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Decision Analysis Model for Passenger-Aircraft Fire Safety with Application to In-Flight Fire Scenarios

S. Wayne Stiefel

U.S. DEPARTMENT OF COMMERCE
Center for Fire Research
National Engineering Laboratory
National Bureau of Standards
Gaithersburg, MD 20899

Final Report

January 1987

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DECISION ANALYSIS MODEL FOR PASSENGER-AIRCRAFT
FIRE SAFETY WITH APPLICATION TO
IN-FLIGHT FIRE SCENARIOS

by

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Abstract

Fire-risk assessment and decision analysis methodologies were developed for the case of major aircraft fires. This document reports on the final phase of the project which concerned refining the model specifically for the in-flight fire scenario. A step-by-step approach has been suggested for use in the evaluation of the risk reduction potential of specific mitigation strategies available to the FAA: prevention, early detection, extinguishment and smoke control. To demonstrate the approach one scenario was examined - gasoline fire in the cabin. The discussion includes the type of information required by the model and the potential sources (test results, mathematical models, accident experience and expert judgment) for obtaining such information.

Keywords: aircraft accidents; aircraft safety; decision analysis; fire risk; fire statistics; in-flight fires; risk analysis.

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EXECUTIVE SUMMARY

Fire-risk assessment and decision analysis methodologies were developed for the case of major aircraft fires. A generic model has been developed covering fatal passenger flight fires and fires involving major fire damage. During the initial phase of this project, emphasis was placed upon the post crash fire scenario and estimating the value of the risk-reduction strategy of seat blocking. This document reports on the final phase of the project which was concerned with developing the model specifically for the in-flight fire scenario.

Benefits models are organized around a data base of historical fires. Because the in-flight fires are even more rare than the post-crash survivable fire, emphasis was placed upon reported non-fatal fire incidents which may have the potential for initiating catastrophic events. This analysis classified the sources, location and relative frequencies associated with these ignitions.

A step-by-step approach has been suggested for use in the evaluation of the risk reduction potential of specific mitigation strategies available to the FAA: prevention, early detection, extinguishment and smoke control. Event trees were developed for use in selection from among the risk reduction strategies and for display of the in-flight fire scenarios requiring analysis. Also, a fire spread and growth model in event tree format provides the tool for calculating the expected deaths per fire for a specific scenario, once a risk reduction strategy is chosen.

To demonstrate the approach one scenario was examined - gasoline fire in the cabin - and the necessary structure was developed to permit the FAA to use their test results in assessing specific mitigation strategies. The example points out and discusses the type of information required by the model and the potential sources (test results, mathematical models, accident experience, and expert judgment) for obtaining such information.

INTRODUCTION

PURPOSE.

The objective for this phase of the effort was to develop further the generic fire risk framework for application to multiple mitigation strategies for the special case of in-flight fires.

BACKGROUND.

This is the second phase report on a project to assist the Federal Aviation Administration (FAA) in the development and implementation of analytic models to assess the public risk associated with various aircraft fire scenarios, and in the assessment of the benefits and costs associated with candidate strategies for the mitigation of such public risk. During the first phase effort, a generic modeling framework was developed and demonstrated through a benefit-cost analysis of the use of seat blocking materials to inhibit the spread of fire in cabin fires. Impacts on fatalities, injuries, and property damage were estimated for the three scenarios of survivable post-crash fire, in-flight fire and ramp or ground fire. A data base of aircraft fires, with limited exclusions, was assembled suitable for application to most fire scenarios of interest and most mitigating strategies. An annotated literature review was prepared, showing the use of existing research projects, models and data sources. The results of the seat-blocking analysis were useful as support for research prioritization and decision on regulatory or other actions.

The FAA, based upon the results of aircraft inspections and investigations of in-flight fires, determined that the second phase of the project should focus on in-flight fires. Multiple classes of mitigation strategies--involving fire prevention, earlier detection, smoke control, fire spread limitation, or improved suppression--were to be accommodated in the analysis structure.

The second phase effort built upon the experience gained in developing the initial models. The fatal aircraft fire data base was expanded to include non-fatal in-flight fires. The data was evaluated to develop the event sequences which have led to in-flight fires and to better define the in-flight fire scenarios. Candidate mitigation strategies were selected and investigated in terms of how they modify these critical events. In order to predict how the risk of in-flight fire and its consequences can be ameliorated, the fire spread and growth model developed in the first phase effort was extended to accommodate the event sequences and mitigation strategies under investigation. An example scenario - gasoline fire in the cabin - was selected for a demonstration of the modeling process.

DISCUSSION

CHAPTER 1. DATA SOURCES FOR IN-FLIGHT FIRES.

Several data sources were used in developing the information contained in this section of the report. The list of international fatal in-flight accidents were based upon reports of the World Airline Accident Summary [1], NTSB Reports, Cominsky [2], and Lucha [3]. Two additional data sources were analyzed for in-flight fire related incidents - the FAA's Service Difficulty

Reports (SDR) and the FAA's Accident/Incident Data System (AIDS). These sources provide information on problems experienced and provide a basis upon which to develop in-flight fire scenarios. Note that, since the focus of this project is on alternatives which ~~lie~~ apply within the cabin, the list of historical fires and fire incidents excludes some classes of in-flight fires that ~~not~~ never enter storage or passenger-accessible areas. Engine fires and tire fires that cause~~d~~ loss of control and a subsequent fatal crash without ever putting fire products into the interior are examples.

Table 1 lists historical fire accidents involving in-flight fire fatalities, 1965-1983, scheduled and non-scheduled passenger flights for U.S. and non-U.S. carriers using U.S. and non-U.S. aircraft. The table provides information on the accident, the aircraft, ~~the flight,~~ total passengers on board, total number killed in the accident and a cause when known. This list was primarily derived from the data compiled in the first phase report [4]. A few accidents were added - one U.S. airline accident which occurred in Boston and three non-U.S. airline accidents which occurred in Cincinnati, Caracas and Columbia. The Air Canada, Cincinnati accident occurred in February 1983, after the 1982 cut-off period for the initial report. Soviet block countries were excluded from these data, since data are particularly scarce and the influence of FAA regulations is minor.

Nine hundred ~~sixty-six~~ thirty-two deaths from in-flight fires, originating in the cabin/fuselage, occurred over this eighteen year period.

Some of these accidents have prompted FAA actions and prompted changes to be made to aircraft designs. The Varig B-707 fire in Paris, France, which involved a rear lavatory fire, resulted in regulations requiring fire containment integrity of lavatory trash receptacles. The ~~Saudia~~ Saudi Air L-1011 fire in Riyadh, Saudi Arabia, which was believed to have originated in a cargo hold, resulted in changing the lining materials for the cargo hold to prevent burn-through and to better confine fires within the space [5]. More recently, the Air Canada DC-9 fire in Cincinnati, which was in a rear cabin lavatory area has raised the problem of dealing with a fire which is hidden within the concealed spaces of an aircraft.

Because of the rare nature of in-flight fatal fires - ~~twelve~~ eleven listed in Table 1 over an eighteen year period; and the incomplete knowledge of what occurred for these accidents, non-fatal fire and near-fire incidents which have been controlled by flight crew actions of various degrees of seriousness were also analyzed. The largest data base in terms of the number of incidents is the Service Difficulty Reports maintained by the FAA's Aeronautical Center in Oklahoma City. The SDR's relating to in-flight fires were being analyzed by this project when it was discovered that a parallel effort had just been completed by the FAA's Safety Analysis Division in support of a project on passenger protective breathing ~~assessment.~~ equipment. The analysis of SDR's which follows is based upon the data compiled by the Safety Analysis Division [6]. These data included eight turbojet transport category aircraft used in air carrier operations (B-727, L-1011, B-747, DC-10, DC-9, BAC-111, B-737 and DC-8). The Boeing 707 and 720 and the Airbus A-300 were not included. A summary of the SDR's collected between 1978 and February, 1984, a total of 1,251 reports involving flame and smoke, and associated evidence of arcing, smoldering, sparking, etc. was provided to the project. Of the 1,251 events - both in-flight (1,071) and on the ground (180) - only 120 or 9.5 percent were reported as fires. During the period January 1978 - February 1984 approximately 31,457,000 flight hours were logged for these aircraft.[1]

Table 2 summarizes the in-flight SDR's by location within the aircraft and indicates these events were generally the result of some system, component, or part malfunction or failure at each location. The largest number of the events occurred within the cabin area (45 percent) with lighting and air conditioning systems combining for two-thirds of the events, lavatories were involved with 12 percent of the cabin events. Thirty-seven percent of the events occurred on the flight deck, and many of these also involved the air conditioning system. Finally, galleys were involved in 19 percent of the SDR's with ovens and coffee makers combining for over 60 percent of the reports. The exact cause is difficult to determine from the SDR's.

Table 3 indicates the proportion of events which are classified as fire, smoke, fumes, arcing or unknown by location for in-flight reports. Note that for fires within the cabin or flight deck, 91 percent are in the cabin. When all events are considered for the cabin or flight deck, 64 percent are in the cabin.

Table 4 indicates by aircraft the frequency of SDR fire and other events per 100,000 flight hours. The L-1011 has the highest rate for fires (1.13) followed by the B-747 (0.73). This compares to an overall average rate of 0.22 for the set of aircraft listed in table 4. When all in-flight fire and associated events are considered together the B-737 (6.39) leads followed by the B-747 (5.64) and the DC-8 (4.01). The average rate per 100,000 flight-hours for all of the aircraft was 3.14.

While rarely do these failures/events result in an uncontrollable situation, the potential is there. Therefore, specific problem areas for each aircraft were included to further pinpoint fires of concern. Table 5 includes both in-flight and on ground fire events, since it may be possible for problems which occur on the ground to occur also while in flight. The specific information indicates that, for example, the L-1011 fires have occurred in a lower galley oven. Galley fires also appear to be a problem for the B-747 and the B-727. Lavatory fires-related to waste containers are indicated in the B-747 and the DC-10. The B-737 appears to have a considerable problem on the flight deck. The auxiliary power unit (APU) has resulted in fires in the B-727, the BAC-111 and the DC-9.

Another computerized data base maintained by the FAA is the Accident/Incident Data System (AIDS). This data base is largely made up from preliminary accident reports. Both Commercial Air Carrier and General Aviation incidents are included, however, the majority are General Aviation. In-flight fire incidents for Air Carriers from July 1978 - July 1984 included 28 cabin/cockpit/cargo fires, 34 engine fires and one brake fire. Table 6 summarizes the cabin/cockpit/cargo fires which are of interest to this effort. The key to containing the majority of these fires was early intervention. Two disconcerting incidents reported inoperative fire extinguishers - one involved a galley waste container fire, the ~~fire~~ extinguisher bottle was empty and ice water was

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[1] Flight hours based upon Aircraft Utilization and Propulsion Reliability Report (RIS-FS83405) and averaged over the 1978 to 1983 period.

used to extinguish the fire. The second was a cabin fire caused by a cigarette ash under a seat; again the extinguisher was empty. Lavatory fires were also troubling, since it appears that passengers are smoking against regulations and improperly disposing of cigarettes and matches among flammable materials. One incident was reported as being set by a passenger.

For the 28 fires located in the cabin, cockpit or cargo areas, seven were galley fires, seven lavatory fires, five in the cockpit, seven in the cabin and two in the cargo area. The lavatory fires involved one which appears to have been set and two reported to either the FBI or FAA Security. The remaining four were trash bin/waste chute fires involving cigarettes or smoking materials. Four out of the seven cabin fires also involved cigarettes or smoking materials.

Table 1. In-Flight Fire Fatalities 1965-1983

U. S. AIRLINES

Date	Phase	Description[1]	On Board	Total Killed	Cause
6/23/67	ENROUTE	Mohawk, BAC-111, Jet Blossburg, PA	34	34	Plenum chamber fire - did not use Cabin as area of spread
3/11/73	ENROUTE	Pan American, B-707, Jet, Boston, MA		3	Fire and Smoke cause by acid-cargo spillage
7/22/73		Pan American, B-707, Jet, Tahiti	79	79	Fire originated outside cabin area, 4 in - air explosions

NON-U.S. AIRLINES USING U.S. BUILT AIRCRAFT

Date	Phase	Description	On Board	Total Killed	Cause
7/11/73	APPROACH	Varig; B-707, Jet, France	134	123	Rear lavatory - possibly cigarette
11/26/79	ENROUTE	Pakistani International; B-707; Jet; Saudi Arabia	156	156	Unknown cause

[1] Carrier; Aircraft Designation; Type; Accident Location

Date	Phase	Description	On Board	Total Killed	Cause
8/19/80	LANDING	Saudi Air; L-1011; Jet; Saudi Arabia	301	301	Cargo hold fire
2/6/83	ENROUTE	Air Canada; DC-9; Jet; Cincinnati, OH	46	20	Possibly concealed electrical unknown cause

NON-U.S. AIRLINES USING NON-U.S. BUILT AIRCRAFT

Date	Phase	Description	On Board	Total Killed	Cause
9/11/68	ENROUTE	Air France; Caravelle; Jet; France	95	95	Unknown cause - rear of cabin
7/26/69	LANDING	Air Algeria; Caravelle; Jet; Algeria	37	33	Electrical components - no spread in cabin
5/6/70	UNKNOWN	Somali; Viscount; Turboprop; Somalia	30	5	Unknown cause Fire from below concealed spaces

Date	Phase	Description	On Board	Total Killed	Cause
3/3/78	TAKEOFF	LAV, 748, Caracas	47	47	Cabin fire crashed into sea
12/21/80	TAKEOFF	Aerovias del Cesar, Jet, Caravelle, Nr Rio Hace, Columbia	70	70	Cabin explosion and fire

Table 2. In-Flight Service Difficulty Reports
1978 to February, 1984

Includes: Fire, Smoke, Fumes and Arcing
B-727, L-1011, B-747, DC-10, DC-9, BAC-111, B-737 and DC-8

LOCATION (% OF TOTAL)	SOURCE	NUMBER OF INCIDENTS	PERCENT AT LOCATION
Galley (19%)	Oven	58	32
	Coffee Maker	52	29
	Other	70	39
	TOTAL	180	
Cabin (45%)	Lighting Ballast	148	35
	APU	28	7
	Air/C Packs	130	31
	Lavatory	52	12
	Other	68	16
	TOTAL	426	
Flight Deck (37%)	Instrument	46	13
	Console	75	21
	Air/C Packs	99	28
	Other	131	37
	TOTAL	351	

Table 3. Location of Events (Fire, Smoke, Fumes, Arcing and Unknown) for In-Flight, Service Difficulty Reports Reported 1978 to February, 1984

B-727, L-1011, B-747, DC-10, DC-9, BAC-111, B-737 and DC-8

	CABIN AND GALLEY	FLIGHT DECK	CABIN AND FLIGHT DECK	OTHER	TOTAL
Fires	62	6	68	15	83
Smoke	366	170	536	13	549
Fumes	157	134	291	13	304
Arcing	44	28	72	13	85
Unknown	9	12	21	38	59
TOTAL	638	350	988	92	1080

Table 4. Service Difficulty Reports Rates Per Flight Hour for In-Flight Events 1978 to February 1984 by Aircraft

	CABIN AND FLIGHT DECK			RATE PER 100,000 FLIGHT-HOURS	
AIRCRAFT	FIRES	TOTAL EVENTS	FLIGHT HOURS	FIRES	TOTAL EVENTS
B-727	11	328	13,195,299	0.08	2.48
L-1011	18	44	1,587,750	1.13	2.77
B-747	20	155	2,749,527	0.73	5.64
DC-10	8	64	2,314,100	0.35	2.76
DC-9	2	114	6,256,453	0.03	1.82
BAC-111	0	5	384,123	0.00	1.30
B-737	6	214	3,350,344	0.18	6.39
DC-8	3	65	1,619,467	0.18	4.01
TOTAL	68	989	31,457,063	0.22	3.14

Table 5. Problem Areas by Location for Specific Aircraft (In-Flight and On Ground SDR Events)

AIRCRAFT	PROBLEM IDENTIFIED
B-727	Flight Deck 1. Windshield arcing/smoke/fire 2. Radar 3. Flight engineer's panel/shorts/arcing Cabin 1. Light ballast 2. Galley/fire 3. APU/fire
L-1011	Cabin Oven fires - lower galley particularly No. 6 oven - halon extinguishers used in 2 cases
B-747	Flight Deck Lights, switches circuit breakers/smoke/fumes Cabin 1. Galley Fires - ovens 2. Lavatory fires - waste container
DC-10	Flight Deck Seat encoder/decoder fires Cabin Lavatory fires
DC-9	Flight Deck APU fuel control leaks at nozzle/fumes Cabin - fumes/odors 1. Water separator (coalescer - bags) 2. Air Cycle Machine

AIRCRAFT	PROBLEM IDENTIFIED
BAC-111	Cabin APU fires
B-737	Flight Deck - fumes 1. Water separator (coalescer bags) Gasper fan inoperative 2. Generator control unit - arcing/smoke/fumes in cockpit - generator off line 3. Glare shield - arcing 4. Air conditioning system - odors in cockpit and cabin
DC-8	Flight Deck 1. Center recirculating fan bearings 2. Radar - smoke/shorts - capacitor

Table 6. Summary of In-Flight Accident
Incident Data System (AIDS)
July 1978 - July 1984

28 - Cabin/Cockpit/Cargo

34 - Engine Fires

1 - Overheated brakes

<u>7 Galley Fires</u>

2 electrical
Service Cart Receptacle

Oven - overrun, circuit breaker was opened to stop fire

2 food spill in galley oven

2 oven fires unspecified cause

1 Galley waste container - ~~fire~~ extinguisher bottle empty used ice water to extinguish

<u>7 Lavatory Fires</u>

1 Passenger set fires in lavatories

4 Trash bin/waste chute

Extinguished by cabin crew

Paper fire in waste chute - found paper match and scorched kleenex

Believed a cigarette caused fire used water to put fire out

Cigarette butt found among paper seat covers
Attendant used extinguisher

1 Minor fire cause unknown - FBI notified
1 Kleenex Box Fixture - crew extinguished - FAA security met aircraft

<u>5 Cockpit (All electrical)</u>

1 Smoke in cockpit. Continuous duty contactor 6041H189 replaced

1 Loose landing light switch terminal caused minor electrical fire

1 Several breakers opened and crew smelled smoke after takeoff

1 Fire behind instrument panel in area of landing gear. Gear solenoid and wiring burned

1 Heard a loud pop. Smoke and flame behind panel. Fire bottle extinguished fire. Windshield heat breakers popped

<u>7 Cabin Fires</u>

2 Lighting ballast

Passenger compartment cove lighting ballast flamed and smoked

Cabin Wall fire from exploding window lighting ballast

4 Smoking/cigarette/lighter

Passenger lighter burst into flames - Flight attendant extinguished with apple juice

Fire in passenger carry on handbag probably due to careless smoking

Fire occurred in a bag under seat resulted from cigarette ash. Attendant put out fire. Bad extinguisher

Smoke and fire in a seat. Found empty cigarette package and napkin stuffed between seat cushion

<u>2 Cargo Fires</u>

1 Low level explosive device smoldering in cargo area caused smoke in cabin

1 Baggage fire in flight. Found package with 24 volt battery pack which may have shorted

CHAPTER 2. GENERIC MODEL TO EVALUATE RISK-REDUCTION OPTIONS FOR IN-FLIGHT SCENARIOS.

Specific models to address the in-flight fire accident scenarios have been developed to fit into the generic model structure for aircraft-fire risk analysis shown in Figure 1. An overview of the generic modeling framework is provided in this figure. The first step involves establishing a structure for the fires to be studied. Aircraft types, activity types, occupant characteristics and fire types of interest are identified and the analyst uses this structure in determining what data are needed for the other models in the framework. Three models use these data in parallel: (1) the Ignition-Initiation Model, which provides estimated probabilities of ignition; (2) the Post-Ignition Model, which provides estimated losses (e.g., deaths, injuries and property damage) given ignition; and (3) the Cost Model. The first two models provide the probabilities of accidents and the severities of those accidents, respectively, which together give the level of risk. While the third model - the Cost Model - provides the corresponding cost.

Each of these models is set up to measure risks and costs relative to a base case, which is defined as the status quo. The measured risk, derived from results of the Ignition-Initiation and Post-Ignition Models, is passed on to a Loss Evaluation Model, which converts different types of losses (deaths, injuries, property damage) to a common scale. Finally, a Cost-Benefit Comparison Model converts costs and losses into a measure of attractiveness for the alternative.

The generic modeling framework was developed during the first phase of this project and used to evaluate aircraft cabin seat-blocking. Using the historical data base of passenger aircraft fires, the number of fire fatalities which could be prevented as a function of extra escape time provided by seat blocking or other alternatives was estimated [7]. The majority of the accidents where extra escape time is critical involves a post-crash fire which usually results from a major fuel spill outside the aircraft. Since preventing ignition was not a major consideration of the project for post-crash fires, the emphasis on model development resulted in development of the Post-Ignition tool shown in Figure 2. This format for analysis was particularly useful for placing a value on the extra time provided by an alternative considering the extra escape time required by the people to evacuate the aircraft. Extra escape time required was derived from an analysis of the circumstances pertaining to each fatality for the historical set of accidents. This Post-Ignition Model requires expansion to accommodate the circumstances occurring in in-flight fire scenarios and therefore, a more detailed event tree model has been substituted to account for the expected occurences for in-flight fires.

In-flight fires occur from many causes which are normally easily controlled resulting in only minor damage. However, the few fires which go uncontrolled have caused catastrophic results. The FAA Technical Center is currently evaluating several options designed to address the in-flight fire scenario. Included are fire prevention, earlier detection, smoke control, fire spread limitation and improved suppression. The risk analysis structure presented is capable of providing a framework for evaluating these options for the major scenarios of fires originating within the aircraft cabin.

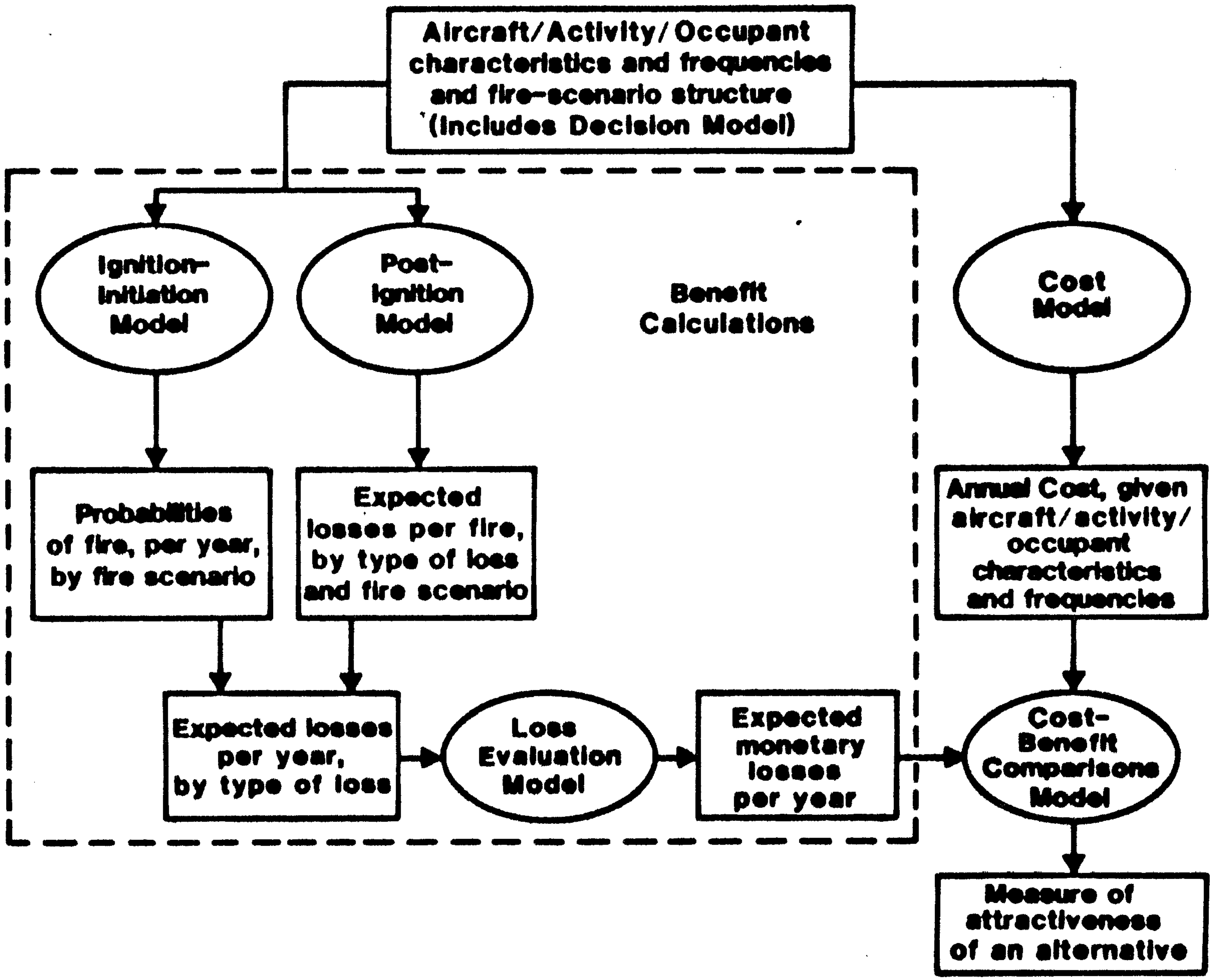


Figure 1. Generic Modeling Framework for Aircraft-Fire ~~Detection~~ Decision Analysis [7]

Note: Persons killed by impact trauma in a crash preceding the fire are not shown.

		Extra Escape Time Provided by Alternative: None	Extra Escape Time Provided by Alternative: Limited	Extra Escape Time Provided by Alternative: Virtually Unlimited
Extra Escape Time Required by Victim	Limited	Fatal fire effects unaffected by alternative, e.g., fire spread primarily along paths not covered by alternative; fatal fire effects not of a kind affected by alternative. Victim mobile and able to escape given time NONE SAVED	Fatal fire effects partially affected by alternative, e.g., fire delayed by alternative. Victim mobile and able to escape given time. SOME SAVED	Fatal fire effects blocked by alternative, e.g., fire suppressed early, prevented completely, or confined to harmless area for indefinite period of time. Victim mobile and able to use extra escape time but does not have to. ALL SAVED
	Virtually Unlimited	Fire effects same as above. Victim unable to use escape time, e.g., stunned, trapped by debris, blocked by unuseable exits, too young, too sick, etc. NONE SAVED	Fire effects same as above. Victim unable to use extra escape time. NONE SAVED	Fire effects same as above. Victim unable to use extra escape time, but that does not matter. ALL SAVED

Figure 2. Compact Post-~~Ignition~~ Crash Display Format for Passenger-Aircraft Fire Fatalities [7]

kilso

AIRCRAFT/ACTIVITY/OCCUPANT CHARACTERISTICS.

Specification of aircraft/activity/occupant characteristics and fire scenarios is intended to: (a) bound the problem by excluding flights and fires that are not within the scope of the study or that would not be affected by the alternative; (b) take account of characteristics that significantly influence either an alternative's likely effect or its cost of adoption; and (c) provide a basis for extrapolating future loss and cost expectations.

DECISION ALTERNATIVES AND FIRE SCENARIOS.

The decision alternatives address the specific configuration and characteristics of the strategies to be applied. Included are details concerning phasing-in, extent of adoption, reliability and degradation in use of the alternatives. For in-flight fire risk analysis, the specific strategies either alone or in combination must be defined prior to using either the ignition-initiation or the post-ignition models. The FAA strategies included for in-flight fire are: fire prevention options which change the expected probability of ignition and thereby reduce the number of fires of the type related to the prevention measure. For example, actions to screen passengers to prevent flammable liquids from being brought on-board will reduce the incidence of fires caused by intentional dousing of seats by gasoline or by other flammable liquids.

The historical fire incident records indicate component/system malfunctions which have caused minor fires. Requiring corrective actions may prevent ignitions which under rare circumstances could lead to catastrophic fire. This may apply either to specific aircraft models where problems can be identified by SDR's or NTSB reports or to all aircraft when a generic problem (e.g., cigarette ignitions in lavatories) has been identified.

The FAA is also considering options designed to change the intensity of fires once they occur thereby limiting the fire's impact on life loss. Included are several classes of options such as:

- Control of fire spread by specification of performance criteria for aircraft cabin lining materials.

- Promote earlier discovery of fires by requiring detectors (type and placement to be specified).

- Provide better suppression of fires by requiring hand-held extinguishers be of a specific type (CO_2, H_2O, halon 1211 or 1301) and number, or requiring automatic suppression type and location to be specified.

- Control products of combustion (smoke and toxic gasses) either by procedures for venting and changing pressurization of the cabin or by use of special equipment (e.g., barriers) modifying aircraft ventilation patterns.

The decision alternative defines the portion of the fleet to be effected and specifies the mitigation strategies to be considered, when they will be in service, and their reliability. This forms the basis for the analysis of ignition-initiation and post-ignition changes which result in quantification of the risk reduction.

Figure 3 illustrates a possible set of decision alternatives and fire scenarios for in-flight fires. Decision alternatives are the actions which the FAA can implement to reduce the expected number of fatalities. A decision alternative must be defined in sufficient detail to allow analysis of its effectiveness in reducing the number of fires, changing the fire's growth and spread or improving passenger survival by other means. Other details related to an alternative implementation include: timing, which aircraft are included and expected compliance. The status quo is included as an alternative and represents what is expected under current operating conditions within the current regulatory environment.

Scenarios are generated by using all available information to develop for the status quo an exhaustive set of significant fires. Heavy reliance is placed on the data sources discussed in the first part of this report. Although it is not possible to capture every possible circumstance leading to a fire, the rare occurrences are either added in with more common scenarios or another class of scenarios is added called "all others" [8]. Since narrow and wide body aircraft exhibit significant differences in fire development, ignition sources, flight patterns, and passenger volume, a set of scenarios and subsequent analysis of the consequences of fire spread are developed for each generic aircraft type. Because the phase of flight influences many factors which relate to ignition, time required to land and evacuate, ventilation and pressurization, etc., which affect the fire or its consequences, phase of flight is another element treated explicitly in scenario generation. Now given an aircraft type and a phase of flight, the fire experience data, inspection reports and expert judgment are used to develop by location in the aircraft an exhaustive set of fires. Those fires which are similar with respect to rates of growth, response to suppression, ventilation, and mitigation actions to be analyzed can be combined to simplify the analysis. The rates of fire development and detection are the final two factors shown in Figure 3 for scenario generation.

IGNITION-INITIATION MODEL.

The ignition-initiation model provides the structure to compute the differences between the historical baseline probabilities of fire and the probabilities expected if the alternative(s) are present. Alternatives which are intended to limit damage once a fire is present do not generally change the ignition probability. However, actions which act on ignition sources (e.g., correcting component or system failures) or reduce the likelihood of materials to ignite from known ignition sources do change ignition probabilities.

The expected change in ignition probabilities from specific actions intended to correct system or component failures, which have resulted in fires, can be calculated using fault tree analysis [9]. Fault tree construction starts with assessing the basic events which initiate a chain of events which determine how a given system failure can occur. Mechanical/electrical systems are subject to failures which can result in ignition of materials within aircraft.

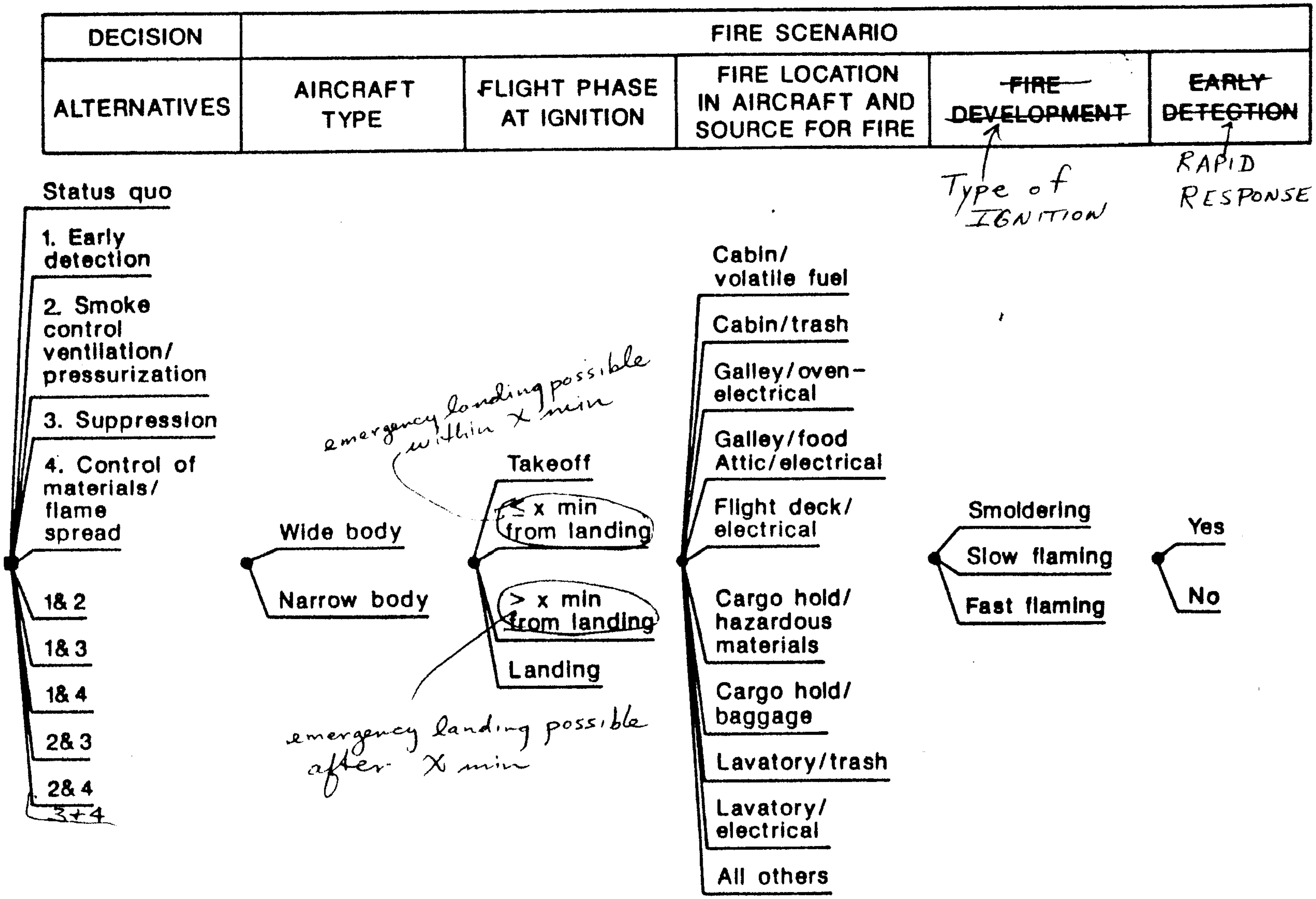


Figure 3. Decision and Fire Scenario Model
(Input to Fire Spread and Growth Model)

The classical use of fault tree analysis has concentrated upon this type of problem.

The issue of the influence of a material's ignition potential from known ignition sources may also be evaluated using the fault tree technique [10] to calculate the probability of ignition of a particular item from the three general types of ignition (smoking, flaming or radiant sources). Figure 4 indicates that self-sustained burning (the top event) can occur from either self-sustained flaming or self-sustained smoldering. The symbol △ in Figure 4 is an OR gate which indicates that either sub-event will cause the top event to occur. At the base of the tree in Figure 4 (IC2), a specific flaming source is ~~also~~ the top event in Figure 5 and shown as possibly occurring by any one of the three sub-events - due to malfunction, misuse of the heat source, or misuse of the fuel item.

The flaming source occurs when any of these three sub-events occur and the item to be ignited is present. The △ symbol is an AND gate, which indicates both must occur to initiate the event. A critical dependent condition (indicated by the ◇ symbol) involves a lack of separation between the ignition source and the item ignited. The conditional criteria of critical distance is introduced, which depends upon the characteristics of the ignition source (heat flux) and those of the item ignited (ignitability). These characteristics may be evaluated in laboratory tests to quantify values not directly available from incident/accident reports. Mitigation strategies which impact ignition by preventing certain types of fire scenarios may require use of fault tree analysis to quantify their impact.

POST-IGNITION MODEL.

The Post-Ignition Model has been structured to facilitate the computation of expected losses per fire for a specific scenario. Like the Ignition-Initiation Model, the Post-Ignition model takes as a starting point the historical losses per fire, given a fire scenario and aircraft/activity/occupant characteristics. The status quo is assumed to be unchanged except for the influence of intervening fire strategies. To the extent that other factors may be influencing expected fire deaths, they too should be assessed. Post-Ignition Model is based on a critical event sequence or tree. A critical event for in-flight fire scenarios is marked by a significant change in the condition of the fire, the status of the fire protective features or systems, fire-related activities, or the conditions of persons exposed to the fire. Therefore, construction of the event tree is scenario specific and must be based upon an understanding of the sequence of events which causes fatalities - either through loss of control of the aircraft and subsequent crash, or through development of the fire to the point where untenable conditions are reached and either a crash occurs or upon successful landing only a part of the aircraft occupants are able to escape. Furthermore, the event tree must enable the analysis to be focused on losses that occur after an alternative activates and, therefore, would be reduced or eliminated if that intervention strategy were in place.

The status quo losses are distributed to scenarios by determining from fire experience (major and minor in-flight fires), expert judgment and the current operating environment the probability that a particular location/source is involved. Given that a location/source is involved, the phase of flight at

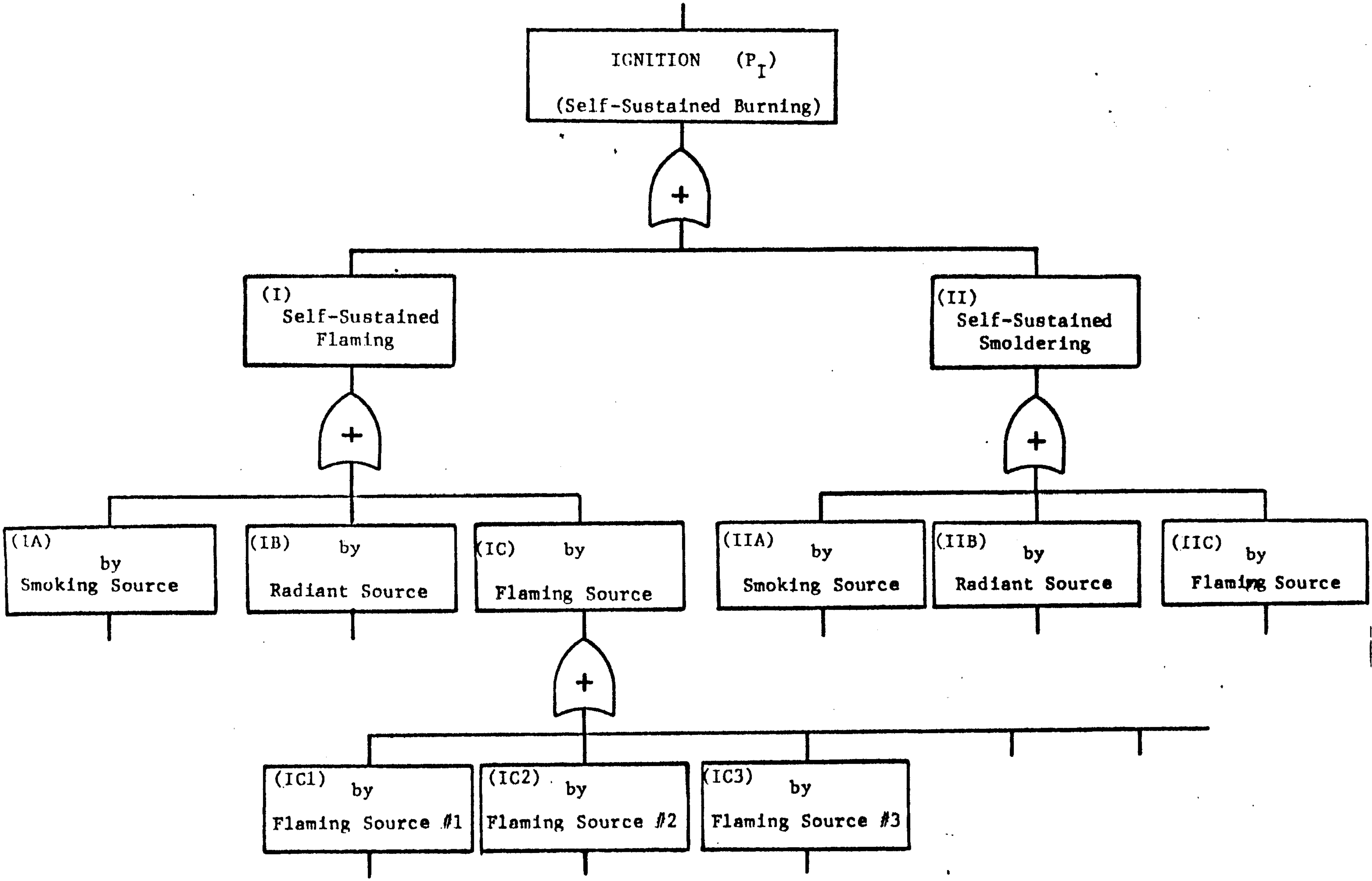
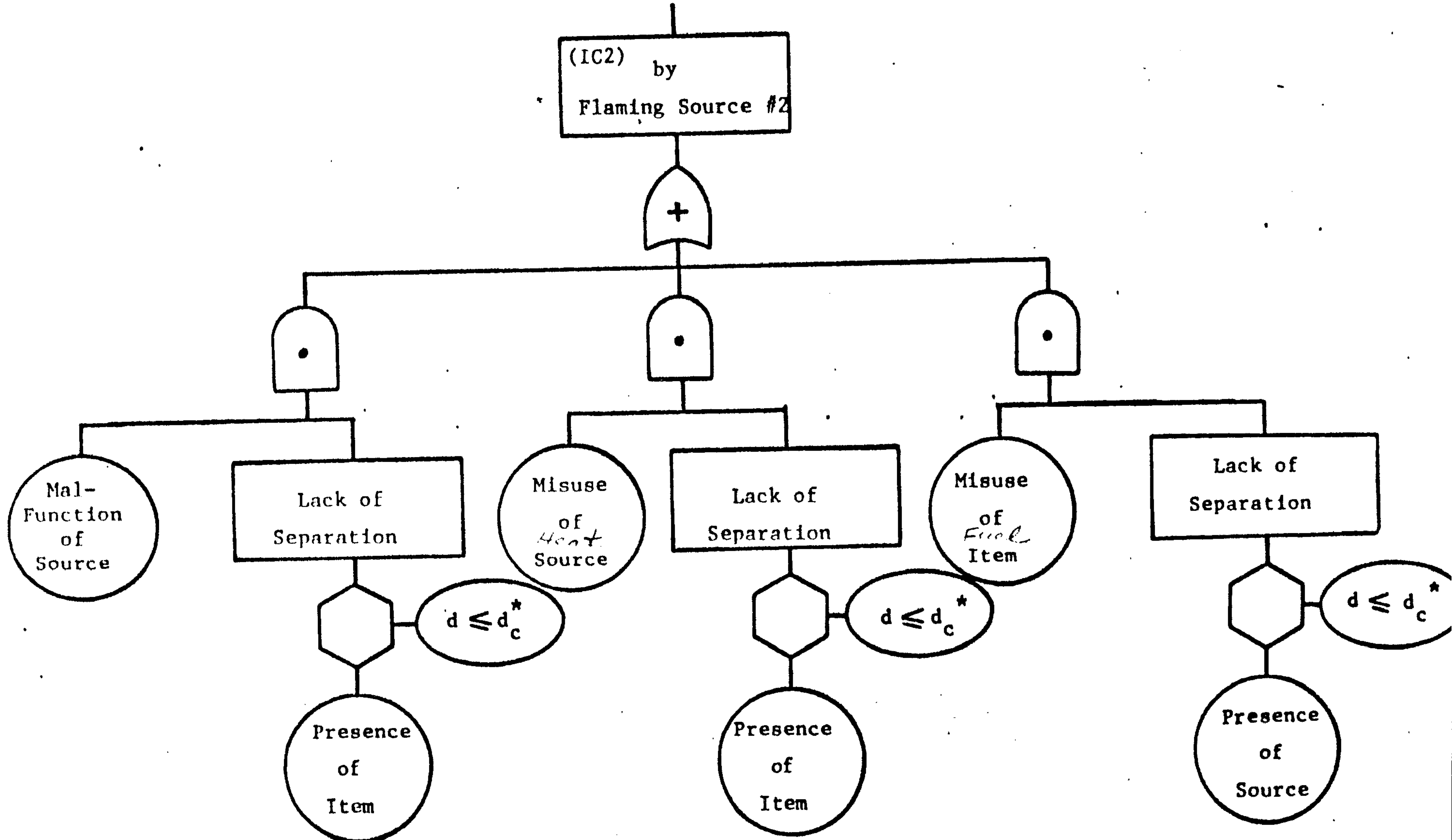


Figure 4. Fault Tree for Ignition (General) [10]



*d = Item-Source Separation
d_c'= Critical Separation

Figure 5. Fault Tree for ignition by flaming or radiant source