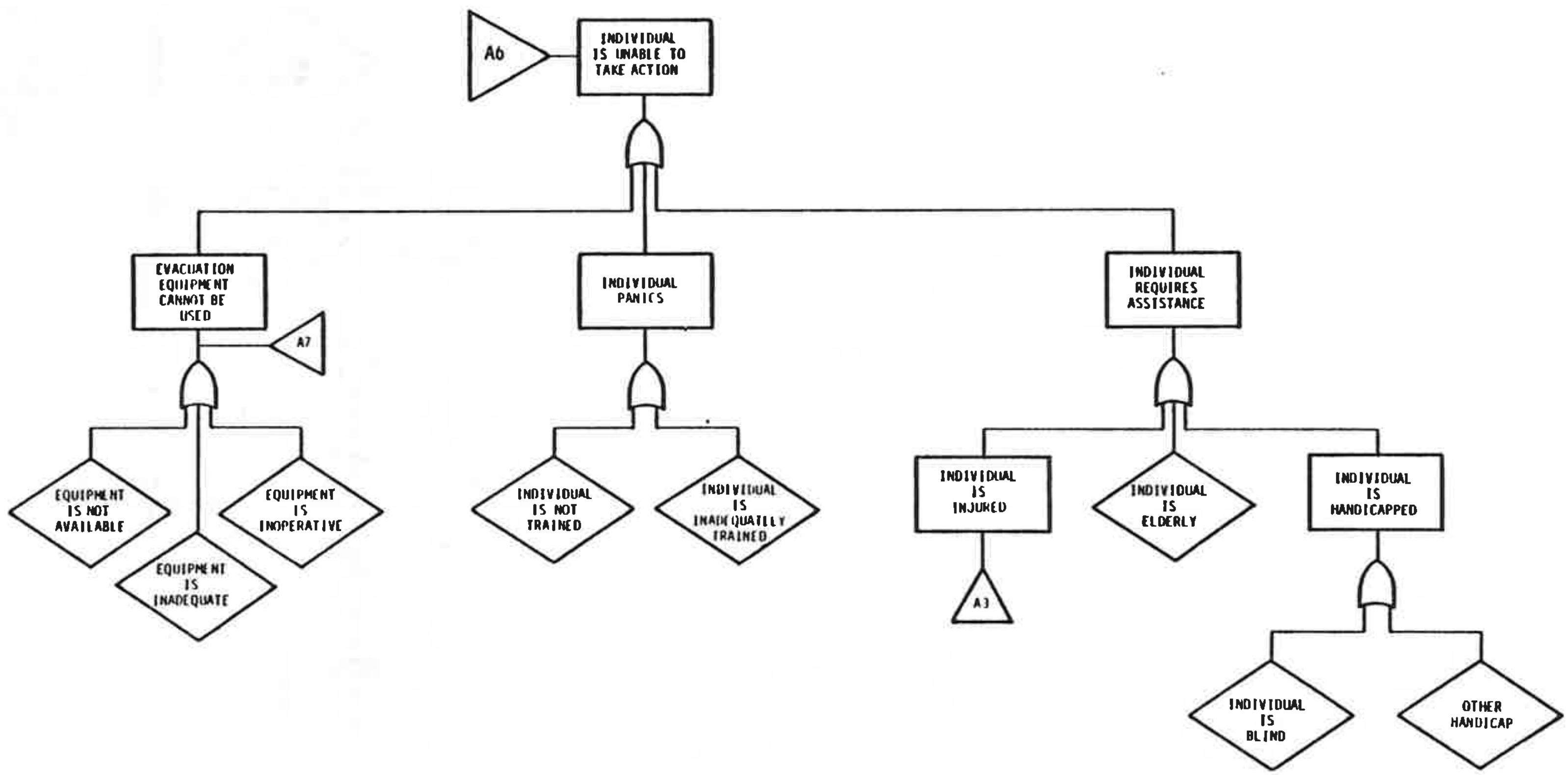

FIGURE 6-1-1. A6: INDIVIDUAL IS UNABLE TO TAKE ACTION

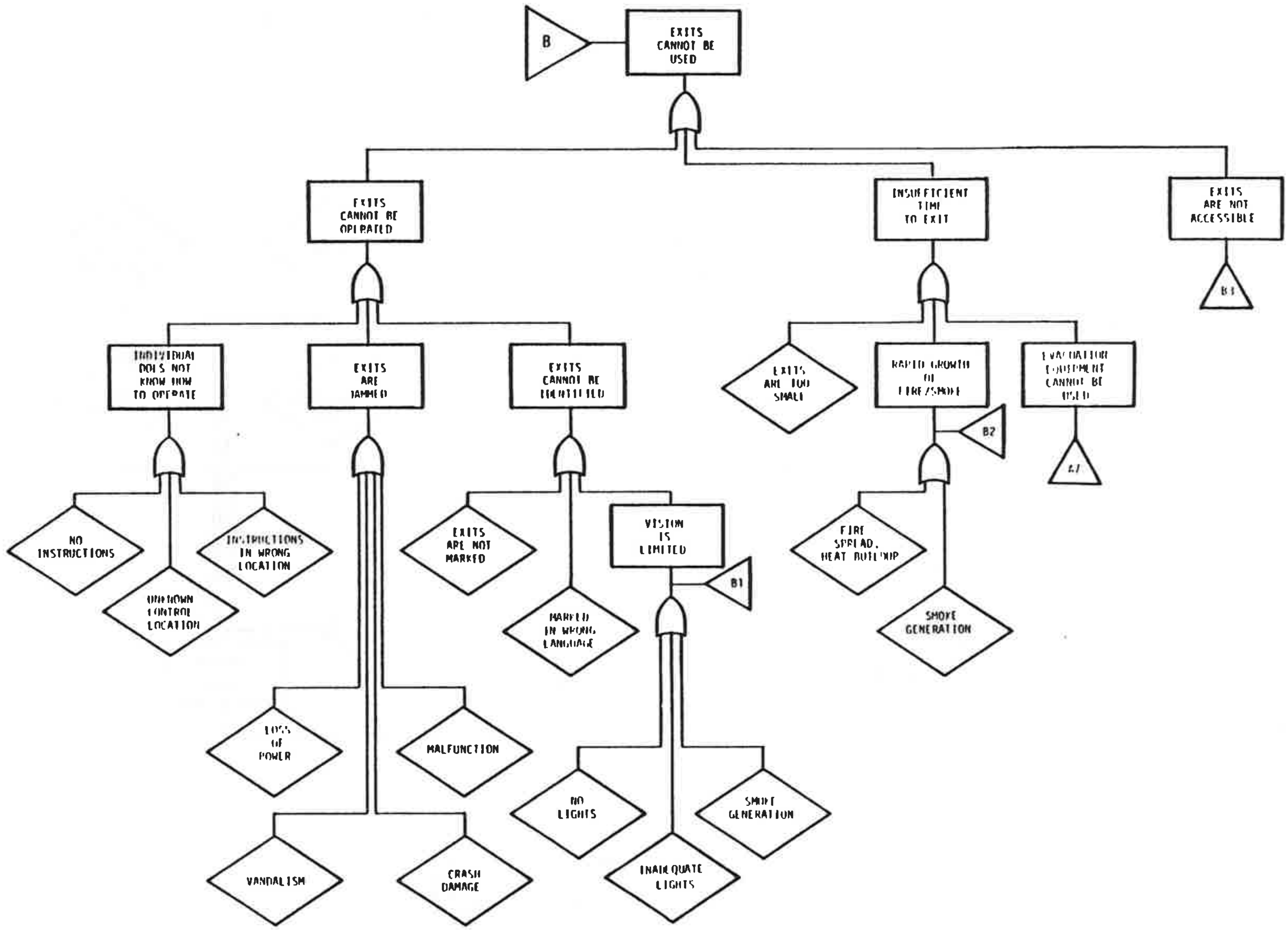

FIGURE 6-2. B: EXITS CANNOT BE USED

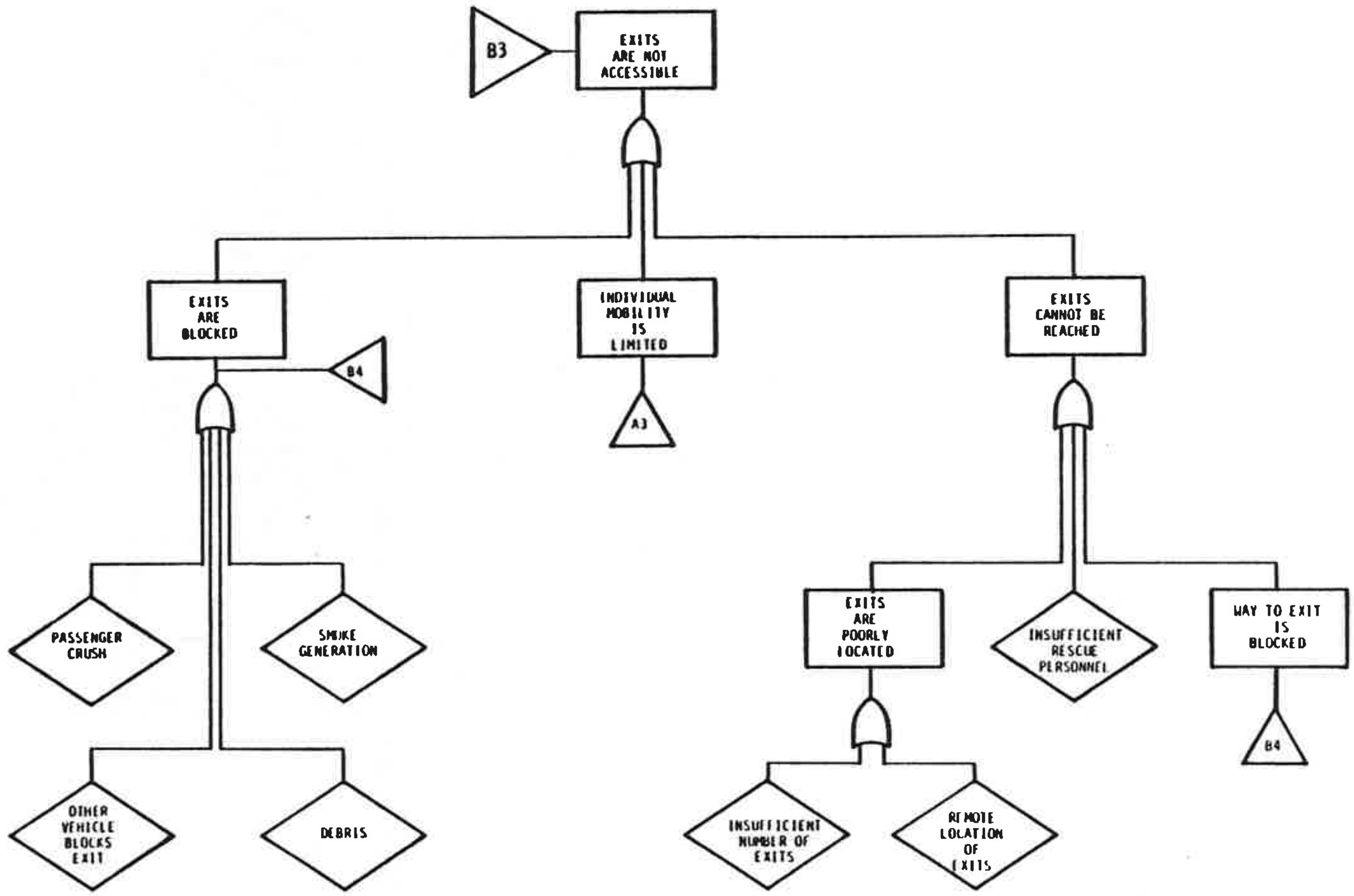

FIGURE 6-2-1. B3: EXITS ARE NOT ACCESSIBLE

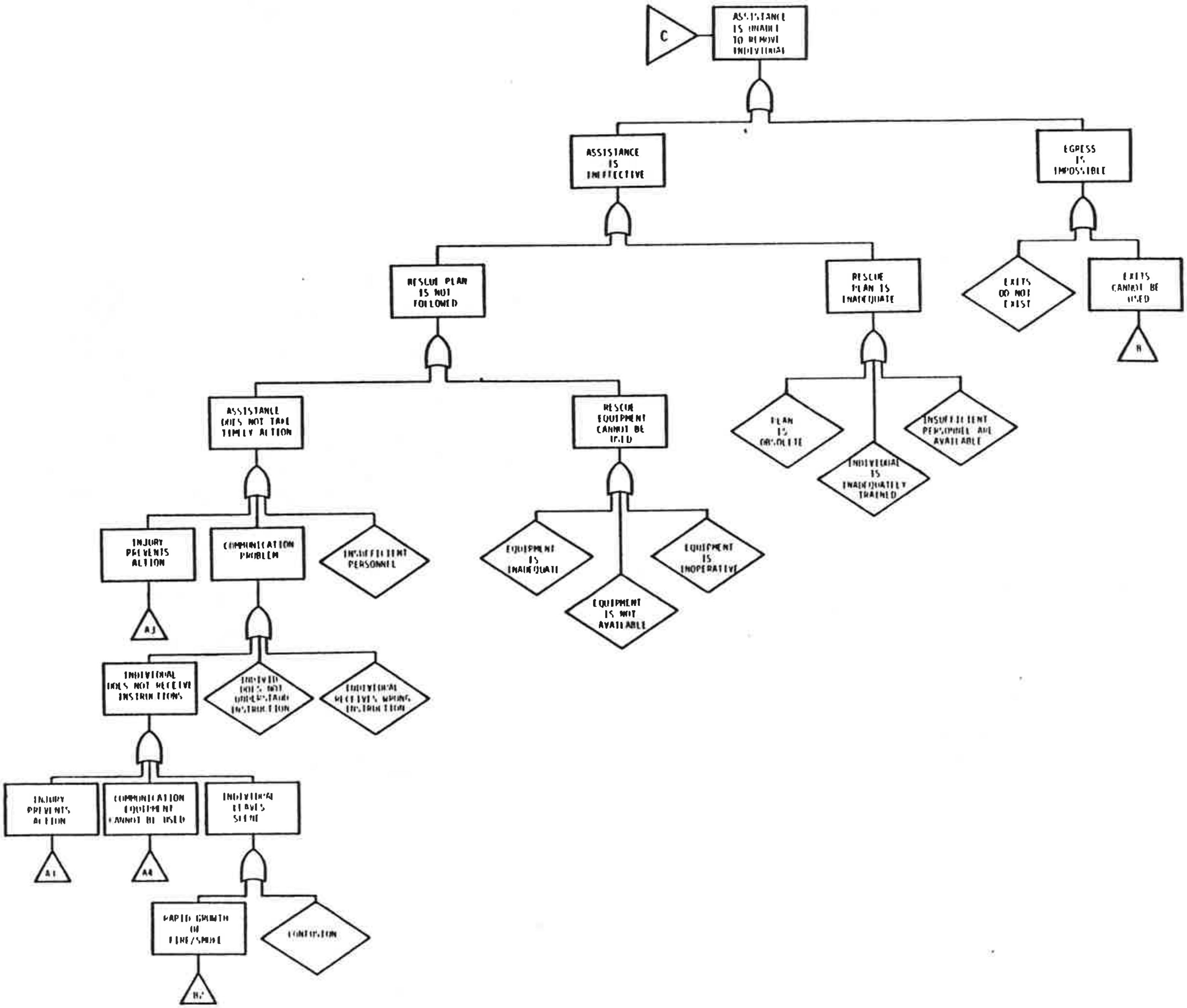

FIGURE 6-3. C: ASSISTANCE IS UNABLE TO REMOVE INDIVIDUAL

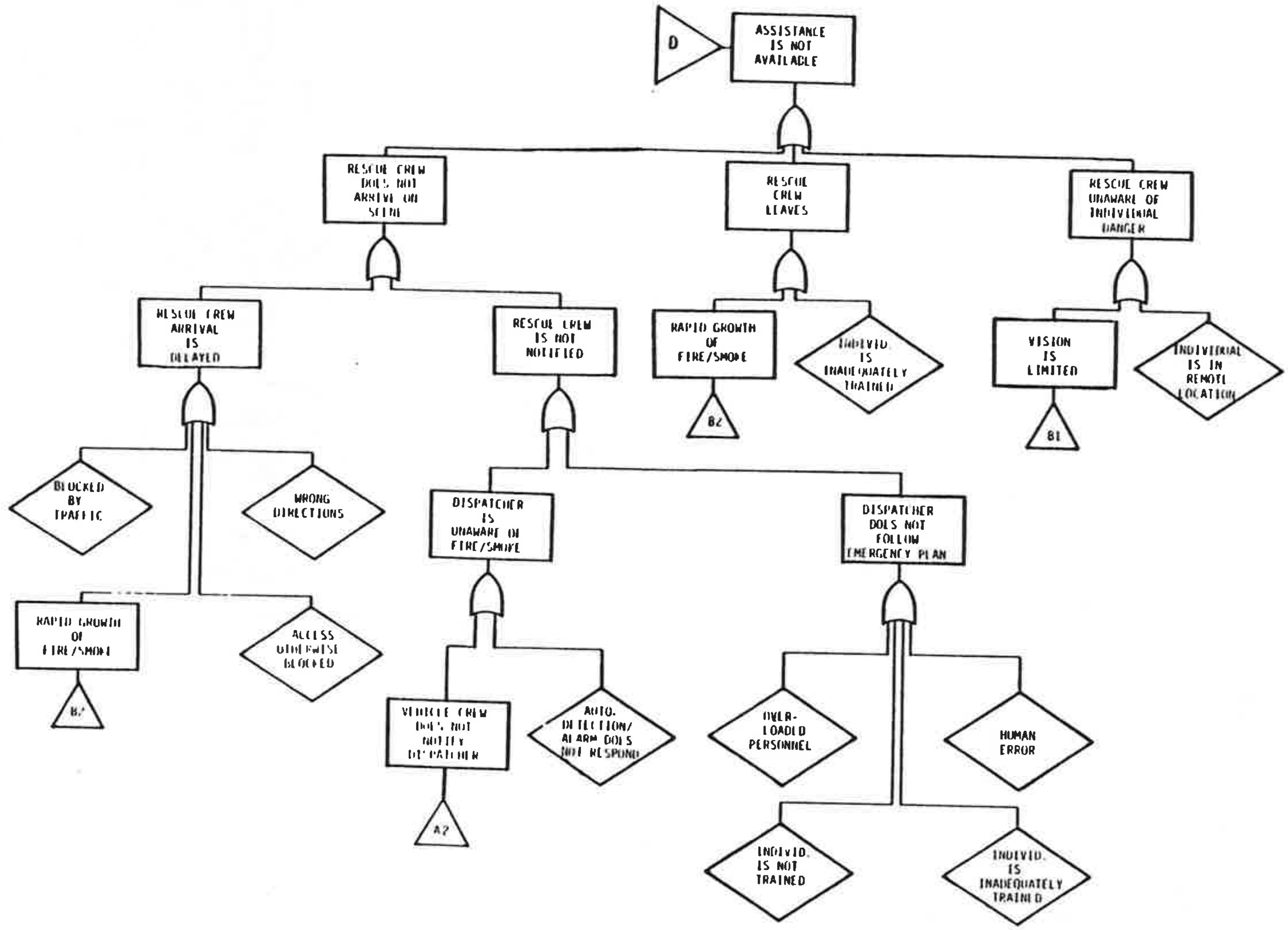

FIGURE 6-4. D: ASSISTANCE IS NOT AVAILABLE

REFERENCES

1. "Identification of the Fire Threat in Urban Transit Vehicles", UMTA-MA-06-0051-50-1, June, 1980.

2. "Fault Tree for Safety", Boeing Support Systems Engineering, Military Aircraft Product Development.

3. "Fault Tree Manual", DeLong, Thomas W.A., Texas A&M University. December, 1970. AD739001.

4. "Handbook of System and Product Safety", Hammer, Willie, 1972.

5. "Safety Manual No. 8: Fault Tree Analysis", National Mine Health and Safety Academy, U.S. Department of Interior.

6. "Commonalities in Transportation Fire Safety: Regulations, Research and Development, and Data Bases", DOT-TSC-OST-80-5, November, 1980.

7. "Guidelines for Design of Rapid Transit Facilities, 1979", American Public Transit Association.

8. "Standard 130 for Fixed Guideway Transit Systems", Revised Draft, March 21, 1980, National Fire Protection Association.