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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

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Aircraft Fire Safety

NORTH ATLANTIC TREATY ORGANIZATION

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THEME

Although the safety standards in aviation are already very high, the risk of accidents which involve fires cannot be completely excluded. It is therefore necessary to strive continuously for the enhancement of fire safety in aviation. One of the main aspects in this problem area is to review fire-related accidents and to learn from them in order to improve safety regulations and to update relevant research programmes. Additional information is taken from studies of aircraft internal and external fires, both full-scale experimental and by numerical modelling of cabin fires where the latter is receiving growing attention. The practical conversion of such knowledge into fire-hardened designs of aircraft, both military and civil, is another aspect of the problem area, where advanced materials and improved structural designs represent the main lines to be pursued towards improved fire safety. Finally, growing interest is placed into the increase of survival times of passengers by means of improved passenger protective methods, concerning not only civil but also military transport aircraft.

* * *

Quoique les normes de sécurité applicables dans le domaine de l'aviation soient déjà très rigoureuses, les risques d'accidents survenant à la suite d'incendies ne peuvent pas être totalement exclus. Un effort permanent doit donc être consacré à l'amélioration des mesures de sécurité dans ce domaine. L'une des principales tâches qui s'imposent en ce qui concerne la recherche d'une solution à ce problème consiste à examiner différents cas d'accidents dus à des incendies pour en tirer des leçons, ce qui permettrait d'apporter des améliorations aux règlements de sécurité et de mettre à jour les différents programmes de recherche. Un supplément d'informations est extrait d'études d'incendies d'avions internes et externes, à la fois à partir d'expérimentations en grandeur réelle et à partir de simulation numérique de feux de cabine, cette dernière faisant l'objet d'une attention grandissante. La traduction pratique de telles connaissances en des conceptions d'avions durcis contre le feu, tant civils que militaires, est un autre aspect de ce même problème, où les matériaux de pointe et les conceptions structurelles améliorées représentent les grands axes de développement vers une meilleure sécurité contre l'incendie. En conclusion, de plus en plus d'intérêt est manifesté dans la prolongation de la durée de survie des passagers au moyen de méthodes de protection améliorées, portant non seulement sur les avions civils mais ausi sur les aéronefs militaires de transport.

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CONTENTS

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Reference

INVESTIGATION AND CHARACTERISTICS OF MAJOR FIRE-RELATED ACCIDENTS IN CIVIL AIR TRANSPORTS OVER THE PAST TEN YEARS

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SUMMARY

This paper will summarize a number of fire-related accidents and incidents that have occurred during the present decade. The selection of accidents/incidents was based on information availability and perceived importance of those chosen. A brief summary of accident data for the past ten years is presented. A methodology is shown for logically calculating the effects of cabin fire safety improvements on survivability utilizing past accidents. Eight accidents and four incidents are discussed and their link to safety improvements is described. The paper concludes with a call for better information from accident investigations.

INTRODUCTION

In 1987, the Federal Aviation Administration (FAA) developed a computer model for calculating the benefits of fire safety improvements. This calculation is based on a detailed analysis of past accidents (1). The model is based on the manipulation of two curves, one being the mobility and the other being the fire hazard.

The mobility rate profile describes the loss in passenger mobility due to physical effects. They could include the number of usable exits, poor visibility due to smoke or inadequate lighting, or blockage of the aisles by passengers or debris.

The thermal hazard profile is based on the buildup of hazard that could cause incapacitation, such as heat, toxic gases, oxygen depletion, and smoke or direct exposure to flames.

It is recognized that the output from the model is based on the subjective input of the operator. The model itself makes no assumptions regarding an accident, it only supplies a logical framework for analyzing the input of the operator. This methodology was employed by the Civil Aviation Authority (CAA) of the United Kingdom (2) for analyzing the safety benefit of smoke hoods.

Table 1 lists the major transport accidents (in-flight and survivable postcrash) having reported fire fatalities during the last ten years (1,2,3).

TABLE 1

Civil Transport Aircraft Accidents (1979-1988) With Fire-Related Deaths or Destruction of the Aircraft by Fire

	Date	Carrier	Place of Accident	Type of Aircraft	Number of Passengers	Number of Fatalities
1	3/13/79	Alia	Doha	B-727	64	44
2	4/26/79	Indian Airlines	Madras	B-737	67	0
3	10/7/79	Swissair	Athens	DC-8	154	14
4	2/27/80	China Airlines	Manila	B-707	135	2
5	8/19/80	Saudia	Riyadh	L-1011	301	301
6	11/4/80	TAAG	Benguela	B-737	134	0
7	11/19/80	Korean	Seoul	B-747	226	15
8	11/21/80	Continental	Yap Island	B-727	73	0
9	2/17/81	Air Cal	Santa Anna	B-737	110	0
10	7/27/81	Aeromexico	Chihuahua	DC-9	66	30
11	3/17/82	Air France	Sanaa	A-300	124	0
12	8/26/82	Southwest	Ishigaki	B-737	138	0
13	9/13/82	Spantax	Malaga	DC-10	393	51
14	3/11/83	Avensa	Barquisimeto	DC-9	50	23
15	6/2/83	Air Canada	Cincinnati	DC-9	46	23
16	6/11/83	United	Chicago	B-727	142	0
17	7/2/83	Altair	Milan	Caravele	89	0
18	12/7/83	Aviaco	Madrid	DC-9	42	42
19	12/7/83	Iberia	Madrid	B-727	93	51
20	12/18/83	Malaysian	Kuala Lumpur	A-300	247	0
21	3/10/84	UTA	Ndjamena	DC-8	23	0
22	3/22/84	Pacific Western	Calgary	B-737	119	0
23	8/30/84	Air Cameroon	Douala	B-737	118	2
24	10/13/84	Cyprus Airways	Zurich	B-707	10	0
25	8/22/85	British Airtours	Manchester	B-737	137	55
26	11/30/85	Mandala	Medan	L-188	45	0
27	11/28/87	South African	Indian Ocean	B-747	161	161
28	8/31/88	Delta	Dallas	B-727	108	14

Based on factual information and test data, a likely fire scenario is as follows: Shortly after takeoff a fire developed in cargo in the C-3 compartment. The fire could have been started by a cigarette left on a bag, matches igniting in a bag or other small ignition sources. A smoke detector in the compartment activated, sending a warning to the cockpit. Smoke began drifting into the aft cabin through the floor grills. Detectors in the compartment became oversaturate with smoke, causing the alarm in the cockpit to go out. The flight engineer inspected the cabin and returned, stating there was smoke in the aft. By then the pilot had turned the aircraft and was returning to Riyadh.

The fire in the cargo compartment had burned through the cargo liner and impinged on the cabin floor, fanning out between the cargo compartment ceiling and the cabin floor. The heat melted the pulleys for the number two throttle cable. Oxygen was consumed in the cargo compartment and the fire subsided in the compartment. As the pulleys cooled, the plastic hardened and the number two engine throttle stuck. Air was then drawn into the compartment through the hole as it cooled, until the flames began again. This time the fire entered the cabin through the floor. Passengers in the aft section were moved forward in the cabin. Flight attendants fought the fire with handheld extinguishers. The fire cycled from flaming to smoldering a number of times.

As the plane began its final approach, the airflow to the cabin was turned off and the outflow valves were closed. At that time, little or no smoke was observed in the forward cabin or on the flight deck. The flight crew were convincing themselves that there was no big problem. Upon landing, the crew took the aircraft to the end of the runway and onto the taxiway before stopping. The flight crew did not use smoke masks in the cockpit. The flight crew reported to the tower that they were beginning an evacuation. However, back in the cabin, as the plane touched down, the flames had impinged on the seats above the C-3 cargo compartment and began to spread. Because the airflow was shut off and the fuselage was closed up, the combustible gases collected at and above the ceiling. Before the evacuation could begin, a flash fire occurred. Flames shot forward at and above the ceiling, producing large amounts of gases and consuming most of the oxygen. All of the 301 passengers and crew were quickly incapacitated and were soon dead.

This accident led to rule changes in the area of cargo compartment fire protection (7). Tests showed that had the seats been fire blocked, they could have stopped the spread of fire from the cargo area to the cabin and prevented the flash fire.

2. Korean Airlines, November 19, 1980.

A Korean Airlines 747 landed short of the runway at Seoul, Korea, causing the main landing gear to collapse into the cargo compartment aft of the gear. The aircraft slid approximately 7,000 feet down the runway before stopping. A fire began in the ruptured cargo compartment from sparks igniting the strut fluid and cargo in the compartment. As the aircraft came to a stop, the fire spread up into the cabin through the air grills and through ruptured cargo liners and the cabin floor. Of the 208 passengers and 18 crew members, 15 (9 passengers and 6 crew members) did not survive (figure 3).

The important fact concerning this accident was that there was no jet fuel involvement in the fire (the tanks remained intact). The major contribution to survivability was from the burning of the interior materials. This accident changed the minds of many people who believed that the fuel fire dominated the fire hazards in all aircraft accidents and that material improvements would not substantially improve aircraft safety.

3. Spantax, September 13, 1982.

A Spantax DC-10 aborted a takeoff and overran the runway in Malaga, Spain, stopping in a field just off the airport. The right wing was torn off the aircraft and a large fuel fire encompassed the aft end of the fuselage (aft of the wings). The fire entered the cabin in the aft areas through tears in the fuselage and burnthrough of the skin. There were 51 fatalities out of the 393 occupants.

This accident pointed out the problems of evacuation. Evacuation was slowed by debris in the aisles and some passengers failed to begin evacuation because of emotional trauma. The fire burned into the cabin in a very rapid manner. This accident also pointed out the problem that the crash fire rescue crews have in extinguishing a cabin fire. Photographs (figure 4) show that the fuselage was almost fully intact when the first trucks arrived and extinguished the external fire; however, the fire in the cabin almost totally consumed the fuselage before it was extinguished.

4. Air Canada, June 2, 1983.

An Air Canada DC-9 experienced an in-flight fire in the area of the left aft lavatory. The fire produced heavy smoke in-flight and progressed very rapidly after the aircraft landed. Twenty-three of the forty-six occupants were able to egress before a flash fire occurred (figure 5).

Investigation into this accident indicated that a fire started in the hidden area of the aft lavatory (figure 6). The actual ignition source or fuel was not determined. It could have been electrical in nature or it could have been caused by a cigarette and trash behind the vanity area. The fire spread rapidly to the aft seats after the aircraft landed (figure 7). Many of the passengers attempted to use some form of protection against the smoke (wet towels, clothing, etc); however, there seems to be no correlation between attempts at smoke protection and survivability.

To estimate the number of added survivors we can utilize the model from reference 1. Knowing that the last person exited at about 4 minutes 20 seconds, and because of the breakage in the fuselage and trauma caused by impact, it was estimated that the full evacuation began 30 seconds after stopping, with a few passengers near breaks evacuating in the 15 to 30 second range. Figure 13 shows the curves developed for this accident. The same figure also shows the curves developed under the assumption of no fire blocking (using an evacuation time of 2 minutes 50 seconds). In that case, the total survivors would have been 57. Therefore, the calculated number of lives saved due to fire blocking was 37.

INCIDENTS

In many cases, the difference between an accident and an incident is pure luck. The probability of the next aircraft accident having similarities to a given past incident are the same as the probability of similarities to a given past accident. It is therefore extremely important that all incidents, considered aircraft or life-threatening, be investigated, analyzed, and understood. It should be noted that because of the limited damage in some incidents, much more information concerning the start and spread of a fire can be learned than in an accident. The following are examples of incidents that have led to research and/or safety improvements in aircraft:

1. UTA - Paris, France.

A fire ignited in the lower area of the forward cargo compartment of a UTA 747 as maintenance personnel were cleaning rollers and track in that compartment. The cleaners had some rags and cleaning solvent in the compartment at the time. The maintenance personnel tried to fight the fire and notified CFR. The fire spread rapidly around the cargo liners and up into the cabin. The oxygen system was breached causing a localized, high intensity fire. By the time the fire was extinguished by the CFR, both the main deck and upper deck cabins had been gutted by fire (figures 14, 15, and 16).

Investigators found that the fire in the cargo compartment destroyed many seams, joints, and fastening systems allowing liners to fall and provide paths of fire egress from the compartment (figure 17). The fire also spread up around the bottom cargo liner seal on the thermal insulations' outer covering. Flames entered into the cabin through the floor grills in the passenger cabin.

This incident was a major force in including seams, joints, and fasteners in the new testing requirements for class "C" and "D" compartments. The requirement for cargo lining material on the lower sidewall of the cargo compartment was also an outgrowth of this incident.

2. ATA - Chicago, Illinois.

A fire ignited in the forward cargo compartment of a DC-10 as cleaners were servicing the cabin area. The fire was started in a container by an activated solid oxygen generator (the generator had accidentally been activated by a mechanic who a few minutes prior to the fire had entered the compartment and container in search of a replacement seat back) in contact with some bubble plastic wrap. The fire spread quickly, with seams, joints, and fastening systems failing, causing cargo liners to fall and the fire to gain access to the cabin area through the floor. By the time the CFR personnel extinguished the fire it had destroyed the aircraft, burning through the fuselage along the top (figures 18, 19, and 20).

Besides reemphasizing the same problems as seen in the UTA incident, concern was focused on solid oxygen generators and their safety.

3. Jordanian Airlines - Singapore.

A Jordanian Airline L-1011 experienced an in-flight fire while at 24,000 feet approaching Singapore Airport. The flight crew experienced electrical faults and an overheat warning in the cheek-area adjacent to the C-3 cargo compartment. Shortly thereafter, a fire warning occurred for the number two engine. Smoke began pouring into the aft cabin, and flames were seen entering the cabin through a floor grill in the aft left side. A flight attendant reported firing a Halon extinguisher at the flames and they disappeared. At about 14,000 feet, the aircraft experienced a sudden depressurization. The smoke subsided in the cabin, and the aircraft landed with no further problems.

Investigation revealed that a fire began with an arc from a power feeder cable to a titanium bleed air duct. The titanium, ignited and fed by the 400 °F bleed air which exited the ruptured duct, continued to burn. A 3-foot length of duct was consumed in the incident. The hot air and molten titanium (3200 °F) then ignited some epoxy/fiberglass ductwork in the area, and the gases produced by the overheated resins caused the fire to spread around the aft pressure bulkhead and into the overhead. Fire impingement on the aft pressure bulkhead melted and shorted wiring, causing the number two engine fire warning, and then causing a rupture of the bulkhead and depressurization of the cabin (figures 21 and 22). Since most of the burning was on the surfaces of materials and gases produced, the sudden rush of air due to the hole in the bulkhead blew the fire out. Luck was with this flight for, as shown in figure 23, the main fuel line running just under the cabin floor, was almost penetrated by fire just forward of the aft pressure bulkhead. What if the fire had started at a higher altitude, further from an airport, or the pressure bulkhead had not burned through?

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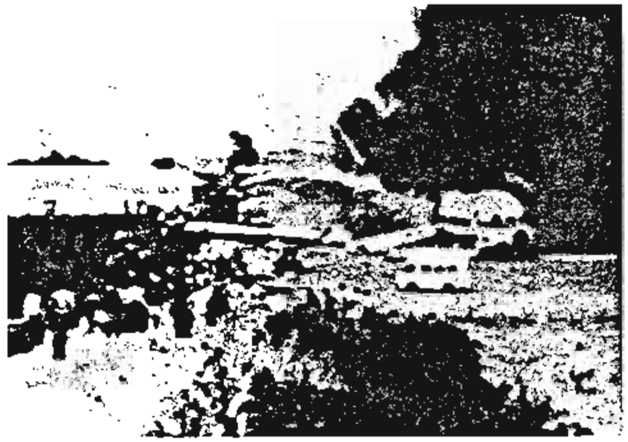

Figure 4. Spantax DC-10 on fire (photo by passenger).

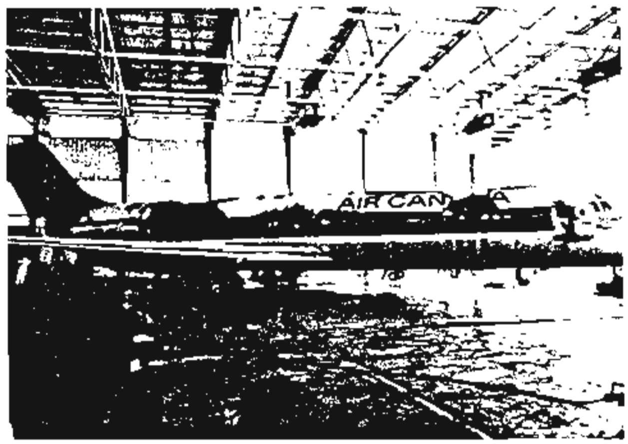

Figure 5. Right side view of Air Canada DC-9 after in-flight fire.

Figure 6. Left, aft lavatory (area of fire origin), Air Canada DC-9.

Figure 10. Aft right side of Delta 727.

Figure 11. Aft left side of Delta 727.

Figure 14. Outside view of UTA 747 after ramp fire.

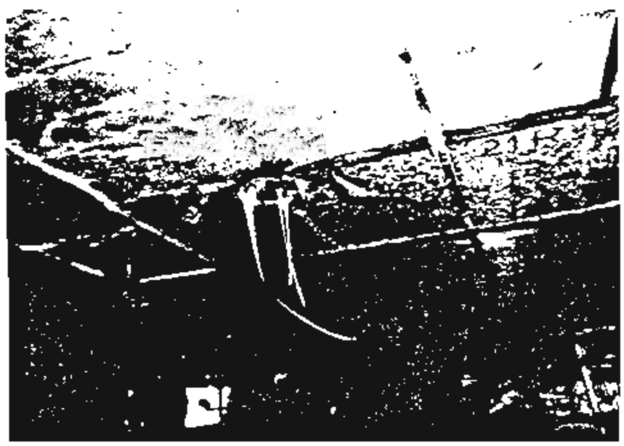

Figure 15. Cargo ceiling with fixtures, UTA 747.

Figure 16. Upper deck view of UTA 747.

Figure 20. Cargo and cargo liner damage, ATA DC-10.

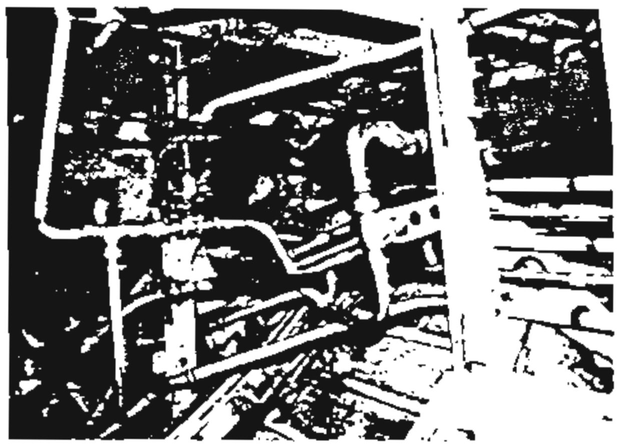

Figure 21. View of the check area adjacent to C-3 cargo compartment, Jordanian Air L-1011.

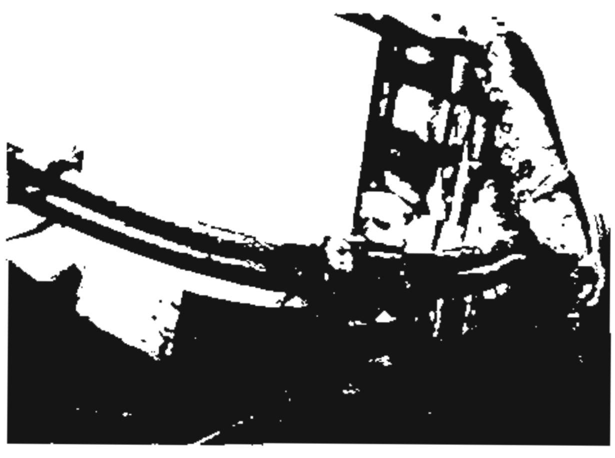

Figure 22. Arced power cable, Jordanian Air L-1011.

(40% or 100%) seems to have no effect on the proportion of people who die. So maybe we do have enough doors or maybe we need to know more of the psychology of evacuation.
Not mentioned so far, but a finding in the AAIB report on the Manchester accident, is that very slight winds can have a dramatic effect on the fire. Amongst their recommendations is one to fit external video cameras to give the crew a view of the aircraft fire and smoke on a cockpit monitor.

AIRCRAFT FIRE SAFETY
LEARNING FROM PAST ACCIDENTS

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The real value of aviation occurrence investigations lies in the lessons we can learn from them to eliminate future accidents or reduce their severity. This paper reviews past accidents with emphasis on the Canadian experience (e.g. Pacific Western Airlines B737 at Calgary International Airport in March 1984). The paper differentiates between the determination of contributing factors and causes and the identification of safety deficiencies as practiced by the Canadian Aviation Safety Board. It also includes areas of current concern and topics requiring further research with a view to further improving aircraft fire safety.

"Why do we investigate aircraft accidents and incidents?" One common answer to the question is: "To determine the cause(s) and prevent recurrence". I contend that such an answer is incorrect - or, at least, inappropriate. First, from purely a safety perspective, the determination of causes has little direct value. The value of investigation lies in the identification of safety deficiencies which then can be reduced or eliminated. Secondly, preventing a recurrence of a given accident is not a worthwhile objective because it is highly improbable that the exact sequence of events which led to that specific accident will ever be repeated. Finally, since (by definition) aviation incidents do not involve extensive damage or serious injuries, preventing incidents achieves relatively small economic benefits. Returning to the question: "Why do we investigate accidents and incidents?", a much better response is "To advance aviation safety by identifying safety deficiencies and determining ways to eliminate or reduce those deficiencies." This latter response comes from the legislation which established the Canadian Aviation Safety Board (CASB).

The difference between these two viewpoints is not just a matter of semantics. It is easy to become pre-occupied with cause-determination and to lose sight of the true objective of advancing safety. Sometimes, the most valuable lessons from an aviation occurrence have little or nothing to do with the cause factors. To illustrate this point with a hypothetical example, let's assume that an aircraft went out of control and crashed on approach to an airport. The investigation determines the cause to be pilot incapacitation from a heart attack. However, when analyzing the wreckage, the investigators also find a serious fatigue crack in the main wing-spar. Inspections of other aircraft reveal similar cracks. Obviously, the principal safety benefit lies in the actions which can be taken to detect and correct such cracks and so prevent other accidents caused by structural failure.

The focus on reducing or eliminating safety deficiencies is particularly relevant for this symposium. Aircraft fires are, fortunately, very rare events; and they are even more rare as the cause of an accident. However, when they do occur, they can turn a relatively minor accident into a catastrophe. Furthermore, for the occupant inside a burning aircraft, it is absolutely irrelevant whether the fire was the cause of the accident or a result. If we can take action to reduce the probability of a fire, to reduce its severity, or to increase the probability of successful evacuation, we are advancing aviation safety.

As mentioned above, aircraft fires are rare events. In fact, for the period from 1980 through 1988, and excluding one case involving torching in the APU, the CASB database contains only two such accidents involving Canadian-registered passenger aircraft of over 12,000 kilograms (i.e. larger than a DC-3). The first of these involved an Air Canada DC-9 at Greater Cincinnati International Airport on 2 June 1983. The second was a Pacific Western Airlines Boeing 737 at Calgary International Airport on 22 March 1984.

Apart from the fact that both aircraft were totally destroyed by fire, these two accidents have very little in common. However, both yielded significant safety messages.

As the Air Canada accident occurred in the United States, the investigation was conducted by the U.S. National Transportation Safety Board (NTSB). The synopsis from the NTSB's final report is as follows:

> "On June 2, 1983, Air Canada Flight 797, a McDonnell Douglas DC-9-32, of Canadian Registry C-FTLU, was a regularly scheduled international passenger flight from Dallas, Texas, to Montreal, Quebec, Canada, with an en route stop at Toronto, Ontario, Canada. The flight left Dallas with 5 crew members and 41 passengers on board.
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> "About 1903, eastern daylight time, while en route at flight level 330 (about 33,000 feet m.s.l.), the cabin crew discovered smoke in the left aft lavatory. After

attempting to extinguish the hidden fire and then contacting air traffic control (ATC) and declaring an emergency, the crew made an emergency descent and ATC vectored Flight 797 to the Greater Cincinnati International Airport, Covington, Kentucky.

"At 1920:09, eastern daylight time, Flight 797 landed on runway 27L, at the Greater Cincinnati International Airport. As the pilot stopped the airplane, the airport fire department, which had been alerted by the tower to the fire on board the incoming plane, was in place and began firefighting operations. Also, as soon as the airplane stopped, the flight attendants and passengers opened the left and right forward doors, the left forward over-wing exit, and the right forward and aft over-wing exits. About 60 to 90 seconds after the exits were opened, a flash fire engulfed the airplane interior. While 18 passengers and 3 flight attendants exited through the forward doors and slides and the three open over-wing exits to evacuate the airplane, the captain and first officer exited through their respective cockpit sliding windows. However, 23 passengers were not able to get out of the plane and died in the fire. The airplane was destroyed.

"The National Transportation Safety Board determined that the probable causes of the accident were a fire of undetermined origin, an underestimate of fire severity, and misleading fire progress information provided to the captain.

"The time taken to evaluate the nature of the fire and to decide to initiate an emergency descent contributed to the severity of the accident."

This was not typical of an aircraft fire occurrence - particularly in that an in-flight fire was the lead event in the accident sequence. For those on board, the elapsed time of only 17 minutes from the discovery of what was initially thought to be a minor fire in a lavatory until the emergency landing at Cincinnati must have seemed like an eternity. During that time, the conditions inside the aircraft became increasingly unbearable. Though the NTSB determined that the crew's response time contributed to the accident severity, their report also had the words of praise: "Considering the conditions which confronted the captain during the descent and landing, the Safety Board concludes that the captain exhibited outstanding airmanship without which the airplane and everyone on board would certainly have perished." Unfortunately, fully half of the 46 did perish and, had it not been for the Crash Fire Rescue service, more lives would have been lost. A flash fire engulfed the cabin within 60 to 90 seconds after the exits were opened, and the aircraft was quickly destroyed.

It is noteworthy that, at no time, from the initial awareness of smoke coming from the lavatory until the flash fire just as the last survivor had exited, did anyone see the actual fire. The NTSB could not identify the precise origin of the fire, but it was able to determine that it had burned undetected for almost 15 minutes before smoke was noticed and for almost 20 minutes thereafter.

In its report on the accident, the NTSB reiterated a number of earlier Safety Recommendations relating particularly to fire prevention, detection, and suppression. It also issued six new Recommendations to the FAA as a direct result of this accident. Parallel action was taken in Canada. Indeed, the first three Aviation Safety Recommendations of the CASB (which became fully operational on 1 October 1984) were similar to NTSB Recommendations A-84-76 through A-84-78. Specifically, the CASB recommended to the Minister of Transport:

- that the training programs for Canadian Air Carriers be reviewed and amended where necessary to emphasize requirements:
  - a) for flight crews to take immediate and aggressive action to determine the source and severity of any reported fire and, if the source and severity of the fire are not positively and quickly determined or if immediate extinction is not assured, for the aircraft captain to begin emergency action so as to effect a landing at the earliest appropriate time;
  - b) for flight attendants to recognize the urgency of informing flight crews of the location, source, and severity of any fire or smoke within the cabin;
  - c) for both flight crews and flight attendants to be knowledgeable of the proper methods of aggressively attacking a cabin fire including hands-on-training in the donning of protective breathing equipment, the removal or penetration of interior panels without risk to essential aircraft components, and the discharge of an appropriate hand fire extinguisher on an actual fire. (CASB 84-01)
- that accessibility to potential cabin fire sources be improved, e.g. through installation of additional inspection panels or through identification by an acceptable and standardized means of those interior cabin panels of transport category airplanes, including panels of lavatories and the galleys, which can be safely removed or penetrated. (CASB 84-02)
- that the appropriate manuals be amended to include comprehensive discussions and illustrations showing the proper use of a fire axe and the location in each model of aircraft where an interior can be removed or penetrated safely to gain access to a fire or smoke emission source. (CASB 84-07)

Both organizations were generally satisfied with the responses received from the regulatory authorities in their respective countries. In addition, safety improvements are continuing to be made as a result of this and other accidents involving cabin fires. For example, on January 12, 1989, the FAA issued an NPRM (Notice of Proposed Rule-Making) related to external signaling from lavatory smoke detectors, hand-held extinguishers in the cabin, and automatic extinguishers in lavatory waste-bins. (It should be noted that the latter had already been installed by Air Canada at the time of the accident.)

As indicated above, the circumstances of the March 1984 Pacific Western B-737 accident were quite different. The accident occurred during the attempted take-off, the fire was external to the aircraft fuselage and was quite visible, and, most significantly, all the occupants managed to escape.

The investigation was started by the former Aviation Safety Bureau of Transport Canada and then taken over by the Canadian Aviation Safety Board upon its establishment over the following six months. The synopsis from the CASB's final report is as follows:

"During the take-off roll, the flight crew heard a loud bang which was accompanied by a slight veer to the left. The take-off was rejected, and all 119 persons successfully evacuated the aircraft when a severe fuel-fed fire developed.

"The Canadian Aviation Safety Board (CASB) determined that an uncontained failure of the left engine thirteenth stage compressor disc had occurred. Debris from the engine punctured a fuel cell, resulting in the fire. The disc failure was the result of fatigue cracking."

The total elapsed time from the compressor disc failure until the last person had exited the aircraft was between four and five minutes. The "History of the Flight" section of the CASB report describes what happened during those four or five minutes:

"Pacific Western Airlines (PWA) Flight 501, a Boeing 737-200 C-GQPW, was to depart Calgary, Alberta at 0730 mountain standard time (MST) on 22 March 1984, on a scheduled flight to Edmonton, Alberta. On board were 114 passengers and a crew of 5.

"Take-off was begun at 0742 from the intersection of runway 34 and taxiway C-1. About 20 seconds into the take-off roll, at an airspeed of approximately 70 knots, the flight crew heard a loud bang which was accompanied by a slight veer to the left. The captain immediately rejected the take-off using brakes and reverse thrust. Both the captain and first officer assumed the noise and slight veer were the result of a blown tire on the left main landing gear.

"The aircraft was quickly brought to taxiing speed. As the speed reduced, the captain decided to taxi clear of the runway at taxiway C-4. Approaching taxiway C-4, both pilots noted that the left engine low pressure unit rpm was indicating 0 per cent. The illumination of annunciator panel lights associated with the loss of electrical power produced by the left engine was also noted. While both pilots were analyzing this new information, the captain continued to taxi and cleared the runway at C-4.

"Twenty-three seconds after the initiation of the rejected take-off, the first officer called clear of the runway on tower frequency. The captain then continued to taxi slowly up C-4 while both pilots continued to question the source of their problem. Forty-five seconds after the initiation of the rejected take-off, the cockpit door was unlocked in response to the knocks of the purser. Upon entering the cockpit, she asked if they had blown a tire. She then stated that there was some fire at the rear of the aircraft. A verbal exchange lasting five seconds ensued in which the captain queried the existence of fire, and the purser elaborated that the fire was "on the back of the wing", "fire on the left wing". During this exchange, there was a brief sounding of the fire bell, and the flight attendant cockpit call chime began to sound repeatedly.

"At the end of this verbal exchange between the purser and captain, the first officer requested confirmation of the fire from the tower. One minute and two seconds after the initiation of the rejected take-off, the tower controller stated that there was "considerable amount off the back - on the left side engine, and it's starting to diminish there. There's a fire going on the left side." Immediately after this the purser further stated that "the whole left-hand side, the whole back side of it is burning", following which, at an elapsed time of 1 minute 11 seconds, the captain advised the purser to prepare for evacuation. About this time, the captain also discharged a fire bottle into the left engine, and the first officer requested tower to dispatch the emergency equipment. He also advised the tower that they had no fire warning. The tower controllers then advised that it would probably be best for the crew to stop the aircraft in its present location. At an elapsed time of 1 minute 33 seconds, the tower controller further advised that flames were coming out the left-hand side of the aircraft.

"Immediately following this transmission, at an elapsed time of 1 minute 36 seconds, the cockpit fire warning bell activated and continued to ring. Simultaneously, the purser re-entered the cockpit and reported that it was getting bad at the back. At an elapsed time of 1 minute 40 seconds, the first officer reported to the tower controller that they now had a fire warning. At the same time, the captain activated the second fire bottle and again directed the purser to prepare for an emergency evacuation. He then stopped the aircraft and, along with the first officer, carried out the procedures for an emergency evacuation.

"At an elapsed time of 1 minute 55 seconds, the flight attendants initiated an emergency evacuation of the passengers, following which the flight attendants and flight crew evacuated the aircraft. Fire consumed substantial portions of the aircraft before being extinguished by airport Crash Firefighting and Rescue (CFR) services."

The investigation quickly identified that the lead event in the accident sequence was an uncontained failure of the left engine thirteenth stage compressor disc. The left engine was extensively fire damaged. The engine case and nacelle were perforated at the one o'clock position when viewed from the rear. This perforation was opposite the thirteenth stage of the high pressure compressor and had been made from inside out. A second perforation was found on the lower surface of the left wing, just inbound and in line with the hole in the engine nacelle. The wing skin had been penetrated and the fuel cell broken. When the high pressure compressor was disassembled, an area measuring about three inches by seventeen inches was missing from the thirteenth stage disc. Two large pieces of the disc, which matched the missing area, were found on the runway about 1300 feet from the starting point of the take-off roll.

A much more difficult task in this investigation was the determination of why the disc had failed. The details are not particularly relevant for the purposes of this symposium. However, it is important to recognize that any uncontained failure in a wing-mounted engine also involves the risk of a serious fire.

The CASB report describes the extent of damage to the aircraft before the fire was finally extinguished.

"The main section of the aircraft, composed of its wings and fuselage forward of the wings, was resting on the nose landing gear, right landing gear, and the left engine. Some of the support structure of the left landing gear had melted away, allowing the left side of the aircraft to settle until the left engine rested on the taxiway. The tail section of the aircraft had burned through at the crown, and the aft fuselage had descended until the tail rested on the ground. It was still attached to the main structure at the bottom.

"The left side of the fuselage sustained smoke and heat damage extending from fuselage station 450 to station 1064. The fuselage had fractured at station 747 and a large section above the window line between stations 747 and 890 was burned away. The right side of the fuselage sustained smoke and heat damage of a lesser nature between stations 480 and 1010.

"The nose area of the aircraft was undamaged, as was the empennage.

"The left front emergency slide was deployed but had deflated because of fire damage. The right front emergency slide was deployed and remained inflated. The right rear emergency slide was deployed and was destroyed by fire. The right over-wing emergency exit window had been removed and was lying on the right wing.

"The right wing sustained heat and fire damage of a minor nature, except for portions of the leading edge devices, spoilers, flaps, and wing undersurface which sustained severe damage. The left wing was extensively damaged from the fuselage out to the wing tip. The leading edge devices and leading edge were almost burned away. All but the leading edge of the aileron was burned away as well. The trailing edge inboard flap and spoilers were burned away and there were numerous protruding surface splits in the upper surface of the wing."

The investigators found pieces of the aircraft structure and left engine on the runway and taxiway. There was also a trail of raw and burnt fuel residues and globules of melted aluminum which continued to the final resting position of the aircraft. In some places, large sheets of fire-damaged aluminum skin and honeycomb material had fallen from the left wing.

Inside the aircraft, heat and smoke damage was evident on the left side windows aft of seat row three. From seat row eight to the break in the fuselage, flame damage had occurred to the interior of the passenger cabin. Windows had melted or burned away, and the fuselage liners and seat upholstery were heavily damaged by fire entering through the window openings. From the break in the fuselage aft to the rear pressure bulkhead, the aircraft interior had been completely gutted by fire.

The fire broke out coincidently with the explosion-type sound which had been heard by people both inside and outside the aircraft. As the aircraft decelerated and proceeded down the runway onto the taxiway, it was trailing flame from the left wing.

The airport CFR crews were immediately notified of the fire by the control tower. Vehicles from the north fire hall reached the aircraft about two minutes after notification, and vehicles from the south fire hall arrived about two minutes later. The CFR crews were able to impede the fire near the exits and so, almost certainly, were a major factor in this being a non-fatal accident. However, extinguishing the fire proved to be very difficult:

"Fire was concentrated in the left wing area between the engine nacelle and fuselage. Dry chemical and foam were expelled into the fire area to control the fire and provide a fire-free escape route for evacuation. The initial positioning of the fire vehicles behind the aircraft and near the left wing tip prevented unrestricted access to the fire, and, as a result, initial attempts to extinguish the fire were not successful. Efforts to combat the fire were complicated by the nature of the fire involved. Fires of this nature are known as "three-dimensional fires" and consist of an elevated fuel source, a running (falling) fire, and a ground pooling fire. Although the fire was substantially knocked down and evacuation routes kept open, the engine nacelle and the wing blocked access from the foam cannons, located on the top of the fire vehicles, to the source of the fire, which was under the left wing, inboard of the engine.

"Fire control attempts were further impeded when one foam truck became mired in the soft ground adjacent to the taxiway, while attempting to move to a more effective position. As a result, time was lost, and the fire-extinguishing agent continued to be applied in a less than ideal fashion. Both foam vehicles ran out of extinguishing agent before the fire could be extinguished.

"Other vehicles continued to apply cooling water, while the foam trucks returned to the fire halls to replenish their water and foam agent supplies. During their absence, the fire significantly increased when the fuel cell vented through the upper surface of the wing. The fire was eventually extinguished by the foam trucks using hand lines when they returned following replenishment."

Those passengers who were seated on the left side of the aircraft near the wing were almost immediately aware of the existence of fire. As the aircraft slowed, several passengers left their seats, and, as more became aware of the fire, a general level of agitation developed. The number two flight attendant seated in the rear of the aircraft heard a passenger yell "fire" within ten seconds of the occurrence; the purser and number three flight attendant both seated at the front of the aircraft, were aware of the fire within twenty-five seconds of its occurrence.

As specified in their procedures for a rejected take-off, the three flight attendants remained in their seats awaiting instruction from the captain. All assumed that, because the aircraft continued to taxi, the captain was aware of the situation and that it was under control. As the fire continued to increase in size, the flight attendants made several attempts to contact the flight crew. The number two flight attendant, seated in the rear of the aircraft, attempted to notify the flight deck of the fire by using the aircraft interphone system. Although the signal tone was heard on the flight deck, it went unanswered because the first officer mistook the tone for that associated with the passenger flight attendant call button. The number two flight attendant continued in his attempts to contact the flight deck and also began to call the front cabin flight attendant station. The purser attempted to enter the flight deck but was unable to do so because the door was locked in accordance with standard company procedures.

About forty-five seconds after the take-off was rejected, the purser entered the flight deck and, after first asking if they had blown a tire, informed the pilots of the fire at the back. She returned to the cabin after having been informed by the captain to prepare for an evacuation. A few seconds later, at an elapsed time of about one minute, the first officer sought and received confirmation of the fire from the tower (but was also told that it was "starting to diminish"). As noted above, the pilots had several additional communications with the tower and the purser over the next 45 seconds while the aircraft continued along taxiway C-4. At an elapsed time of 1 minute and 50 seconds, the flight crew began the shutdown procedure and the aircraft was stopped. The evacuation was started at 1:55 and took an estimated two to three minutes.

The following excerpts from the "Survival Aspects" section of the CASB report describe the conditions experienced by the occupants of the cabin:

"There was no general announcement of the evacuation made by either the captain or the flight attendants. Evacuation commands were given to passengers as they exited the aircraft. The passengers' decisions to leave their seats and evacuate were based on their perceptions of the emergency situation and their observations of the flight attendants opening the exits. Passengers were at the doors awaiting the inflation of the escape slides.

"Four exits were used during the evacuation; these were as follows: main entrance door (left front); galley service door (right front); right over-wing exit; and right rear service door. The main entrance door was opened by the number three flight attendant and the galley service door by the purser. The right over-wing exit was opened by the passenger seated next to it at the urging of several passengers seated nearby. The first few passengers out this exit reported that the escape slide at the galley service door had not yet deployed when they exited the aircraft. The right rear service door was opened by the number two flight attendant.

"Shortly after the evacuation commenced, fire melted windows along the left side of the aircraft. When the windows melted through, heat and smoke entered the aircraft, and the cabin environment quickly deteriorated. Substantial quantities of smoke also entered through the right over-wing exit and right rear service door.

"Conditions within the aircraft cabin were significantly worse in the aft section. Heat was felt as the windows melted through. Those passengers who had been seated beside the windows nearest the fire experienced some singeing of hair and clothing. Smoke obscured visibility almost totally during the latter stages of the evacuation.

"Passenger perceptions in the forward part of the cabin differed markedly from those in the aft. It took much longer for them to be aware of the existence of fire, and, even then, some did not perceive the seriousness of the situation.

"Most passengers chose the closest exit for evacuation. Many stopped to retrieve handbaggage before they left. Those passengers who exited through the main entrance door and galley service door were seated primarily in rows one through seven. Most initially chose to use the main entrance door until the number three flight attendant began directing alternate passengers to the galley service door. The passengers who exited through the right over-wing exit were almost all seated in rows 8 through 16. With only a few exceptions, the rear exit was used by all passengers seated aft of row 16.

"The evacuation was without panic; however, a sense of urgency prevailed. There was some pushing, and several people went over seat backs to get to the exit ahead of others already in the aisle. There was no noticeable yelling or screaming.

"As the evacuation progressed, smoke began to thicken and obscure vision. Smoke conditions were worse in the aft section of the cabin. Passengers who exited via the rear exit reported that they were unable to see the exit and were required to follow the person ahead to locate it. By the time most had reached this exit, the smoke had lowered to about knee height. The bottom portion of the door and the slide were all that was visible. The passenger who was the last one to exit via the over-wing exit reported he had to drop to his knees to breathe fresh air before he was able to reach the exit. Only when he neared the exit, did it become visible through the smoke.

"All passengers who exited via the over-wing exit jumped off the leading edge of the wing. The vertical drop from the wing to the ground is in excess of six feet, and this distance increases as one moves outward from the wing root. Smoke and flames near the trailing edge influenced the passengers to go forward after they had left the aircraft. Most jumped down from the wing inboard of the engine, although several proceeded out the wing before dropping to the ground.

"The rear slide was observed to deflate, because of fire damage, immediately after the number two flight attendant exited the aircraft.

"Four passengers sustained serious injuries during the evacuation. All four exited the aircraft via the right over-wing exit. Three of these passengers sustained bone fractures of varying severity when they jumped to the ground from the leading edge of the wing. The fourth passenger, who was apparently the last person to exit the aircraft, sustained pelvis and rib fractures when he fell to the ground, after slipping on foam on the wing.

"Numerous other passengers sustained minor bruises, cuts, abrasions, and sprains during the evacuation. Some singeing of hair and mild blushing of the skin from heat were also reported. Blood samples were taken from the 29 passengers who reported to hospital. Carbon monoxide levels were minimal when measured, and there were no reports of other toxic substances."

The report noted that the CFR crews were unable to extinguish the fire, because of the location of the hole in the lower wing skin. The foam cannons used were mounted on the top of the foam trucks, making it impossible to get low enough to hit the main source of the fuel and knock down the flames at that point. The fire therefore continued until the left wing fuel cells were almost completely empty.

The CASB made seven "Cause-related Findings", including the following:

- An uncontained rupture of the left engine thirteenth stage compressor disc occurred approximately 1,300 feet into the take-off roll.
- Some stator repair procedures carried out at the last major overhaul were not in accordance with the provisions of the Pratt & Whitney JT8D engine overhaul manual; as a result, deficiencies in the thirteenth stage stator assembly occurred.
- Fuel leaking from the punctured fuel cell was ignited instantaneously.
- The fuel-fed fire increased in size and engulfed the left wing and aft section of the aircraft.

The Board also made nineteen "Other Findings", including the following:

- The flight crew reacted promptly to the abnormality in the take-off run by initiating a rejected take-off.
- The aircraft was not brought to a stop in accordance with the published rejected take-off procedure.

- Communication and coordination between the cabin and the flight deck did not result in an early appreciation of the problem and resulted in a significant delay before the flight crew was aware of the existence and seriousness of the fire.
- Air traffic services personnel were immediately aware of the fire but did not immediately inform the flight crew.
- The flight crew relied excessively on the cockpit fire warning indicators to confirm the existence of fire.
- Published emergency procedures and training did not provide adequate guidance in the event of a general aircraft fire.
- Once aware of the fire, the flight crew did not immediately take appropriate emergency action.
- Most passengers were regular travellers, familiar with the Boeing 737; this contributed to the success of the evacuation.
- The last passengers to evacuate the aircraft evacuated at about the last possible moment.
- The aircraft was not brought to a stop on the runway, thereby limiting the paved manoeuvring space available for the Crash Firefighting and Rescue vehicles.
- Crash Firefighting and Rescue services were hampered by the difficulty encountered by a vehicle traversing the soft, wet terrain.

The CASB has developed a variation on the ICAO format for the "Recommendations" section of an occurrence investigation report. In CASB reports, this section is titled "SAFETY ACTION". This modification permits the inclusion of a description of actions taken subsequent to the occurrence as well as a qualitative description of action required and safety concerns in addition to the traditional "Recommendations".

Under "Action Taken" in this report, the Board made the following observations:

"The Canadian Aviation Safety Board notes that as a result of this occurrence, the air carrier has taken the following corrective action with respect to its Boeing 737 emergency and standard operating procedures:

a) Pacific Western Airlines has instituted combined recurrent emergency procedures training for flight and cabin crews in order to improve total crew coordination during emergencies;

b) Modifications to the service interphone system and cabin to cockpit call lights are underway to allow direct and immediate communication between the flight and cabin crew; and

c) Emergency procedures training now emphasizes the need to stop the aircraft immediately and determine the cause of the rejected take-off. For fires on-the-ground, training puts greater emphasis on visual inspection by opening the cockpit window and by soliciting information from any and all sources."

Under "Action Required", the Board made nine Aviation Safety Recommendations (which were issued to the Canadian Minister of Transport) and re-emphasized the importance of training to ensure rapid and appropriate response, by all parties, to emergencies such as an aircraft fire. Three of the Board's Recommendations dealt with quality control of engine overhaul procedures, better airport emergency procedures for the control of accident survivors, and the need for authorization from the investigator-in-charge before an accident runway is cleared and returned to service. The other six Recommendations were as follows:

- The Department of Transport revise its training syllabus, procedures, and Air Traffic Control Manual of Operations (MANOPS) to require that air traffic services personnel take immediate action to inform the pilots of an aircraft of any observed condition that may adversely affect that aircraft's safety, such as a fire. (CASB 87-02)
- The Department of Transport require that aircraft-on-the-ground emergency procedures and training emphasize the need to stop an aircraft immediately and determine the nature of the emergency. (CASB 87-03)
- The Department of Transport require that emergency procedures and training incorporate coordinated responses by the total crew complement. (CASB 87-04)
- The Department of Transport require that transport category aircraft have a means for the cabin crew to alert the cockpit crew directly and immediately of any critical on-board emergency. (CASB 87-05)
- The Department of Transport require that emergency procedures be implemented for those fires which do not immediately activate on-board fire or smoke detection systems. (CASB 87-06)
- The Department of Transport review current aircraft design criteria with the long-term objective of reducing or eliminating the hazard of uncontained engine components compromising the airworthiness of the aircraft. (CASB 87-07)

Finally, under "Other Safety Concerns", the Board expressed support for Transport Canada efforts to develop improved all-terrain CFR vehicles and made several observations with respect to aircraft cabin safety. The latter, which are of particular relevance to this symposium, are as follows:

"Fires that occur in transport category aircraft continue to provide graphic proof of their swift and catastrophic effect on passengers and crews. The CASB notes that much effort has been expended over the years to improve cabin safety in transport category aircraft, particularly, the recent revisions to Air Navigation Orders (ANO) Series II, Nos. 28, 29, and 30, requiring the installation of fire-blocking materials, floor proximity emergency escape path marking and Halon fire extinguishers in passenger compartments of transport category aircraft. These revisions to ANOs were signed by the Minister of Transport on 06 June 1986, and compliance is required by 31 December 1988.

"While the CASB commends these much-needed advances, fire-related occurrences such as this one confirm the need for further effort. Toxic gases generated by synthetic materials used in aircraft cabins quickly create a lethal environment for passengers and crew of a burning aircraft. Additionally, dense smoke in the cabin reduces visibility and limits survivors' ability to quickly select the best escape route.

"A number of the recommendations put forth as a result of this occurrence seek to improve the emergency procedures used to evacuate survivors and thereby reduce the time passengers and crews are exposed to risk in a burning aircraft. The CASB will carefully monitor such on-going efforts to improve cabin safety, such as passenger smoke hoods, and will consider further safety action to reduce the lethal nature of fires in transport category aircraft."

It is indeed unfortunate that research into potential safety improvements such as fuel additives, improved fire-blocking materials, smoke hoods and aircraft cabin sprinkler systems has been hindered by non-constructive debate and some rigid, even parochial, attitudes. I don't know whether any or all of these would be cost efficient; what is important at this stage is that there be international cooperation in objectively researching all such potential improvements until it can be determined which, if any, are worthy of implementation. To the pregoing list of research topics, one can add: prevention of uncontained engine failures, seat-resistance to "g forces" and other aspects of crashworthiness, carry-on baggage regulations, the appropriate number of emergency exits, and means of improving the reliability of emergency escape slides.

Note that the vast majority of the safety improvements mentioned in this paper are not directly related to accident causes. Certainly, we should contine to attack the causes of aircraft accidents. But, we must never lose sight of the fact that we are also advancing aviation safety if we can reduce accident severity and increase survivability.

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DEVELOPMENT OF IMPROVED FIRE SAFETY STANDARDS ADOPTED BY THE FEDERAL AVIATION ADMINISTRATION

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SUMMARY

This paper summarizes a series of improved fire safety standards for transport aircraft adopted or proposed by the United States Federal Aviation Administration over the past five years and describes the technical development of these standards. Important test results and analyses employed to develop the new standards are described. Reference is made to technical publications issued by the FAA for each fire safety area. Emphasis is placed on recent and high-impact rulemaking actions such as the heat release standard for large surface area interior panels (based on the Ohio State Rate-of-Heat-Release Apparatus). Other activities summarized include heat resistance evacuation slides, smoke detectors and fire extinguishers, cargo compartment fire protection, seat cushion fire blocking layers, floor proximity lighting, and crewmember protective breathing equipment.

INTRODUCTION

The Federal Aviation Administration (FAA) has undertaken an unprecedented series of regulatory actions over the past five years for the purpose of improving transport aircraft interior fire safety. These initiatives were part of a broad, scheduled program to enhance airliner safety that includes such diverse topics as water survival, child restraints, and crashworthiness (1). They are a culmination of a number of factors, including advisory committee recommendations (2), congressional support, product oriented FAA technical programs, accident pressures, and industry cooperation.

Aircraft interior design for fire safety covers three broad areas: material fire test methods, fire management and suppression, and evacuation and survival. Because of the overriding concern with the effect of the hazards of burning interior materials on occupant survivability, the FAA has placed greatest emphasis in its research, engineering and development program for cabin fire safety on the development of improved fire test methods for interior materials. Products from this program were incorporated into new fire test standards for seat cushion fire blocking layers (3), low heat/smoke release interior panels (4,5), burnthrough resistant cargo liners (6), and radiant heat resistant evacuation slides (7). New requirements for detectors and extinguishers (8) will improve in-flight fire management and suppression. Evacuation and survival has been enhanced by new standards for floor proximity lighting (9) and flight crewmember fixed protective breathing equipment and cabin crewmember portable protective breathing equipment (10).

SEAT CUSHION FIRE BLOCKING LAYERS

Aircraft seats are typically constructed of fire retardant polyurethane foam and upholstery fabric, which previously was required to pass the vertical Bunsen burner test prescribed in Federal Aviation Regulation (FAR) 25.853 (11). However, under the conditions of a severe cabin fire, the foam core ignites readily and burns rapidly, significantly contributing to the spread of fire. The concept of a fire blocking layer material to encapsulate and to protect the polyurethane foam was recommended for evaluation and development by the Special Aviation Fire and Explosion Reduction (SAFER) Advisory Committee (2).

The initial phase of FAA evaluation consisted of a series of full-scale tests to determine the effectiveness of the seat cushion fire blocking layer concept under the conditions of an intense postcrash fuel fire. Prior work by others was limited to the evaluation of fire blocking layers under moderate fire conditions for office, theater, institutional, and surface transit vehicle settings. The FAA full-scale tests were conducted in a new building with the capability of subjecting aircraft test articles to large jet fuel pool fires under controlled environmental conditions (12). A C-133 airplane modified to resemble a wide body interior was employed as the test article (figure 1). Basically, a section of the C-133 test article was lined and furnished with actual cabin materials and subjected to an intense external fuel fire placed adjacent to a simulated fuselage rupture. The results of four tests with modified seat cushions (13), but with all other test aspects identical, are shown in figure 2. In this figure the fractional effective dose (FED) accounts for the assumed additive effect of measured levels of toxic gases and elevated temperature on survival (12). An FED value of unity corresponds to incapacitation and indicates the hypothetical survival time. The additional time available for escape when the seats were protected with Vonar™ and Norfab™ fire blocking layers was 60 and 43 seconds, respectively, and was comparable in the case of Vonar to the safety benefits provided by noncombustible foam cushions. Further testing demonstrated that blocking layers could provide even greater improvements against certain types of ramp and in-flight fires, for example, preventing fires that may otherwise become out of control when initiated at an unprotected seat and left unattended (14). Although these data demonstrate the efficacy of the fire blocking layer concept, extensive additional FAA work was needed to make the concept into a viable product. This additional work covered the subjects of weight optimization and durability (15), flotation (16), cost-effectiveness (17), and certification testing of cushions (18).

The final rule established that transport aircraft seat cushions meet new and more severe flammability requirements by November 26, 1987 (3). The new test methodology, developed by FAA, subjects seat back and seat bottom cushion specimens to a burner with temperature and heat flux typical of a cabin fire (figure 3). Unlike most flammability tests, the test specimens simulate the end use seat configuration and allow for the burning interaction of upholstery cover, fire blocking layer, and foam cushion. In addition, other important effects such as seat construction features (thickness, seams, foam layering, etc.) and the melting, dripping, and pool burning behavior of urethane foam are taken into consideration. Acceptance criteria consist of 10 percent weight loss and a burn length of 17 inches - performance essentially matching that attained by the Vonar™ and Norfab™ blocking layer materials proven effective in full-scale tests. An advisory circular was issued by FAA to provide guidance material for testing seat cushions to show compliance with the rule (19).

Approximately 350 fire blocking layer materials were evaluated by FAA following the development of the seat cushion flammability test methodology. About 130 materials met the performance criteria, including, for example, thin foams, fiberglass cloths, aluminized fabrics, and graphitized fabrics, demonstrating the availability of suitable fire blockers. Many of the materials later proved to be impractical from weight, comfort, and durability considerations upon subsequent indepth evaluation by seat manufacturers. Today, the majority of seats manufactured in the United States are constructed of either polybenzimidazole felts or aramid fire resistant quilts, weighing 6 to 10 ounces per square yard. The entire United States airline fleet, consisting of approximately 650,000 seats, is protected with seat cushion fire blocking layers.

LOW HEAT RELEASE INTERIOR PANELS

The interior panels of an aircraft cabin, such as the sidewalls, ceiling, stowage bins, and partitions, are very important to the cabin fire load because of their large surface area and, in some cases, location in the upper cabin where fire temperatures are greatest. This importance was evidenced in the full-scale fire tests with fire blocking layers (figure 2). In the test with noncombustible seat cushions, the flashover was caused primarily by the burning panels. Interior panels are usually complex composites consisting generally of a Nomex™ honeycomb core, resin-impregnated fiberglass facings, and a decorative laminate finish.

The next logical step in fire-hardening the interior of a transport aircraft, after the establishment of a seat cushion flammability standard (3), was to improve the fire performance of the interior panels by development of more stringent and new fire test requirements. The issue of improved test methodology was complicated by the requirement to consider the interrelated concerns of flammability, smoke, and toxicity. However, test methodology development was preceded by the need to document (by full-scale fire tests) the potential benefits of fire-hardened panels for several fire scenarios.

The potential for improved safety was examined in the C-133 wide body test article used earlier for evaluation of the effectiveness of seat cushion fire blocking layers. A section of the test article was fitted with sidewalls, stowage bins, a ceiling, and a partition, each constructed of an advanced composite panel selected by the National Aeronautics and Space Administration (NASA), as well as fire blocked seats and carpet, and subjected to three types of full-scale fire conditions. The same tests were repeated with a panel design used extensively in early wide body interiors and still retained for some interior applications. The safety improvement associated with the advanced panel when compared to the in-service panel was significant. With the advanced panel, flashover was actually prevented when the external fuel fire was adjacent to a door opening or when an in-flight fire was started from a gasoline drenched seat. In the more severe ruptured fuselage scenario, wherein seats are more directly exposed to the external fuel fire, use of advanced panels resulted in a 2-minute delay to the onset of flashover (20).

The full-scale fire tests in the C-133 wide body test article, conducted to examine the benefits of seat cushion fire blocking layers and fire-hardened interior panels, demonstrated that occupant survivability was largely driven by cabin flashover. Flashover may be defined as the sudden and rapid uncontrolled growth of fire from a relatively small area surrounding the ignition source to the remainder of the cabin. Typical C-133 test data exhibiting this behavior are shown in figure 4. Before the onset of flashover, which occurred at about 150 seconds, the smoke and toxic gas levels were minimal and survival was clearly possible. After the onset of flashover, smoke and toxic gas levels and temperature increased rapidly to a level that would have made survival highly unlikely.

It should be noted that flashover is a phenomenon that generally occurs when fire in an enclosure generates heat at some critical rate that is effected by heat transfer and ventilation. Flashover to a large degree is caused by the heat release rate of burning interior materials. Thus, a rate of heat release test methodology will tend to yield the contribution of a given material to the flashover event. Also, selection of interior materials on the basis of minimizing heat release rate also serves to implicitly reduce the cabin smoke and toxic gases hazards since it is the flashover event that generates hazardous quantities of combustion products (figure 4).

Several studies were conducted to correlate the performance of composite panels in a heat release test device and under realistic cabin fire conditions. Initially, a variety of laboratory flammability tests were evaluated in terms of panel performance with results in a 1/4-scale cabin model (21). The Ohio State University (OSU) rate-of-heat-release apparatus exhibited the best correlation with model fire test results. Although probably any of the available heat release rate tests would serve to yield the flashover potential of various panel materials, the OSU apparatus was selected specifically for further evaluation and development. The decision to select the OSU apparatus was based on the above correlation study as well as recommendations of the SAFER committee (2), the use of the OSU apparatus in the development of the Combined Hazard Index (22), the availability of the OSU apparatus with the airframe manufacturers and its standardization by the American Society of Testing and Materials (ASTM). A second study corroborated the earlier good correlation results in that it established an inverse relationship between heat release measurements in the OSU apparatus and the time-to-flashover of a series of composite panels evaluated in the full-scale C-133 test article under postcrash fire conditions (23).

The second correlation study involved C-133 tests of five composite panel constructions under a scenario consisting of an external fuel fire adjacent to an open door. To realistically evaluate panel performance, the flat panel test specimens were installed in a typical configuration that included sidewalls, stowage bins, a ceiling and partitions (figure 5). In this arrangement, other factors such as ease of ignition and flame spread rate for the panels, as well as the contribution of fire-blocked seats and carpet, were allowed to come into play. The results of these tests are shown in figure 6 as an FED history plot. The graph indicates a wide range in behavior for the five types of panels. The phenolic/Kevlar™ and epoxy/fiberglass panels displayed the earliest flashovers, whereas the phenolic/fiberglass panel delayed flashover by about 3 minutes. Moreover, there was a monotonic, inverse relationship between heat release measured by the OSU apparatus and time to flashover. Also, the data indicate that small changes in heat release by materials may result in large changes in the time to cabin flashover.

The actual criteria for material selection were driven by the level of benefits evidenced by full-scale testing. The phenolic/fiberglass panel tested well under virtually any test condition (23), and this construction was achievable by state-of-the-art manufacturing processes. Thus, the phenolic/fiberglass panel was used as a benchmark for selection of the performance criteria for OSU testing of panel materials. A pass/fail criterion of 65 kw-min/m^2 for a 2-minute total heat release was selected to embrace the performance of the phenolic/fiberglass panel. An additional criterion of 65 kw/m^2 for peak heat release rate was included to eliminate usage of those materials that burn rapidly but produce small quantities of heat because of their low weight. The final rule also contains a new requirement for smoke emission testing in order to minimize the possibility that emergency egress will be hampered by smoke obscuration (5).

A schematic of the OSU apparatus is shown in figure 7. The equipment is basically a flowthrough device that measures the heat release rate as a function of time by a material subjected to a preset level of irradiated heat. Although the relationship between heat release rate data measured by the OSU apparatus and cabin fire conditions was demonstrated, the OSU data have been found to be sensitive to certain design features and operational conditions. Three round-robin test programs between FAA and the United States Aerospace Industries Association (AIA) were necessary to reduce the reproducibility of data between laboratories to an acceptable level (24). Results from the third round robin, with Boeing, Douglas, OSU, and FAA as participants, however, indicate that consistent results are attainable (figure 8). For example, the reproducibility of the third round robin, as measured by the percentage average relative standard deviation, was 7.7 and 7.8 percent for total heat release and peak heat release rate, respectively (24). Moreover, in a more recent round robin involving FAA and four laboratories in Europe, the reproducibility was quite acceptable after the initial comparison - 5.4 and 10.9 percent for total and peak measurements, respectively.

CARGO LINER BURNTHROUGH RESISTANCE

Lower cargo compartments in large transport aircraft are categorized as either class C or class D types (11). The latter are small compartments designed for fire containment by oxygen starvation, while the former are larger compartments that are required to have a fire detection and suppression system. FAA conducted full-scale fire tests to investigate the resistance of cargo liners to flame penetration for both compartment classifications. In a class D compartment, where it is critical that liners not be breached in order to allow oxygen starvation to take place, it was found that some types of liners failed (25). Fiberglass liners resisted burnthrough, whereas Nomex liners were penetrated by the flames (figure 9). It was concluded that a class D cargo fire was controllable if fiberglass or equivalent were the liner materials; but, if Nomex were used, the fire would continue to burn because of the availability of oxygen due to liner failure. In tests conducted inside a class C cargo compartment, even with a detection/suppression system, liner burnthrough resistance equivalent to fiberglass was required to ensure fire suppression under all scenarios (26). For example, Kevlar liner burnthrough occurred when sudden, intense flaming fires were employed and when a time lapse was allowed between the points of detection and discharge of suppression agent. Although the fire may be suppressed by the agent, it was determined that the breached cargo liner would cause a more rapid depletion of agent concentration and re-ignition at an earlier point in time than in an intact compartment. The main conclusion from the testing was that a more realistic and severe test requirement was needed for cargo liners used in both class C and class D cargo compartments.

A new fire test method that measures the burnthrough resistance of cargo liners, shown in figure 10, was developed with the features of severe liner exposure (matching the maximum heat flux and temperature measured during full-scale tests) and realistic ceiling and sidewall liner orientation (27). This test method is the basis for more stringent test requirements in newly certified aircraft (6) and a similar proposal for certain transports now in service (28). Criteria for acceptance are that there must be no flame penetration of ceiling and sidewall specimens and that the temperature measured above the ceiling specimen must not exceed 400 °F. The flame penetration criterion can be met by fiberglass liners but not by Nomex or Kevlar liners (27). However, many fiberglass liners cannot meet the peak temperature criterion because of the type or weight of resin and type of cloth weave (29). It appears that fiberglass suitably tailored to meet the peak temperature criterion will be the material of choice for new burnthrough resistance requirements although several new materials or combinations are being studied.

In a more recent, separate action, the FAA has proposed a new airworthiness directive (AD) for "combi" airplanes certified with a main deck class B cargo compartment (30). This action was prompted by the loss of a 747 airplane that apparently developed a major fire in the main deck cargo compartment. The AD proposes design changes that would require that the class B compartments be modified to a class C configuration or that burnthrough resistant cargo containers, meeting the more stringent test requirements for cargo liners (6) and employing smoke detection and extinguishing systems, be used to carry all cargo.

RADIANT HEAT RESISTANT EVACUATION SLIDES

In 1978, a DC-10 experienced an aborted takeoff resulting in a major jet fuel fire and the resultant collapse of a deployed evacuation slide caused by radiant heat damage. Although the two fatalities were not attributable to loss of the slide for emergency egress, the FAA undertook a test and development program to improve the radiant heat resistance of slide fabrics. From a series of full-scale fire tests in which pressurized slides were subjected, at various distances, to a 30-foot-square fuel fire, it was determined how slides failed and the time duration for failure (loss of pressurization) to occur (31). For example, a typical urethane nylon slide, located 15 feet from the edge of the fuel fire, where the irradiance was 1.5 Btu/ft^2-sec, failed in 25-30 seconds on the plain surface (non-seam area). Also, it was shown that an aluminized reflective coating significantly improved the airholding qualities. The uncoated urethane nylon slide that failed in 25-30 seconds held pressure for 70-75 seconds when protected with an aluminized coating and loss in pressure occurred at an opened seam.

To permit the development and qualification of improved slide fabrics, a laboratory test was developed (31). The essential features of the laboratory test, shown in figure 11, are a radiant heater, calorimeter, pressure holding cylinder, specimen holder, pressure gage, pressure transducer, and recording device. Basically, a slide fabric specimen is mounted to the pressure holding cylinder which is then pressurized. The irradiance to the specimen is set by the calorimeter. Pressure holding capability of the specimen at the set irradiance level is determined by the recorded pressure history.

On June 3, 1983, FAA issued Technical Standard Order (TSO)-C69a, Emergency Evacuation Slides, Ramps, and Slide/Raft Combinations, which made general improvements to the equipment requirements and contained new requirements for radiant heat resistance (7). TSO-C69a required that all evacuation slides purchased after December 3, 1984, meet the new standards. For radiant heat resistance, the requirement is retention of pressure for 90 seconds at an irradiance of 1.5 Btu/ft^2-sec. The pressure holding members of all TSO-approved inflatable evacuation slides are now constructed of aluminized materials in order to provide adequate radiant heat resistance.

SMOKE DETECTORS AND FIRE EXTINGUISHERS

As the result of investigations of in-flight fires, including the Air Canada DC-9 on June 2, 1983, (that resulted in 23 fatalities) and an inspection survey of the United States air carrier fleet, the FAA amended the FARs with the following requirements: a smoke detector in each lavatory, an automatic fire extinguisher in each lavatory trash receptacle, increased number of hand fire extinguishers, and the use of Halon 1211, or equivalent, as the extinguishing agent in at least two of the hand fire extinguishers (8). A separate time period was specified for implementation of each requirement, with the longest period extending to April 29, 1986.

FAA supportive experimental and analytical studies for these amended regulations have concentrated on the effectiveness and safety of Halon 1211 (bromochlorodifluoromethane) hand extinguishers. Initial tests showed the superiority of Halon 1211 in knockdown and extinguishment capability against fuel drenched seat fires in comparison to water, dry chemical, and carbon dioxide extinguishers. However, opposition to the usage of Halon 1211 centered on the toxicity associated with the agent and, in particular, its decomposition products. Subsequent tests by the FAA clearly showed that virgin agent and decomposition gas concentrations peaked at levels significantly below values considered dangerous and rapidly dissipated due to the effect of adsorption, stratification, dilution, and ventilation (32). Typical gas profiles measured near an extinguished seat fire in the C-133 test article are shown in figure 12. Hydrogen fluoride (HF) and hydrogen bromide (HBr) concentrations peaked at about 10 parts per million (ppm), hydrogen chloride (HCl) peaked at 17 ppm, and the peak virgin agent concentration was 1800 ppm (0.18 percent). Most importantly, it became evident that the hazards associated with an uncontrolled seat fire would quickly surpass those transient hazards resulting from Halon 1211 decomposition (32) and would possibly result in cabin flashover within 3 to 4 minutes if left unchecked (13).

To place a conservative upper limit on the quantity of agent that could safely be discharged inside a compartment, a perfect stirrer model was used to analyze the decay of agent concentration due to ventilation (33). Nomographs developed from this analysis predict maximum safe agent weight for a given compartment volume and ventilation rate and are incorporated in a revised advisory circular (AC) on hand fire extinguishers (34).

In related studies, the FAA has examined the safety of Halon extinguishing agent discharge in small airplanes (35,36,37). A major concern is the warning label on Halon bottles against discharge in a small enclosure volume. For example, for the common size 2 1/2 pound Halon 1211 extinguisher, the upper volume limit for "safe" agent discharge is 312 cubic feet. However, FAA tests conducted under simulated flight conditions in a Cessna 210 with a cabin volume of 140 cubic feet clearly demonstrated that both Halon 1211 and Halon 1301 could be safely discharged in this relatively small airplane cabin (35,36). The absence of significant concentrations of agent near a seated occupant was shown to be primarily the result of accumulation of the heavy agent near the floor and, to a lesser degree, high cabin ventilation rates. Apparently, the Halon bottle warning labels are based on safety factors for human exposure as well as assumptions of zero ventilation and homogeneous agent distribution. Fire tests conducted inside a Piper Commanche airplane also demonstrated the effectiveness of Halon 1211 and Halon 1301 in extinguishing hidden electrical and hydraulic fires behind an instrument panel (37). In summary, the safety and effectiveness of Halon hand-held extinguishers has been demonstrated for both large and small airplane cabin applications.

FLOOR PROXIMITY LIGHTING

Rapid passenger evacuation is the most critical and overriding consideration in postcrash cabin fire safety. Buoyant hot smoke from a cabin fire, however, clings to the ceiling and rapidly obscures conventional ceiling mounted emergency illumination and exit signs, thereby reducing the visibility of occupants and prolonging evacuation time. The resultant reduction in visibility and escape guidance often occurs when the lower portion of the cabin is relatively free of combustion products. FAA tests have demonstrated the effectiveness of emergency lighting placed below the smoke layer in the proximity of the cabin floor. In one study, the improved visibility of floor proximity lighting systems, including lights mounted on armrests, floor mounted electroluminescent lights and self-powered betalights, was evidenced during full-scale postcrash cabin fire tests (38). Another study translated the improved visibility of low level lighting to faster evacuation rate (39). People were able to evacuate in approximately 20 percent less time from a cabin simulator filled with stratified theatrical smoke when seat mounted lighting illuminated the main aisle than from the simulator with conventional ceiling lights. In a third study, the degree of merit of 11 improved emergency lighting systems was evaluated on the basis of illumination, reliability, cost, and other parameters (40).

The final rule, published on October 26, 1984, required floor proximity emergency escape path marking to enable passengers to visually identify the emergency escape path along the cabin aisle and to readily identify each exit by reference only to markings and visual features not more than 4 feet above the floor (9). All in-service airplanes, type certificated after 1958, were required to comply with the new design standards within 2 years, or by November 26, 1986. Issuance of the rule was followed by an advisory circular (AC) to provide guidance material for use for demonstrating compliance with the floor proximity lighting rule (41). The AC clarified, by example, systems that could or would not meet the requirements of the rule. To meet the requirements of 25.812(e)(1) for markings that enable each passenger to visually identify the emergency escape path along the cabin aisle floor, the AC states that the system must provide a reasonable degree of illumination over the entire length of the escape path along the aisle floor. A distant light at an exit that allows the escape path to remain essentially dark would not be acceptable. Also, the requirement to readily identify each exit by reference only to markings and visual features not more than 4 feet above the floor would not be met by a system that provides only general diffused light in the vicinity of the exit or a system which merely marks the fore and aft location of the exit along the aisle floor, and not the exit itself.

CREWMEMBER PROTECTIVE BREATHING EQUIPMENT

Protection of crewmembers against smoke and toxic gases produced by an in-flight fire includes fixed protective breathing equipment (PBE) for flight deck crewmembers and portable PBE for cabin crewmembers. Criteria for design of flight crewmember PBE are contained in TSO-C99 (42) and include requirements for testing masks and/or goggles for smoke leakage. Portable PBE for cabin crewmembers is required for all transport aircraft by July 6, 1989 (10). Basically, a portable PBE must be located at each approved hand-held extinguisher station.

FINAL COMMENTS

In recent years the FAA has issued an unprecedented series of new standards to improve fire safety in transport aircraft. Many of the new standards are products of FAA's research, engineering and development (R, E & D) program. The use of fire blocking layers for seat cushions and low heat/smoke release interior panels are expected to furnish the greatest gains in airliner fire safety from these standards. However, it is unlikely that further improvements in fire safety from even more fireworthy interior materials can be anticipated in the foreseeable future due to the fact that the new, stringent FAA fire test requirements, especially for interior panels, are driving technology to produce suitable composite designs. Exclusive of fuels and fuel systems safety considerations, additional improvements in aircraft fire safety are more likely from current R, E & D activities related to active fire protection, such as cabin water mist fire suppression or enhanced smoke venting.

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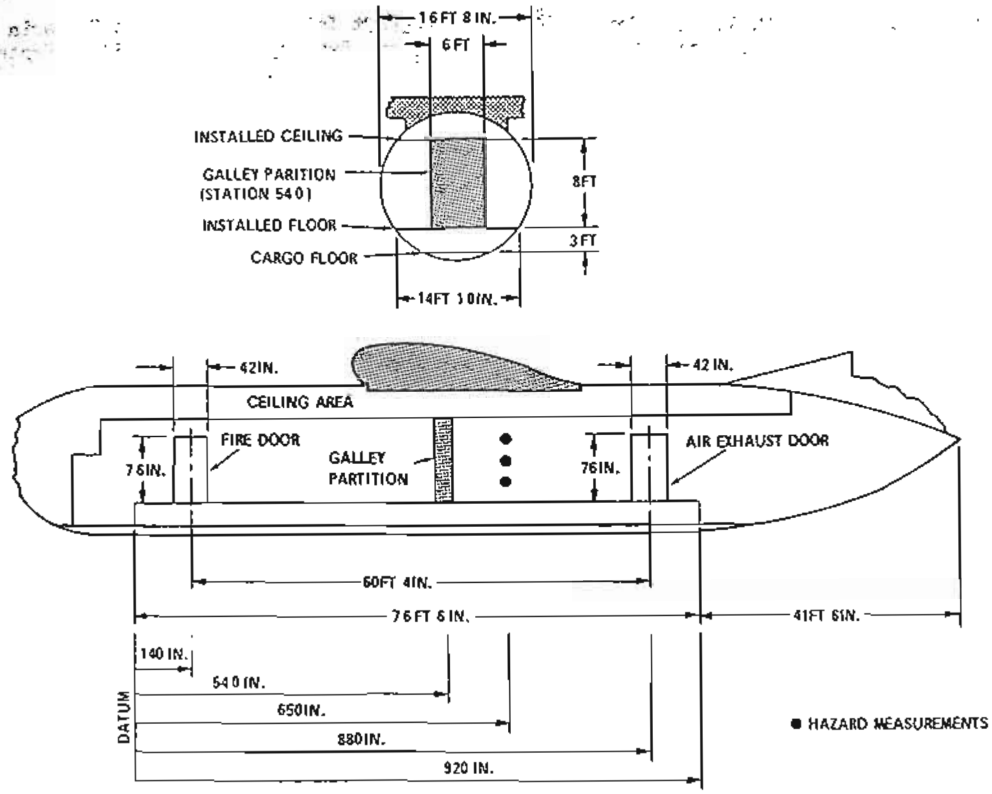

FIGURE 1. C-133 WIDE BODY CABIN FIRE TEST ARTICLE

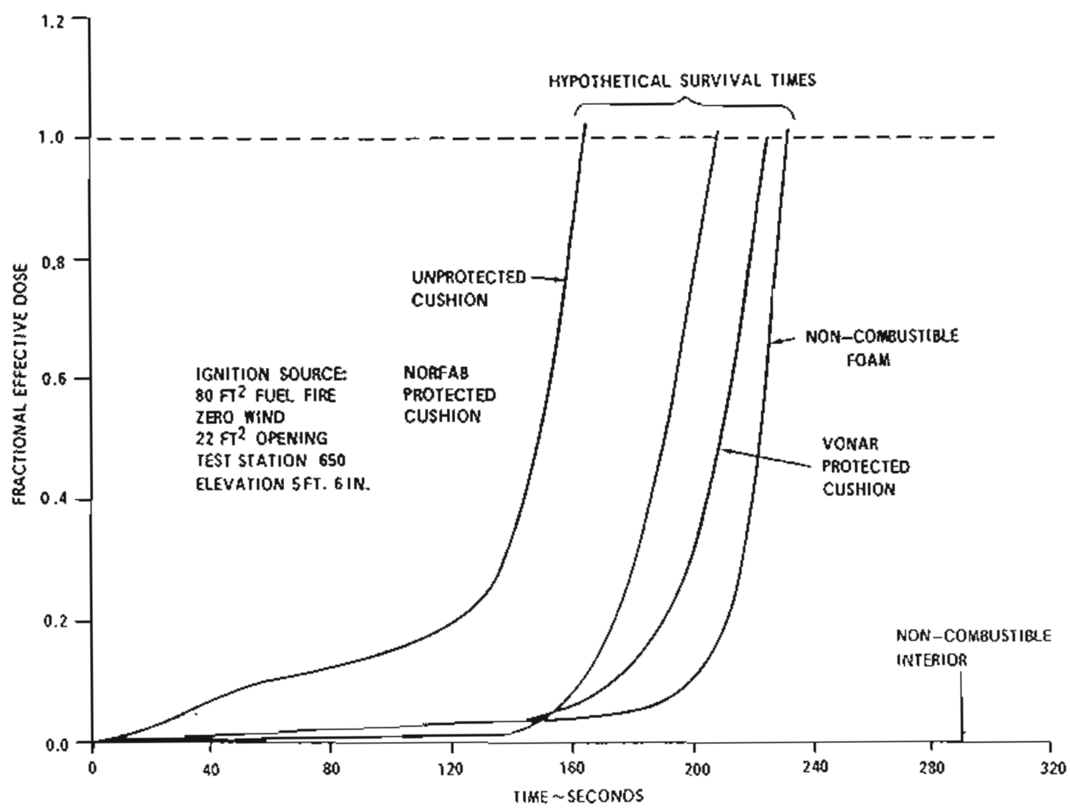

FIGURE 2. EFFECT OF SEAT CUSHION PROTECTION ON FRACTIONAL EFFECTIVE DOSE

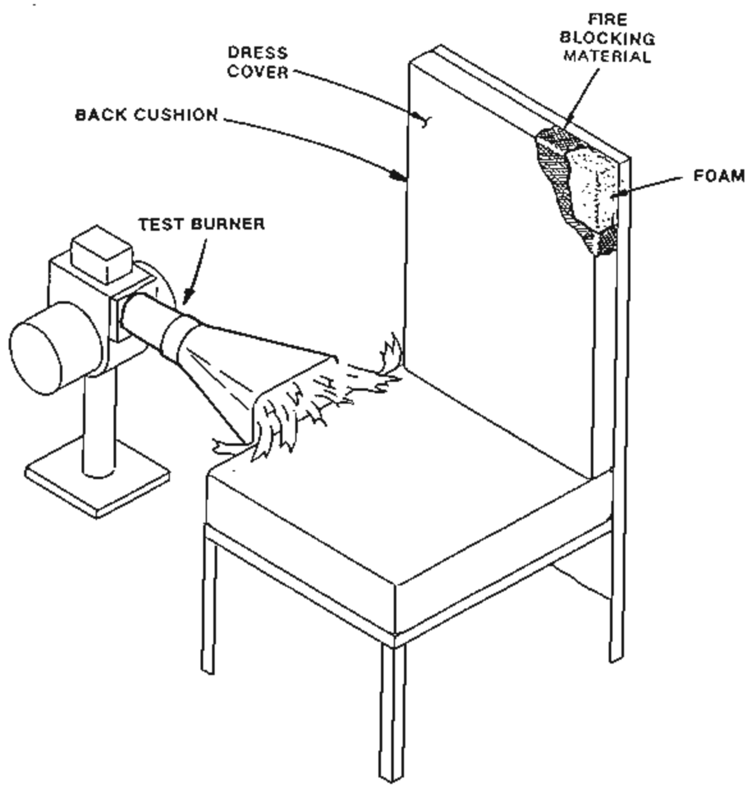

FIGURE 3. FAA SEAT CUSHION FLAMMABILITY TEST APPARATUS

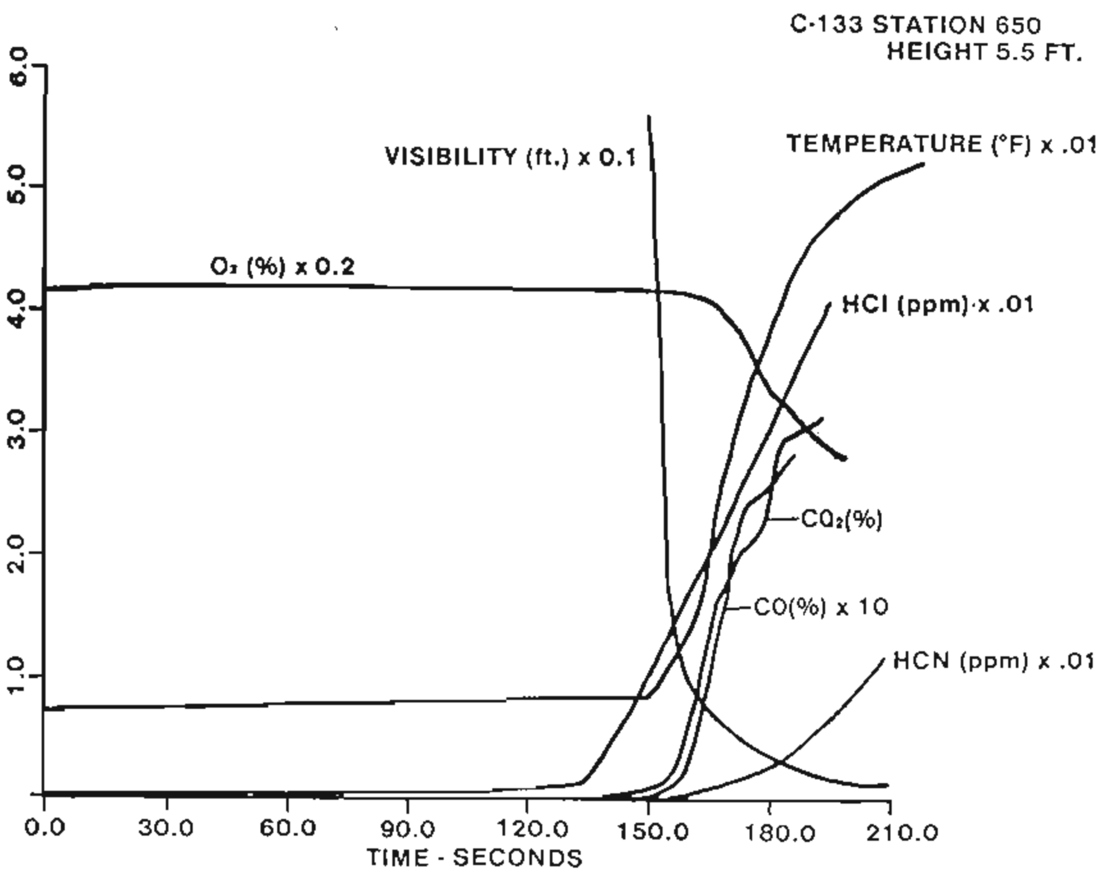

FIGURE 4. TYPICAL C-133 CABIN FIRE HAZARDS PROFILE

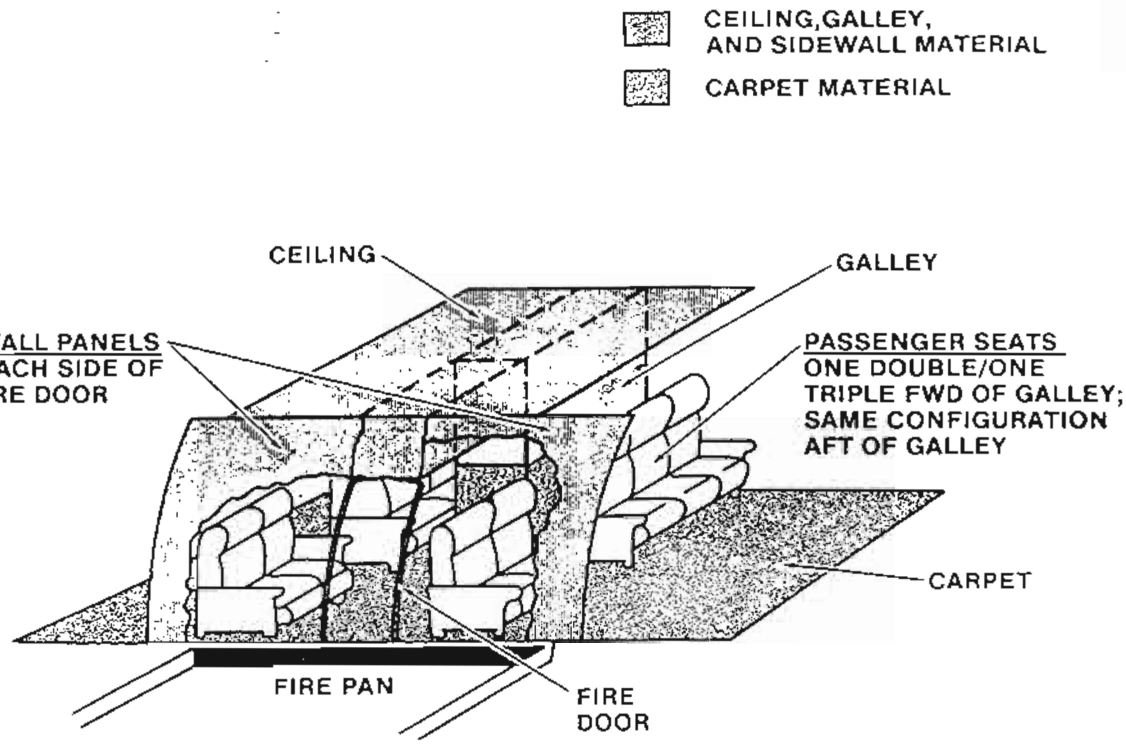

FIGURE 5. POSTCRASH FUEL FIRE OPEN DOOR SCENARIO

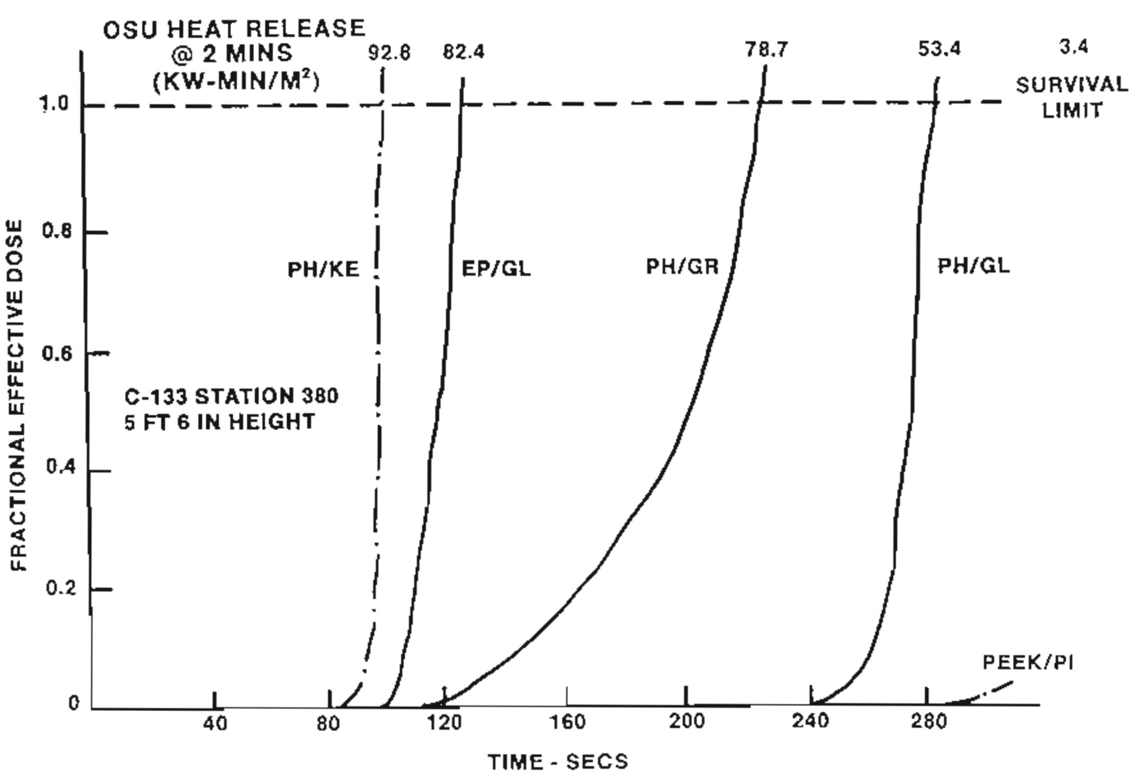

FIGURE 6. EFFECT OF COMPOSITE PANEL DESIGN ON FRACTIONAL EFFECTIVE DOSE

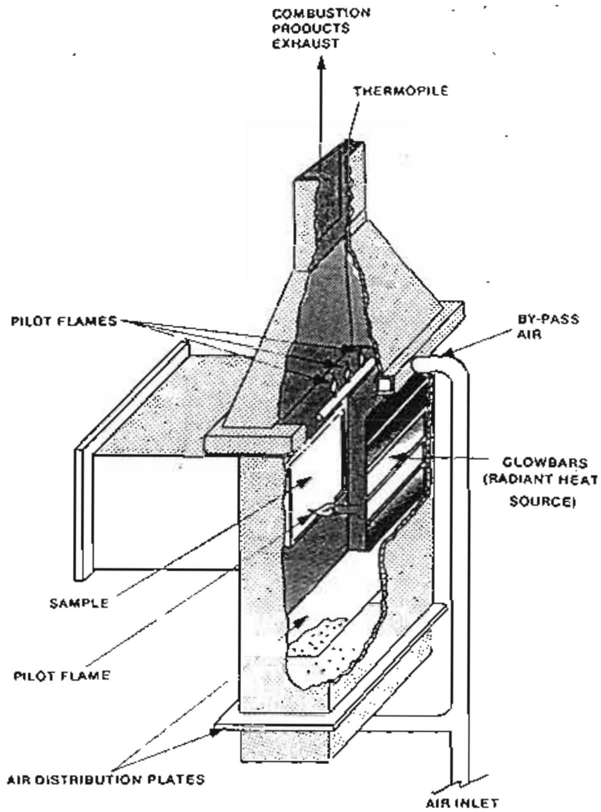

FIGURE 7. FAA OSU RATE OF HEAT RELEASE APPARATUS

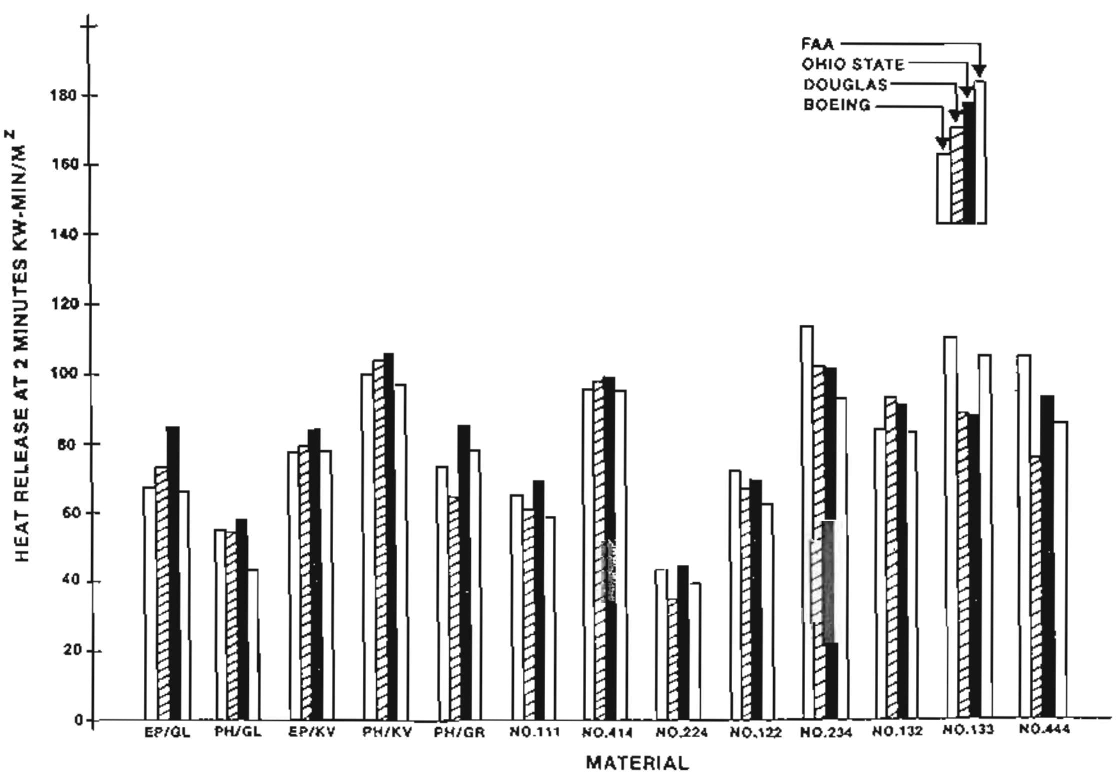

FIGURE 8. REPRODUCIBILITY OF HEAT RELEASE APPARATUS - FAA/AIA THIRD ROUND ROBIN

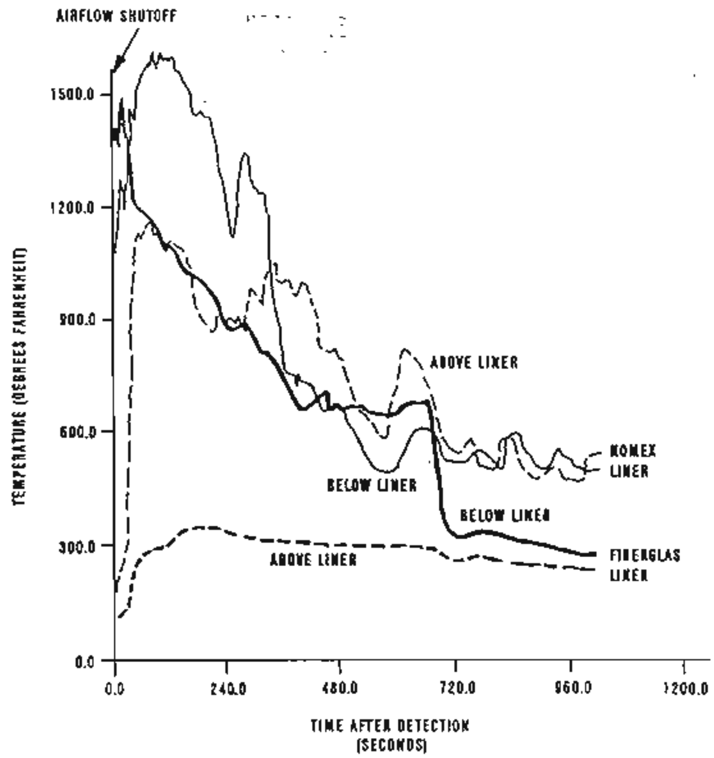

FIGURE 9. CARGO LINER RESISTANCE TO BURNTHROUGH

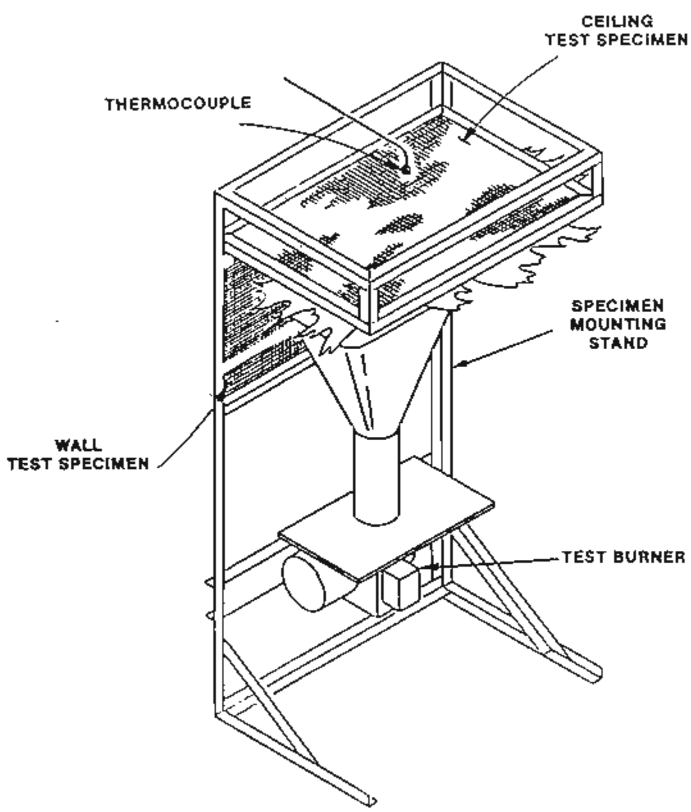

FIGURE 10. FAA CARGO LINER BURNTHROUGH TEST APPARATUS

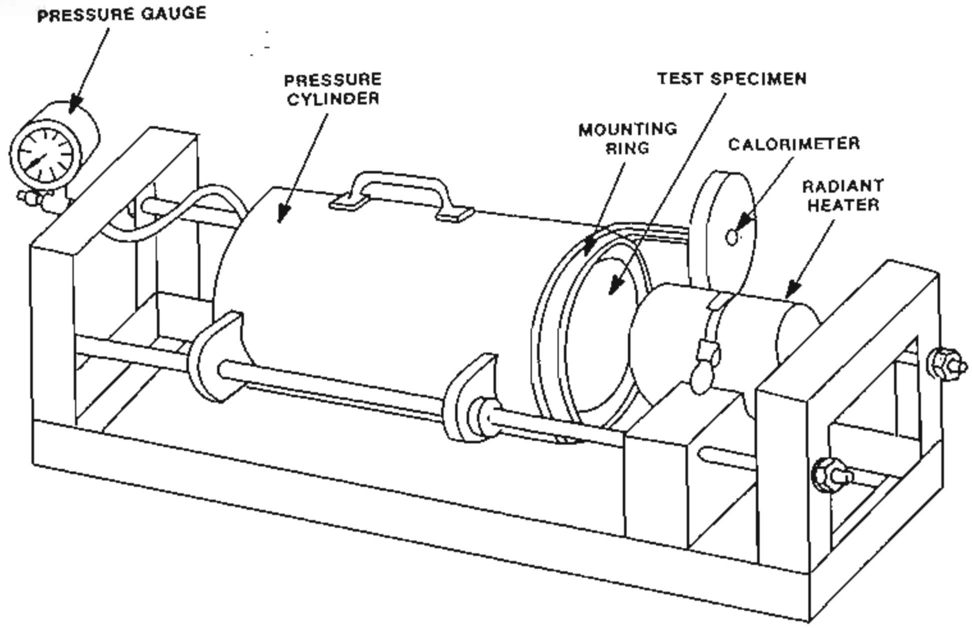

FIGURE 11. FAA EVACUATION SLIDE RADIANT HEAT TEST APPARATUS

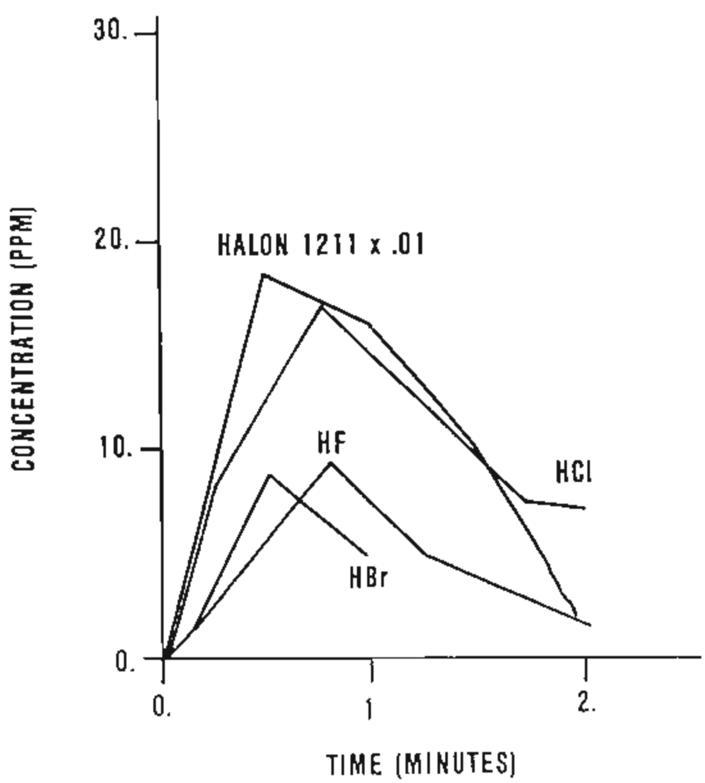

FIGURE 12. CABIN GAS PROFILES DURING HALON 1211 SEAT FIRE EXTINGUISHMENT

A REVIEW OF UK CIVIL AVIATION FIRE AND CABIN SAFETY RESEARCH

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SUMMARY

The paper presents a broad overview of current research in the UK into cabin safety with particular emphasis on fire research. The status of passenger protection equipment is reviewed and work in the UK on cabin water sprays is reported on. Work on fire blocking layers and small scale tests for the measurement of heat release from aircraft furnishing materials are discussed along with the suppression of fire in cargo compartments. Other topics include work on the mathematical modelling of aircraft cabin fires and on the human factors side, a study of the behavioural aspects of passengers evacuating an aircraft in a competitive situation.

INTRODUCTION

The Civil Aviation Authority (CAA) are supporting a programme of research activities in the UK designed to improve cabin safety and passenger survivability with particular reference to the on-board fire situation. Some of the major items from this programme are as follows:

PASSENGER SMOKE HOODS

The CAA has collaborated with all interested parties to produce a rigorous specification against which equipment can be approved. This collaboration has resulted in CAA specification No 20 being issued in May, 1988 which sets out the minimum performance requirements. These cover the ease of donning, vision, duration and level of protection, workload, respiratory resistance, inhalation temperature, communications, reliability, storage and fire and thermal resistance.

In conjunction with the Airworthinss Authorities of the United States (FAA), France (DGAC) and Canada (Transport Canada) the CAA carried out a study to assess the safety benefit of smoke hoods and any likely offset due perhaps to delays in evacuation induced by their use. The Study was conduction by reference to past accidents to large (more than 30 passengers) passenger aircraft since 1966. The Study took into account the improvements in safety already provided by fire blocking of seats, floor proximity escape path lighting, lavatory smoke detectors and fire extinguishers. The results of this Study were published in November 1987 as a CAA Paper (Reference 1) which concluded that the provision of effective smoke hoods in public transport aircraft of more than thirty seats would result in a modest saving of life of the order of nine per year world-wide. It also concluded that if smoke hoods were to provide even a modest benefit they would have to be of a very high quality not only in terms of the protection they provide but also in terms of ease of use.

The CAA has a serious concern that, in some circumstances, smoke hoods might cause more loss of life than they save. In some severe fire accidents where some passengers are shocked and/or injured, and the cabin situation is perhaps fast deteriorating, it is unlikely that a high proportion of passengers (with varying degrees of manual dexterity) can be relied on to don this unfamiliar and unnatural equipment. Not only might individuals place their own lives at risk by lingering in the cabin trying to put on the hood correctly when they should be escaping, but they might also delay others. Indeed there could be loss of life in circumstances where a rapid evacuation without hoods would not have resulted in fatalities. It was therefore the unanimous view of the group of Authorities (CAA, FAA, DGAC and Transport Canada) not to make the provision of smoke hoods for passengers mandatory, but the CAA has decided to keep this decision under review.

FIRE BLOCKED SEATS

The CAA has been concerned that the performance of fire blocked seats may deteriorate with wear, soiling and repetitive dry cleaning of the seat coverings. A small experiment was carried out using the standard FAA burner test (Reference 2) where the fire blocking performance of a number of seats taken out of airline service representing fairly heavy wear and soiling were compared with new seat cushions of the same type. The results were not statistically significant and a rigorous analysis showed that a sample size of over 400 seats would be necessary to obtain statistically significant results. This has strengthened our view that a small scale test would be useful to monitor the fire performance of seats in service.

A small scale test would also be useful to the seat manufacturers as a quality control test for the fire performance of each batch of newly manufactured seats. A UK seat manufacturer has been approached to provide a number of small samples and it is planned to use a small scale test developed in the UK (Reference 3) by the International Wool Secretariat to further investigate these areas.

RATE OF HEAT RELEASE

A programme has been established by the CAA to assess the variability of the results obtained from the Ohio State University (OSU) rate of heat release apparatus, (Reference 4). The object of the evaluation programme is to provide a comparison of the performance and test results between organisations in Europe using the OSU apparatus and the apparatus located at the FAA Technical Centre in New Jersey. A number of test houses in Europe are participating in this activity. The CAA are also keeping abreast of the developments of the Cone Calorimeter (Reference 5) which is gaining popularity in test houses around the world and it is hoped to evaluate this apparatus on a number of aircraft cabin furnishing materials.

TESTING OF AEROSOLS

Previous tests on the flammability and explosion characteristics of aerosols indicated that these would not present a major hazard to aircraft, however new developments are that some aerosols are now being produced with a plastic body rather than a metal one and the majority of aerosols now contain flammable hydrocarbon propellants. It has therefore been decided to carry out some further tests on aerosols to determine more accurately the ambient temperature for rupture, to look at aerosols rupturing inside luggage and to look at impact damage on aircarft wiring looms and hydraulic piping. Also of concern is the likely overpressure resulting from the rupture of an aerosol in the toilet compartment, the luggage hold and the passenger cabin. This work is being carried out for the CAA by the UK's Fire Research Station.

MATHEMATICAL MODELLING OF AIRCRAFT FIRES

The Centre for Numerical Modelling and Process Analysis at Thames Polytechnic in the UK are carrying out development work on mathematical field models describing aircraft cabin fires. Mathematical modelling offers a cheaper and more general alternative to the experimental approach, provided that the models can be reliably validated. The effect of various openings in the fuselage on the temperature distribution within the aircraft cabin are being studied. Preliminary results show that with the forward and aft bulkhead doors open, allowing for natural convection, temperatures are kept much lower than in a sealed cabin. Results also suggest that reverse flow air conditioning (ie, cold air injected at floor level and hot air sucked out at ceiling level) dramatically reduces the temperature throughout the fuselage. Further work is continuing and it is hoped to investigate more sophisticated models using heat release and smoke and incorporating the effects of a water spray in the cabin.

CAGRO COMPARTMENTS

Research has been carried out by Graviner Limited to evaluate the single shot, double phase cargo fire suppression systems in class C compartments and fire growth in smaller class D compartments without fire suppression. Preliminary conclusions indicate that:

Halon 1301 at an initial concentration of 5% with a 3% bleed can control but not extinguish deep-seated fires inside a Class C cargo compartment.

Variation in "Reaction Time" by the crew from 1 to 2 minutes from detection of a fire to initiation of the suppression system has no significant effect on the control of the fire.

In both suppressed and unsuppressed fires there is a considerable build-up of combustible gases and explosions can occur when these gases are ignited by the heat of the fire.

Both flame and smoke detectors were studied during the test programme and circumstances can arise where one system would not alarm. It may be necessary to consider using both systems.

COMPETITIVE PASSENGER EVACUATION TRIALS

The Applied Psychology Unit of the College of Aeronautics, Cranfield, UK, have run a comprehensive programme to study the behavioural aspects of passengers evacuating an aircraft with an element of competition. Each trial has about sixty people in a Trident aircraft and incentive payments are made to the first thirty people to vacate the simulated emergency. The study considers the effects of different seating arrangements adjacent to the auxiliary overwing exits and varying widths of bulkheads leading to the vestibules at the main door exits. It is already apparent that in a competitve situation serious blockages can occur at the auxiliary overwing exits but preliminary results suggest that the changes made by the CAA Airworthinss Notice 79 have significantly improved the situation. Similarly, the study of bulkhead configurations has confirmed an increase in passenger flow rate, and reduction of jamming, as the bulkhead gap increases. However, the results of the whole programme need to be assessed before an optimum configuration can be determined.

CABIN WATER SPRAY SYSTEMS

A post-crash fire suppression system, internal to the fuselage has been developed in the UK with the design objectives of:

- Delaying the penetration of an external fire, through the skin of an aircraft into the cabin interior.

  Minimising the combustion of the cabin furnishings.

  Preventing "flash over" fires from occurring.

  Delaying the transfer of combustion products, including toxic gases, into the occupied areas of the cabin.

  Providing a level of "clean up" of combustion products such that breathing and sight are not severely impaired in the occupied spaces of the cabin.

  And

  At a later stage of an accident enable the rescue services to extinguish any fire in the cabin and improve further the environment and thus enhance the chance of survival.

The company (SAVE Limited) carried out its development work in the laboratory and in a VC10 fuselage. This work showed sufficient promise for the CAA to decide that a demonstration was appropriate in a fully furnished aircraft. Three fire tests of the system were carried out on a fully furnished Trident II at the Fire Service Training School at Teesside. The first fire test represented an external pool fire developing under the rear of an undamaged aircraft comparable to the fire in the Manchester accident. The second fire test was a repeat of the first fire but on an aircraft having suffered significant structural damage allowing the fire early access to the aircraft interior. The third fire was a "worst-case" test with the system partially disabled allowing a major fire to develop within the rear fuselage, but without the venting of smoke, toxic gases and heat that would be expected if the aircraft had suffered the fuselage break necessary to damage the system.

The results of these tests have been published as a CAA paper (Reference 6) and it is concluded that:

> The tests have shown that the system delayed substantially the penetration of the fire into the aircraft and maintained a cabin environment which would have permitted safe evacuation. Even with an improbable combination of an intact cabin upper section and a damaged spray system, neither temperature or loss of visibility would have prevented passengers from escaping. Whilst toxic gas levels built up in the sprayed spaces the system, nevertheless, substantially increased the chance of passenger survival.
>
> Work should be undertaken to investigate the application of the system and its effectiveness in a wide bodied aircaft. Further investigation is also needed to understand more precisely the system's ability to control the build-up and migration of toxic gases.

The CAA has kept the US, Canadian and European Authorities informed about the progress of this research. A collaborative programme of further research between the UK, US and Canadian Authorities has been established and it is expected to include other European Authorities in the near future.

CONCLUSIONS

The CAA is supporting a wide ranging research programme into cabin safety and fire research. A major activity is now aimed at maintaining a survivable cabin atmosphere through the use of interior water spray systems and a large amount of research has been carried out. This is supported by a programme of smaller, detailed investigations of appropriate fire technologies.

In addition an important, on going programme is underway to gain a clearer understanding of the human factors aspects of cabin safety. This work is intended to provide guidance both for the design and operation of aircraft.

There are no easy panacea solutions to the problems of fire and cabin safety but the CAA is dedicated to playing its part in a worldwide assault on these problems with a broad range of research activities.

REFERENCES

1. Civil Aviation Authority, Smoke Hoods: net safety benefit analysis, 1987, Paper 87017.

2. FAR Part 25, Appendix F, Part II, Amendment No. 25-59, Flammibility Requirements for Aircraft Seat Cushions; Final Rule; issued 26 October 1984.

3. M M Shaw, Fire Testing of Seat Blocking Layers in the UK, Aviation Safety 2nd International Symposium, Toulouse, November 1986.

4. A description of the OSU apparatus is in Specification ASTM E.90683.

5. A description of the oxygen consumption calorimeter is in Specification ASTM E5 Proposal P-190.

6. Civil Aviation Authority, Aircraft cabin fire suppression by means of an interior water spray system, 1988, Paper 88014.

OBJECTIVES AND RESULTS OF CABIN FIRE RESEARCH IN GERMANY

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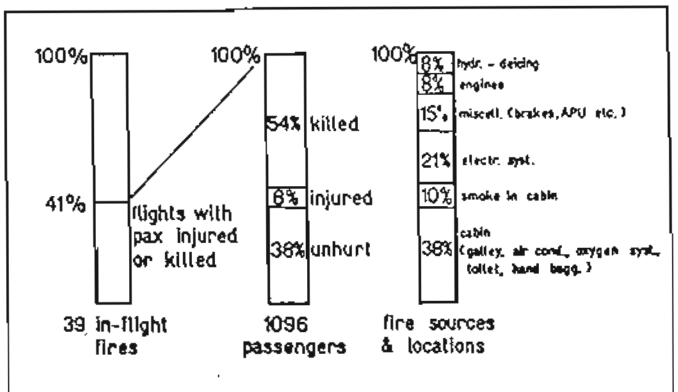
SUMMARY

German activities in aircraft cabin fire safety started in the early 1980's, highlighted by a full scale test in 1986, simulating an aircraft in-flight fire in a modern widebody fuselage. Beginning with a statistical analysis of in-flight fires in the period 1970-82, the paper presents the efforts from the political side to improve aircraft fire safety and outlines the philosophy why Germany concentrated on in-flight fire research. It describes the consequences drawn out of the studies and test results for the design of aircraft cabin interiors and for post-crash fire situations. Finally, a view to future activities, including full scale component tests, is presented.

1. INTRODUCTION

An overall view of safety in world-wide air traffic is characterized by the statistical mean value of one killed passenger per 1.2 billion passenger-kilometers. Or in other words: An aircraft passenger has to fly daily for about 8 hours for more than 500 years before he meets the probability 1 of being killed by an aircraft accident. Looking to these figures - is it really worth improving aircraft safety any further?

In the 1970's the German Federal Minister of Transport, in cooperation with the German research institution DLR and the aircraft manufacturer MBB, began to analyse the present knowledge in the field of aircraft fire safety and started to define items, which in his opinion needed further clarification. In the frame of these pre-considerations the ICAO flight accident statistics was analysed for the period of 1970 to 1982 (Fig. 1).



1 ANALYSIS OF 39 IN-FLIGHT FIRES 1970 - 82

During this period in-flight fires occurred on 39 flights. 16 flights (out of the 39), with in total 1096 people on board, were combined with personal damages of the passengers. From these people - and this is a most awful result - 54 % lost their lifes through fire, another 8 % got hurt, and only 38 % remained without injuries. The statistics also showed that almost 50 % of all in-flight fires occurred in the aircraft cabin. One need not remind of the well-known catastrophic aircraft fire accidents of Paris in 1973, of Jeddah, Cincinatti, or Manchester later on (presented in details in the paper no. 2 of Mr. A.F. Taylor) to come to the straight forward conclusion that aircraft fire safety is a pre-dominant area for improving overall aviation safety.

2. POLITICAL EFFORTS TO IMPROVE AIRCRAFT FIRE SAFETY

It was in 1982, when the Committee on Transport of the European Parliament discussed safety measures on aircraft, leading to a resolution of the European Parliament on Dec. 17, 1982. This resolution emphasized the problem of flammability and toxicity of the materials used for the interior equipment of civil aircraft, and requested to reconsider the safety regulations and standards.

This European resolution was accepted by the German Federal Parliament on Sept. 14, 1983, and the German government was consequently asked to undertake all efforts towards a fulfillment of the European recommendations.

Dec 17, 1982:	RESOLUTION OF EUROPEAN PARLIAMENT, COMMITTEE ON TRANSPORT, ON AIRCRAFT SAFETY MEASURES
Sept 14, 1983:	ADOPTING OF THE RESOLUTION BY THE GERMAN FEDERAL PARLIAMENT
End of 1981:	GERMAN FEDERAL MINISTER OF TRANSPORT, MBB, DLR, STARTED STUDIES & RESEARCH ON AIRCRAFT FIRE SAFETY
Nov, 1984:	MOU ON COOPERATION IN AVIATION RESEARCH, SIGNED BY THE GERMAN FEDERAL MINISTER OF RESEARCH AND TECHNOLOGY, AND THE FAA USA, INCLUDING ANNEX 4: AIRCRAFT CABIN FIRE SAFETY
June 19, 1986:	FULL SCALE TEST WITH MODERN WIDEBODY FUSELAGE (SIMULATION OF IN-FLIGHT FIRE)

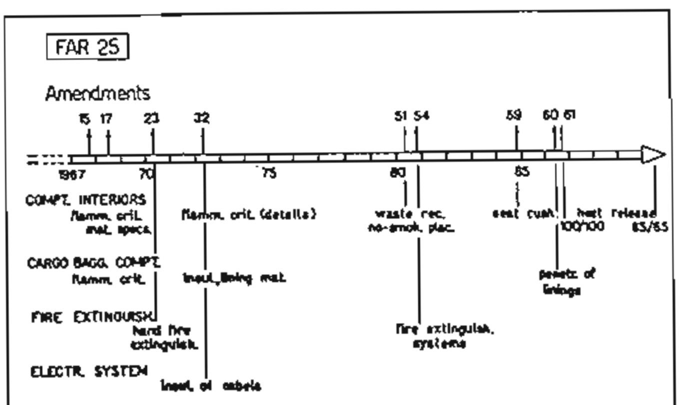
2 HISTORY OF GERMAN FIRE SAFETY EFFORTS BMV LR 15

Already before these European initiated activities, the German Federal Minister of Transport and the German Airworthiness Authority started discussions by the end of 1981 with the MBB company, the German partner of Airbus Industrie. The aim was to contribute to an improvement of fire safety in civil aviation by research activities in areas to be selected.

In the following years, the Minister of Transport awarded several contracts to MBB and the DLR (then DFVLR), with the aim to improve the test methods for fire safety and smoke density, in order to come to more precise requirements for cabin materials. These activities were later on extended on investigations about the toxicity of emitted fire gases, highlighted by a full scale test in June 1986, using a modern wide-body passenger aircraft fuselage. Since 1984 the German Government and the FAA have agreed to cooperate on the basis of a "Memorandum of Understanding" in certain areas of mutual interest in aviation, one area being "cabin fire safety".

3. CONSIDERATION OF IN-FLIGHT AND POST-CRASH FIRES IN AIRWORTHINESS REQUIREMENTS

Since decades the Airworthiness Authorities tried to improve the survivability of aircraft occupants during fires within an aircraft and to develop the fire safety standards. A rough overview of the history of regulations for large commercial transport aircraft is given in fig. 3.



3 DEVELOPMENT OF FIRE SAFETY STANDARDS BMV LR 15

Starting from the first more general requirements for flame resistent and self extinguishing materials via more detailed specifications for single structural or interior components and more accurate test methods, the airworthiness standard of FAR Part 25 Amdt. 32 of 1972 has, regarding flammability, reached a level which in its essential parts is still acceptable today. However, these standards do not contain any realistic requirements for smoke density nor do they cover the toxicity problem of emitted fire gases.

In 1978 in USA the SAFER Advisory Committee (Special Aviation Fire and Explosion Reduction) discussed among other things the chances to survive post-crash external fuel-fed fires. Four years later full scale fire tests were carried out at the FAA Technical Center, using a military Hercules C-133 aircraft fuselage. Comparing the results of the investigated post-crash and in-flight fire scenarios, the FAA found that the in-flight fire scenario was the least severe of the various scenarios studied. Depending on the installed cabin materials for the in-flight fire scenario a flashover, which is practically not survivable, occurred only 8 minutes after having started the fire or even not at all.

The outcome of the various laboratory and full scale tests were transferred into the airworthiness requirements for civil transport aircraft with the obvious results that under the tested conditions smoke generation and toxic gases play no essential role concerning survivability up to the time when a flashover occurs. With other words: The airworthiness requirements give way to the interpretation that for both, post-crash as well as in-flight fire, the probability for occupants to survive can be improved by delaying the flashover, which in turn can be reached by limiting the heat-release rate of the installed burning materials.

4. WHY GERMAN STUDIES ON AIRCRAFT IN-FLIGHT FIRES ?

Discussions within various German industrial and research institutions on the complex physical and chemical interconnections during such fires raised many questions. For instance, one basic problem, the ranking concerning survivability of the highly dangerous parameters

oxygen deficiency (for breathing)
temperature
toxic gases
smoke generation

was not clear, especially in the context that the airworthiness requirements do not make reference to all of those parameters.

SURVIVABILITY PARAMETERS	FULL SCALE TEST (values after 2 min)
oxygen	down to 2%
temperature	up to 1000 °C
toxic gases	far above lethal dosis
smoke	zero visibility

4 SURVIVABILITY IN IN-FLIGHT FIRES BMV LR 15

To highlight the situation: The German full scale test, mentioned before, showed that after 2 min. a passenger would be suffocated, and burned, and poisoned, and that all in an atmosphere full of smoke, where the deplorable victim is not able anymore to see his hands in front of his eyes.

In addition, one was not really convinced that the fire safety requirements existing at the early 1980's in practice covered both, post-crash and in-flight fires, because their scenarios are so different.

POST-CRASH FIRE	IN-FLIGHT FIRE
- structure must sustain fire for 5 min	- restriction of fire location for 20 min (continent. flights) 180 min (intercont. flights)
- attack of fire on ground after 2 min	- no external help before landing
- external help for pass.	- passengers in cabin
- passenger evacuation in 90 sec.	

5 AIRCRAFT CABIN FIRE SCENARIOS BMV LR 15

For post-crash fires the time for which the fuselage structure must sustain the fire can be assumed to be in the order of 5 minutes, whereas the time intervall before the fire can be attacked from external sources will be 2 min., and the passengers have been evacuated from the aircraft within 90 seconds (according to the regulations). Concerning in-flight fires, one must face the fact that for instance on continental flights a fire has to be restricted as far as possible to its location where it has started for at least 20 minutes (on intercontinental flights in the order of 180 min.), and during this time the fire must not endanger the safe operation of the aircraft and the lifes of the occupants. Help from the outside is not possible before landing.

According to the experiences and test results, some of the comments related to the FAA full scale test in 1984 simulating a post-crash fire, like
- a safe evacuation of the cabin is possible until the time when a flashover occurs,
- the mutual dependence of flammability and smoke generation does not necessitate separate test methods,
- the amount of toxic gases, generated before a flashover occurs, is below the lethal dosis,

have at least to be put into question for in-flight fires.

Apart from these pure technical considerations the German side felt especially responsible for the development of aircraft fire safety, because the MBB company manufactures among other things the complete interior layout for all Airbuses.

5. LABORATORY TESTS

To ensure that the interior components (e.g. hatracks, seat cushions, linings, foldable tables, carpets etc.) used for the 1:1 scale in-flight fire test comply at least with the applicable requirements, a series of accompanying lab tests was defined. The following fig. 6 summarizes the most essential ones.

TESTS / TEST EQUIPMENT	PURPOSE OF TEST / REQUIREMENT
- FLAMMABILITY (bunsen burner test)	FAR 25.853 Am. 32
- NBS-CHAMBER smoke density toxic gases	Airbus Specification ATS 1000
- OSU-CHAMBER	heat flux 3.5 & 5 W/cm²
- OIL BURNER TEST (seat fire blocking layer)	FAR 25.853 Am. 59
- FULL SCALE COMPONENT TEST	determination of fire source

6 LABORATORY TESTS BMV LR 15

While the existing airworthiness requirements at that time asked for the Bunsen burner test only to show compliance with the flammability requirements, in addition lab tests related to smoke density and toxicity values of the emitted gases were performed on the basis of the requirements of the Airbus internal specification ATS 1000.

Furthermore, all main parts installed in the cabin were tested in the OSU-chamber (Ohio State University) to show compliance with the heat release requirement "100/100" (100 kW/m² maximum within 5 min., 100 kW min/m² integral value for the first 2 min.), which became valid by mid of 1986, and the more severe "65/65" heat release limit, required by mid of 1990. To be in the position to evaluate how the materials of the installed parts and components alter their behaviour, if they are exposed to a fully developped fire with higher heat load, the OSU-chamber tests were conducted with a heat flux of 3.5 and 5 W/cm². To check the effect of the fire blocking layers in seat cushions (requirement since Nov. 1984), they were tested in an oil burner test. The main parameters for the fire source (e.g. fire duration), to be used in the 1:1 scale test, were determined by a number of full scale component tests.

During the evaluation of the final in-flight fire test results it turned out that some of the components in the cabin, like linings, seat arm rests, and foldable tables, contributed to the propagation of the fire and above all to the generation of smoke and toxic gases to an unexpected extent. It could not be foreseen before the full scale test that such a small portion of material of the interior equipment played such a great role on the high concentration of toxic gases.

6. REMARKS ON THE OSU CHAMBER

For the determination of the smoke density and of the toxic gas emissions from materials used in aircraft interior fittings, the NBS chamber (National Bureau of Standard/USA) provides an appropriate test means. However, this chamber can not be used for heat release measurements. For this purpose another test equipment, the OSU rate-of-heat-release apparatus (Ohio State University/USA) was introduced on recommendation of the SAFER Committee. The FAA declared, the OSU chamber would be most representative of post-crash fire environments, and the ranking of materials from the OSU tests would be identical to that obtained in full scale fire tests.

However, it seems to us that not all questions arising from the use of the OSU chamber have already been solved. For instance, a number of round-robin tests, in which several US and European OSU chambers were involved, showed that obviously small differences in the design of the chamber caused relatively large variations in the test results. Up to now it can not for sure be excluded that one particular material could be found acceptable in one chamber and unacceptable in another one. At least, when the more severe 65/65 heat release requirements come into force in 1990, a good and reproducable accuracy is required.

The necessity to use different test facilities for showing compliance with the flammability, smoke emission, heat release, and toxicity requirements and recommendations led to a study in Germany to investigate the feasibility of the OSU apparatus for more than only heat release measurements. It came out as a preliminary result that the OSU chamber could be extended without major problems for smoke density measurements, and in principle also for analysing toxic gases. However, this task is not followed anymore at the moment and stays as an open question to be studied in more details in the future.

7. SURVEY ON THE FULL SCALE IN-FLIGHT FIRE TEST

The test set-up and the results will be presented in details by a separate paper (Full Scale Study of a Cabin Fire in an A300 Fuselage Section, K. Dussa, R. Fiala, R. Wagner, B. Zensus/DLR Germany). Summing up the test conditions, the simulated in-flight fire scenario was close to the real flight condition during a fast descent phase, with the air condition running, and atmospheric pressure inside the cabin before the fire started. As fire source, a burner was positioned between the side wall panel and a seat, thus simulating a fire breaking through the cabin floor from a cargo hold below into the cabin. The burner was activated for 105 seconds. After it was shut down, the fire propagated into the cabin by itself.

The following consequences could be drawn out of the test results and out of the burnt remains found in the cabin after the test:
- The fire blocking layers of the seat cushions distinctly reduced the total heat release. However, they could not avoid the propagation of the fire and the occurrence of a flashover after about 2 minutes.
- The breaking down of hatracks must be avoided by structural means or by the use of different materials.
- The generation of smoke must drastically be reduced.
- The carpet of the cabin floor could relatively well withstand the heat. (Immediately above the floor the temperature did not rise much over 200 °C.)
- The seats equipped with fire blocking layers were in relatively good condition after the fire (weight loss below 10 %).
- Due to the temperature peak the survivability of occupants after the flashover is zero. Additional high danger represent the reduction in oxygen and the concentration of toxic gases. (For instance, the measured maximum concentration of HCl of 5400 ppm is far above the lethal dosis.)

8. CONSEQUENCES FOR THE DESIGN OF "FIRE SAFE" AIRCRAFT CABINS

To shift, in terms of time, the life threatening occurrence of a flashover as far as possible, several structural and design related means are at disposal:

a) The use of appropriate materials with the following characteristics:
heavy inflammable and self-extinguishing,
slow flame propagation,
low heat release,
small generation of toxic gases and smoke.

b) Division of the cabin in several sections,
which are smaller than the volume required for a flashover,
smoke venting in the individual sections.

c) Immediate extinguishing of the fire under development by using on-board fire extinguishers:
Determination of the amount of appropriate extinguishing agent in dependence on the fire object,
flooding of the cabin by an on-board water mist system. (Disadvantage: Cann't be directed towards a special location, difficult use for the attack of hidden fires, problems for the passengers.)

9. CONSEQUENCES FOR POST-CRASH FIRES

For fire brigades and rescue squads it is important to know, in the case of opening the fuselage exit doors, that they will be faced with 250 °C hot gases (possibly escaping under pressure), mixed with a high amount of soot and 3 to 7 % carbon monoxid. The amount of oxygen can be reduced to 2 %. Only after 4 minutes, that means 2 min 15 sec after having shut down the original fire source, the visibility inside the complete cabin, also close to the floor, was reduced to zero.

The fire brigade, when entering the fuselage by the emergency doors, must be aware that parts might have been broken down from the cabin ceiling, and possibly openings must be broken from the outside into the fuselage structure on other locations. To extinguish a fully developped cabin fire at least 2500 kg Halon 1211 are necessary.

10. VIEW TO FUTURE GERMAN AIRCRAFT FIRE SAFETY ACTIVITIES

The experiences gained from the lab tests, the full scale test and the study of the respective literature have shown that some questions can only be solved by further experimental investigations. For instance, frequent fire causes, like galleys or toilet units, were tested in very few cases only. In addition, it is not known until now, how the air flow in the cabin, caused by the running air condition, influences the propagation of a fire and the smoke generation. Because full scale tests in fuselage sections are very expensive, further component tests are planned to clarify the relation between air flow rate, air flow distribution, fire intensity, smoke density and smoke distribution.

For this purpose the DLR research institution designed and built a full scale test set up, reusable for a great number of tests at reasonable costs, with complete seat rows, galleys etc. The test stand, suitably equipped with a data acquisition system, consists of a 6 meter long part of a simulated aircraft cabin. Beginning this year, these full scale component tests will present a major event in German fire research activities.

The component test stand shall also be used for testing new products almost continuously offered by the chemical industry and aircraft equipment suppliers (for instance: new foams for seat cushions). Furthermore, theoretical investigations are intended on the basis of existing calculations on fires in buildings taking into account air flows in corridors and passage ways.

In summary, the tasks which will be supported in Germany during the next years can be divided into several groups:

1 COMPONENT TESTS
combinations of components of interior equipment
(seats, wall panels, hatracks, galleys, toilet units etc.)

2 LAB TESTS (NBS & OSU chamber)
new materials and component structures,
for which fire data are not yet available

3 CORRELATION OF LAB & FULL SCALE
COMPONENT TESTS
related to fire propagation, temperature, heat flux,
smoke generation

4 2nd FULL SCALE TEST
using modern widebody fuselage section

7 FUTURE GERMAN CABIN FIRE RESEARCH

At least one further full scale test is planned, which however is not yet defined in details. But it is ensured that the existing widebody fuselage section of the first full scale test can be used for one or even two more fire tests.

11. CONCLUSION

Solving the questions of the physical-chemical reactions of fires occurring under the special conditions to which aircraft are exposed, and developping new materials etc. are not enough to minimise the risk of cabin fires in future air traffic. More decisive is the application of all these new means and safety systems by the aircraft manufacturers and operators. This is not an easy task, even for new aircraft, because this is always a question of costs. The transfer of the knowledge on fire safety is even more important for older aircraft. The situation becomes obvious if you take into account the worldwide number of 2300 transport aircraft built before 1968 and still being in service. The youngest fleet in Europe (Swissair) has still an average age of 5.7 years, the average age of the total US-fleet is just over 12 years. Before not all aircraft will be equipped according to the latest fire safety knowledge the risk of danger will not be reduced decisively.

To come to a reasonable solution within a reasonable period of time, it is the Airworthiness Authorities which have to define requirements presenting a compromise between realistic time intervalls for application and the justified safety demand of the passengers.

NEW AIRCRAFT CABIN AND CARGO FLAMMABILITY STANDARDS FOR TRANSPORT CATEGORY AIRCRAFT

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SUMMARY

In transport aircraft, passenger safety is of paramount importance in establishment of criteria and requirements covering fireworthiness. Thus for cabin and cargo interiors, regulators and aircraft manufacturers have established flammability standards and/or criteria for materials used in these areas. The aircraft manufacturers in turn furnish aircraft with existing state-of-the-art materials technology which will satisfy or exceed the standards and/or criteria requirements. This paper outlines the evolution of these flammability standards to-date and test methods used to ascertain compliance and an indication of the materials used to meet these standards.

INTRODUCTION

Passenger safety is of prime importance in the estabishment of criteria and requirements covering fireworthiness for transport category aircraft. To satisfy as much as practical the desire for passenger aircraft manufacturers generally take the following approach:

1) Eliminate ignition sources.

2) Systematic application of design provisions to contain, suppress and/or extinguish fires that may occur.

3) Use of materials that are highly resistant to fire and fire spread, and that minimize the emission of smoke and toxic gases.

With regard to the latter, this paper traces and outlines the history and evolution of passeger aircraft material flammability standards and associated test methods regulated by the FAA and voluntary standards adopted by industry to upgrade fireworthiness and reduce toxic gas emissions of burning materials.

INTERIOR CABIN MATERIALS

The history of FAA's flammability standards up to 1972 can be summarized by reviewing the original burn requirements for interior wall and ceiling panels (See Figure 1).

The first flammability requirement was implemented in 1953. It required cabin linings to be tested to a horizontal burner flame test. Criteria for passing this test was that the burn rate was not to exceed four inches/minute.

In 1967 cabin flammability standards were upgraded to include a vertical burn test. Criteria for passing this test was that materials be self extinguishing without having a burn length longer than eight inches in the vertical test nor 4 inches in the horizontal test.

In 1971/72 with the introduction of wide bodied aircraft the flammability standards were further upgraded. The horizontal test was eliminated and the test specimens were required to be self extinguishing within fifteen seconds. When tested vertically, the time of flame exposure was increased from twelve seconds to sixty seconds. Additionally the burn length could not exceed six inches nor could drippings burn more than three seconds.

In approximately 1979, industry established some voluntary standards and objectives in addition to those decreed by the regulatory bodies in selection of materials. These standards and objectives included low smoke emissions, low flame spread rate and maximum toxic gas emissions. For typical objective values see Figure 2.

It is evident from the foregoing, that since 1953 significant improvements had been enforced and voluntary standards or objectives implemented to increase the fire resistance of cabin materials. However, not withstanding these improvements, there was still a major concern about the ability of passengers to survive in a post crash. Thus in 1979/80 a Special Aviation Explosion Reduction (SAFER) Committee was formed and this committee along with its technical supporting groups, examined the factors affecting the ability of passengers to survive in the post crash fire environement and the range of solutions available. The committee recommended, (a) further research and development in regard to cabin materials, (b) implementation of a method using radiant heat for testing cabin interior materials, (c) establish the contribution of cabin interior materials relative to the post crash fire hazard, (d) develop for aircraft seats fire blocking layers, e.g. fire barriers for polyurethane foam cushioning materials in order to retard fire spread.

As a result of the above recommendations the FAA initiated the necessary research and development, conducting full scale testing using a C-133 aircraft fuselage to represent wide body transport. The test conditions simulated representative post crash external fires and numerous laboratory tests were conducted to correlate possible material qualification test methods with full scale tests. Additionally in-flight fire scenerios were conducted with the C-133 fuselage using various on-board fire sources such as carry-on luggage, arson fires using flammable liquids and on-board paper trash.

Significant findings of the FAA testing were as follows:

(a) Burning cabin materials can be a primary factor affecting occupant survivability in certain types of post crash fires.

(b) Fires in an intact fuselage will produce "flash-over" conditions which will be followed by loss in survivability throughout cabin.

(c) Seat blocking layers can be affective to subdue the burning of polyurethane seat cushions.

(d) The Ohio State University (OSU) rate of heat release apparatus as standardized by ASTM E-906 was the most suitable for material qualification.

After completing and documenting their work, the FAA in 1985 introduced a notice of proposed rule making (NPRM 85-10) for improved flammability standards for all large interior surface materials installed above the floor in compartments occupied by the crew or passengers. The rule established more stringent test requirements by measuring the intensity of heat release by utilizing the OSU apparatus.

In the OSU test procedure (See Figure 3), a vertically oriented specimen is exposed to the thermal assault from a radiant heat panel for an exposure time of five minutes. At ignition the combustion products leaving the chamber are monitored by the output/intensity radiation located at the outflow of the apparatus. The heat release measured is (a) total heat release at two minutes and (b) peak heat release rate.

Following the original issue of the NPRM 85-10, industry had considerable technical concerns with the rule and testing. Preliminary testing by industry yielded results considerably different from those obtained using the FAA test results. This resulted in a series of round robin testing of the same groups of materials by various laboratories to assess repeatability and reproducibjlity of results. Based on the results of these tests, the following changes were made to the test procedure and acceptance criteria.

1) Adjustment of specimen exposure heat flux from 5 watts/sq.cm. to 3.5 watts/sq.cm.

2) Elimination of oxygen depletion method for measuring heat release.

3) Adjustment of acceptance criteria over first two minutes of sample exposure from 40 to 65 kilowatt-minutes/sq.meter.

4) Inclusion of the requirement of peak heat release rate of 65 kilowatts/sq.meter.

The FAA introduced the peak heat release rate to exclude materials which have low levels of total heat release but none the less emit a large amount of heat over a short duration causing rapid fire spread.

During the discussion and commentary period of the NPRM the Air Transport Association (ATA) and the Air Industry Association (AIA) at one point proposed an alternate test criteria, comprising of a two tier certification system (See Figure 4).

Tier 1 - Certification of Material Systems used in the various construction types in major support parts, with requirements involving OSU radiant heat release test and smoke test.

Tier 2 - Certification of individual parts by the vertical flammability test FAR 25.853(a).

The pass/fail smoke and heat release limits were set to allow use of the state-of-the-art marterials and the inclusion of smoke release was intended to distinguish between "desirable" and "less desirable" material systems in a straight forward and conclusive way. A less desirable material in the 100/100 heat release range was considered to have excessive smoke release characteristics (See Figure 5). Additionally it was pointed out that essentially there were five construction types used for major support interior parts and each of these construction types is represented many times in a typical cabin with variations between constructions being minor. Thus by using the two tier certification, the amount of testing necessary for certification and quality control would be brought into manageable bounds and would allow separation of desirable from less desirable material systems.

Industry further contended that -

(a) their data did not support peak heat release rate as being of any greater value than heat release as a material selection criteria, as rapidly burning materials were already excluded by the material flammability test requirements;

(b) although reasons for correlation between smoke emission and time to flash-over were not perfectly understood, a direct relationship had been observed during tests of actual production materials;

(c) history had shown that smoke emission can be of significant importance during in-flight fires.

The FAA contended that the proposal to use two tier procedure was inadequate essentially for the following reasons:

- critical factor in survivability is time afforded for egress before flash-over occurs and the release of large quantities of heated gases which eventually result in flash-over is not relative to the amount of smoke released;
- no known scientific correlation of smoke release and flammabililty of materials;
- insufficient flammability data to determine whether there is a correlation between flammability of individual components of assembled system and the flammability of the system.

However, not withstanding the above objections, considering the general belief that smoke testing should be conducted to eliminate the use of materials which produce excessive obscuring and irritating smoke which can cause distress and panic and the fact that industry already uses smoke emission criteria, the FAA amended the final rule to require smoke testing. The final cabin liner rule presently is as shown in Figure 6.

The availability of complying materials to meet the 65/65 heat release standards by 1990 was an industry concern, as it was generally felt that the requirements could not be met with known materials that would satisfy the standards while meeting practical fabrication, durabililty, maintenance and appearance standard requirements. Essentially, presently in wide body aircraft, the bulk of the sidewalls are basically composed of Nomex (aramid) honeycomb core with fibreglass or Kevlar facings impregnated with Epoxy or Phenolic resins and a decorative laminate composed of Tedlar (PVF) or Tedlar and Polyvinyl Chloride (PVC) layers. Many of these parts with or without minor changes will meet the interim 100/100 rule but will not meet the 65/65 rule. To meet the 65/65 rule sandwich panel construction must be modified and newly developed decorable thermoplastics or textiles need to be applied.

Typical changes that are occuring in cabin interiors to meet the 100/100 rule are as follows:

EXISTING CONSTRUCTION	NEW CONSTRUCTION
Epoxy/Kevlar Sandwich Panel with Decorative Laminate	Phenolic/Glass Sandwich Panel with Decorative Laminate
Epoxy/Kevlar Sandwich Panel with Grospoint Decorative	Phenolic/Glass Sandwich Panel with Replin/PBI
Polycarbonate Integral Color	Polyetherimide (Ultem) Painted Finish
Dado Carpet	LW40 PBI Replin backed with Nomex Felt
Polyester/Glass Laminates	Phenolic/Glass Laminates

Some aircraft have sidewall panels constructed of aluminum with a laminated decorative finish. These panels would comply with the 65/65 rule. However the use of composite construction is considered more preferable from the industry point of view as it affords reduced weight (aluminum panels 2½ times heavier) and provides superior burn-through resistance from an external fed fire source which might occur in a crash situation. (It was estimated by industry that the additional added fuel burn to account for added weight on a 100 furbished aircraft per year to be one million gallons of fuel.)

In response to the above the FAA contends that their tests indicated that -

(a) flame penetration through windows or possibly through cabin air grills would occur much earlier than penetration through the fuselage external surface, any insulating material and aluminum interior panels;

(b) flash-over from an external fire source would occur much later than it would occur from a fire that enters the cabin through a fuselage rupture giving occupants more time to egress safely;

(c) Phenolic resin fiberglass construction as produced by some manufacturers will meet the 65/65 standard.

SEAT CUSHION FIRE BLOCKING

A major danger in aircraft fires is what is termed as "flash-over" where flammable vapours trapped high up towards the ceiling of the cabin will suddenly ignite and propagate the fire across the whole upper interior portion of the aircraft like a wave. It was recognized that a major source of flammable vapours leading to this condition is the decomposition of polyurethane foam.

One option was to replace the polyurethane with materials that do not yield flammable vapours on pyrolysis, e.g. Polyimides. However it was found that these foams could not be produced to obtain the comfort, resiliency and durability required for seats. Another option was to use a neoprene foam. Neoprene foams have excellent flame resistance and some formulations were available which had reduced smoke emissions and weight. However the density of this neoprene foam (7-8 lbs) was still too high for aviation use. An additional option considered was the use of fire retardant additives. The known fire retardant additives could not suppress production of combustible vapours from polyurethane foams under sustained heat fluxes.

With the option of fire retardants considered ineffective and since there was no commerical available foam cushion systems in early 1980 which had all the qualities needed for seats, such as comfort, durability, acceptable weight, etc., and yet provide sufficient fire protection, the concept of a fire blocking layer encasement was developed. The fire blocking layer encasement is designed to inhibit or prevent the fire involvement of the flammable polyurethane foam underneath. This involves covering the polyurethane foam cushion with a layer of fire resistant material that will provide ablative (sacrificial) protection of the polyurethane foam such that it would delay the fire involvement of the polyurethane foam.

Tests conducted by the FAA and others demonstrated the superiority in fire performance of cushions protected by fire blocking layers over the unprotected cushions. As a result in 1985 the FAA issued new flammability performance criteria involving the use of a Kerosene Burner Test under FAR 25.853(c). See Figure 7 for the requirements.

The materials generally presently being used as fire blocking layers are PBI Felts, Woven Carbon Fiber Fabrics, Woven PBI/Nomex Fiber Fabrics, Woven PBI/Kelvar Fiber Fabrics wrapped around a fibreglass core. The foams used under the fire blocking layers are generally flame resistant molded polyurethane foams which have improved fire resistance over the flame resistant slab foams. Also being used for passenger seats is a flame resistant modified polyurethane foam called Metzoprotect FR. The seat bottoms manufactured from this foam is a sandwich construction consisting of a core foam plus a 13mm outer layer of Metzoprotect FR. The back rest cushion is a solid Metzoprotect FR perforated foam. For flight attendant seats in which there are no major concerns regarding weight and which do not require foams of similar physical properties as foams for passenger seats, flame resistant silicone and neoprene foams are being used.

CARGO LINING MATERIALS

The majority of commercial aircraft lower cargo compartments are certified as Class D or Class C compartments. Class D compartments are generally smaller (1000 cu.ft. max) than Class C compartments and are not required to have smoke protection or fire suppression systems. They depend on the limited availability of fresh air in the compartment to eventually suppress any fire through oxygen starvation. The integrity of the liners in Class D compartments is critical because a burn-through would allow entrainment of exhaust air which flows around the compartment. This would feed oxygen to the fire and limit the fire containment capability of the compartment.

Class C cargo compartments are required to have smoke detection and fire suppression systems as well as the ability to control ventilation systems to control environment in the compartment. Burn through would allow cabin exhaust air to mix with air in the cargo compartment. This would provide (a) fresh air in a fire (b) dilution of the fire extinguishing agent in the compartment.

Prior to 1986 cargo liners (Class B through E) were only subjected to vertical and 45 degree burn tests using a 3/8 inch I.D. Bunsen burner. A minimum flame temperature of 1550°F was required and applied for 30 seconds. Criteria for passing the 45 degree burn test was no penetration of the material after the removal of the flame source, flame time not to exceed 15 seconds and average glow not to exceed 10 seconds.

The FAA work on compartment liners completed in 1985 concluded that the above burner tests did not assure that liners in Class C and D compartments would not burn through when subjected to realistic fire exposure test conditions. As a result in 1986 a new fire test was adopted for ceiling and sidewall panels of Class C and D compartments which exposed sample sidewall and ceiling liners simultaneously to a flame at 1700°F and 8 BTU/ft^2.sec. at 8 inches above the flame for five minutes. The criteria for passing are that no flame penetrates either liner and that the temperature measured 4 inches above the ceiling liner not exceed 400°F.

Of the 46 combinations of materials tested by the FAA, only 20 were capable of meeting the 400°F limitation. Liners using Kevlar or Nomex were unable to meet the burn through and/or the 400°F limitation. One surprising result of the testing was the inability of unidirectional fibreglass liners to pass either the burn through or 400°F limitation.

Materials presently used for liners to meet the new test criteria are fibreglass cloth with Phenolic, Epoxy or Polyester Resins. The Phenolic resin materials have superior smoke emission properties.

CONCLUSION

The new cabin and cargo flammability standards adopted will no doubt enhance passenger safety and will be further improved in time when improved state-of-the-art materials are developed and voluntarily adopted by the airlines during scheduled refurbishment practices. To meet the 65/65 heat release standards by August 20, 1990, Industry will need to carry out extensive evaluations of heat, smoke and toxicity requirements of new materials and development of new production processes.

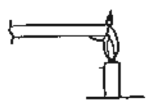
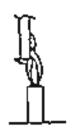
	15-SEC EXPOSURE BUNSEN OR TERRILL BURNER SPECIMEN SIZE: 4 BY 14 IN.	MAXIMUM BURN RATE: 4 INCHES/MINUTE
 VERT  HORIZ	15-SEC EXPOSURE (HORIZ) 12-SEC EXPOSURE (VERT) BUNSEN OR TERRILL BURNER SPECIMEN SIZE: 4½ BY 12½ IN.	SELF-EXTINGUISHING MAXIMUM CHAR LENGTH: 8 INCHES VERTICAL 4 INCHES HORIZONTAL
	1600 = 50°F 60-SEC FLAME EXPOSURE	SELF-EXTINGUISHING AVERAGE BURN LENGTH: 6 INCHES MAXIMUM FLAME TIME - 15 SEC MAXIMUM DRIPPINGS SELF-EXTINGUISHING 3 SEC MAXIMUM

FIGURE 1: Flammability Resistance Interior Linings Regulation Evolution.

FLAMMABILITY — FLAME SPREAD INDEX MAXIMUM 25:

- APPLICABLE TO ALL MATERIALS EXCEPT TEXTILE SOFT GOODS

SMOKE — 2.5 WATTS/CM^2 HEAT FLUX:

SMOKE EMISSION AFTER 4 MINUTES: D_s MAXIMUM 50

- APPLICABLE TO ALL MATERIALS

TOXICITY — 2.5 WATTS/CM^2 HEAT FLUX:

GAS EMISSION (PPM)	CO	HCN	HF	HCl	SO_2	NO_x
AFTER 4 MINUTES	3500	150	200	500	100	100

- APPLICABLE TO ALL MATERIALS

FIGURE 2: Industry Materials Fireworthiness Objectives

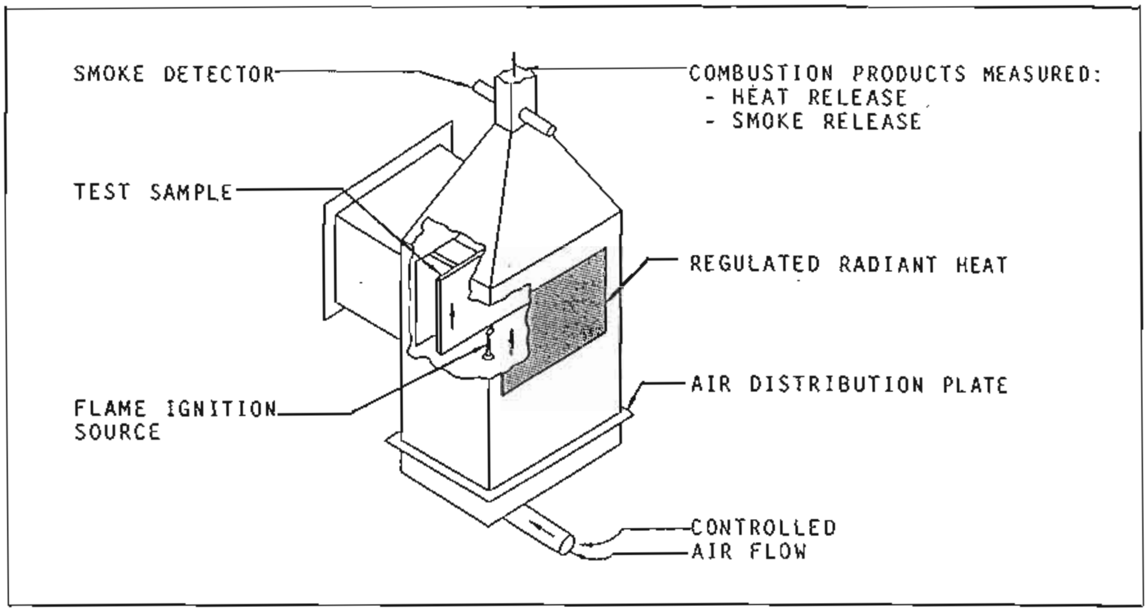


FIGURE 3: Ohio State University (OSU) Calorimeter

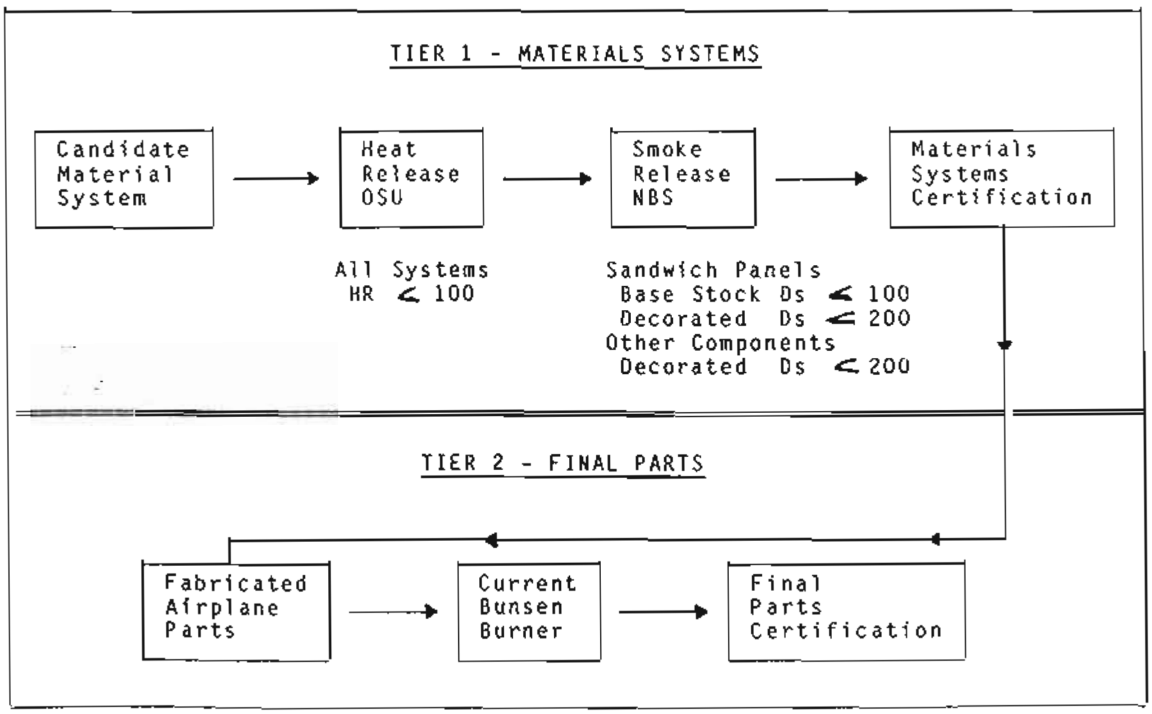


FIGURE 4: Certification of Materials Systems and Fabricated Parts

GENERIC PANEL TYPE	TIME TO FLASH-OVER	DESIRABLE/ LESS DESIRABLE	SMOKE RELEASE (4 min) Ds
	(C-133 full scale results)		
	(seconds)		
Epoxy/Glass	75	Less desirable	218
Phenolic/Glass	240	Desirable	18
Epoxy/Kevlar	not run	Less desirable	212
Phenolic/Kevlar	75	Less desirable	118
Polycarbonate	---	Less desirable	200
ABS	---	Less desirable	400

FIGURE 5: Characteristics of Generic Panels

BY AUGUST 20, 1988

- 100 Kilowatt-Minutes/sq.meter - Total Heat Release Over First 2 Minutes
- 100 Kilowatts/sq.meter - Maximum Peak Heat Release

BY AUGUST 20, 1990

- 65 Kilowatt-Minutes/sq.meter - Total Heat Release Over First 2 Minutes
- 65 Kilowatts/sq.meter - Maximum Peak Heat Release
- 200 Maximum Optical Smoke Density After 4 minutes
  - Heat Release Measurements by OSU
  - Smoke Density measured in flaming mode per ASTM F814
  - Vertical Bunsen Burner Test per FAA 25.853(a) also required.

FIGURE 6: Cabin Liner Heat and Smoke Release Rule

"UPON THE FIRST SUBSTANTIALLY COMPLETE REPLACEMENT OF THE CABIN INTERIOR..."

AFTER AUGUST 20, 1988 - HEAT RELEASE REQUIREMENTS OF 100/100

AFTER AUGUST 20, 1990 - HEAT RELEASE REQUIREMENTS OF 65/65
SMOKE EMISSION REQUIREMENTS OF 200

FIGURE 6A: Airplane Retrofit Cabin Liner Heat and Smoke Release Rule

. 2 MINUTES DIRECT FLAMING
. TEMPERATURE 1000 - 1078°C
. RADIATION INTENSITY 11,5 W/M^2
. WEIGHT LOSS LESS THAN 10%
. BURN LENGTH LESS THAN 43 CM

FIGURE 7: Requirements - Kerosene Burner Test FAR 25.853(c)

Fire Prevention in Transport Airplane Passenger Cabins

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Summary:
The most important aspect in air transportation is safety, a part of which is fire prevention. In the environment of the passenger cabin there are different ways to prevent fires. The most obvious one is to provide adequate detection and extinguishing devices. The second way is to design in a fire-preventive manner. The third and most challenging way is to be concerned with fire-resistant materials of the latest state of the art. Although airplanes are designed and built by big airframe manufacturers the airline engineers can take some influence on a fire-hard cabin. Aside from continually requesting changes from aircraft manufacturers the engineers can force the interior equipment vendors to use advanced techniques and materials. This, however, requires a certain degree of know-how and the good intention to assist these vendors.

GENERAL

Before I begin with my report I want to point out one fact: as an airline man I cannot present any latest scientific news, nor can I offer an outstanding know-how about things like new technologies or advanced materials. The basic task of an airline engineer is to keep the planes flying and thereby care for safe, punctual, economic and - from the view of our passengers - most comfortable conditions. The only thing I can present, is our way of understanding and realizing safety and our experience we made with all resulting actions.

The most important aspect in air transportation is of course safety, a part of which again is fire safety. Fire safety can and must be approached in different ways. We all remember that there have been very interesting measures such as the development of AMK (anti-misting kerosene) or the presentation of a water sprinkler installation. There have been improvements in crew training and fire fighting techniques. There are useful discussions about things like reduction of the quantity of newspapers on board as well as restrictions of carrying duty free alcohol in the cabin. In this paper I will restrict myself only to actual technical measures mainly in the passenger cabin. In the technical field of cabin fire safety there are three ways:

- adequate fire detection and fighting provisions

- fire-sensitive design

- selection of fire resistent materials.

Although airplanes are designed and built by big airframe manufacturers the airline engineers can take some influence on a fire-hard cabin. To get some desired results from the airframe manufacturers is not an easy task and the success is limited. However, by continually requesting changes from aircraft manufacturers the engineers can at least achieve some compromises. A better situation exists on the BFE (Buyer Furnished Equipment) market: a strong airline can force the interior equipment vendors to use advanced techniques and materials. This,however, requires a certain degree of know-how and the good intention to assist these vendors.

FIRE DETECTION

Let us begin with the detection. With the word "detection" we assume that there is a relatively small fire at first which has to be detected and fought before it becomes unmanagable. The typical case is an inflight fire. As a rule of thumb, any device should be installed where the fire is likely to occur. Sources of fire are usually cigarette butts or failure of the electrical equipment. In the cabin itself we can live without technical systems, as the cabin is normally under control of the cabin crew and the passengers. A similar situation is in the galley areas; however this requires a continuous occupancy of the galleys - also during the time between the service preparations. A watch has to be there because there is equipment like ovens, coffee makers and hot jugs which can be a source of fire.

A more sensitive area are the lavatories; mainly because they "are hidden" places with potential sources of fires: electrical components (flush motor) and smokers. Therefore, it makes good sense to install a detection system. LH decided for a smoke warning system which warns by illumination of warning lights in the cabin and sound of an acoustical sign.

FIRE FIGHTING EQUIPMENT

The most important fire fighting component is of course the **fire extinguisher**. LH uses BCF-extinguishers (In the cabin 1.1 kg; in E&E compartments 2.5kg and MD Cargo Compartments 7.5 kg). For instance, in our 747 we use 1 extinguisher in the cockpit, 1 on the upper deck and 10 on the main deck, i.e. 1 each at every cabin attendant station.

There could be a dispute about the locationing in the cabin, because there are arguments in favor of locations where fires are more likely to occur, for instance in galleys. We believe in the importance of an easy reachability for a seated and belted attendant and for an even and obvious distribution over the cabin. Moreover, our location standard - which is valid for all types of our aircraft - makes sure that different lavatory and galley locations and layouts do not affect the attendants' orientation: the fire extinguisher can always be found on the lower outboard side of an attendant seat.

Another area of concern is the type of the extinguishers. Although the FAA is going to require also water type extinguishers our experts believe that the Halon extinguishers are still superior, and this opinion is shared by airport authority firemen.

Automatic fire extinguishers are installed in the lavatory trash cans. However, this installation is usable only, if there is a scheduled check of these bottles. There were some instances of bottles having been discharged without reason. We at Lufthansa perform visual inspections for discoloration every B-Check and weigh the bottles at every C-Check.

Although the fire extinguisher is the most important equipment for fire fighting there are several other helpful devices:

- **Crash axes** serve to break-off blocked accesses,their handles are insulated against high voltages.
- **Crow bars** serve to separate burning partitions and serve as lever-arms.
- **Protective gloves** are to take hold of hot or burning objects.
- **Smoke goggles** are worn in addition to Quick Donning Mask in case of smoke and gas emission.
- For fire fighting in connection with heavy smoke emission we have **portable oygen equipment** in connection with **full face masks**.

An item of discussions is the introduction of **smoke hoods** as standard passenger safety equipment. Whereas smokehood advocates suggest smokehoods to become mandatory (like oxygen and life vests), we are not sure whether in the panic and confusion of a real case the seeking and donning of the hoods and the confined visibility will adversely affect the evacuation time. And still the discussion goes on what type of equipment could be used: there is a variety from a real hood with breathable gas supply down to a mask with a small filter just covering eyes and nose. And the next problem is: where can that equipment be stowed so that it is really and effectively usable? The only answer can be: in the easy reach of the passenger and that means either the armrest or the seatback, both of which are exposed to vandalism and are space-limited. One can take measures against vandalism - but at the expense of quick donning. One can reserve space in the seatback - but one has to compromise against comfort and space claimed for other purposes, like oxygen equipment (DC10), seatback video monitors or life vests.(There is a "stiff-back" vest under development which can be put on much more easily than the present one and which fits only into the seat back).

A special case is the **fire fighting in the cargo section of combi airplanes.** Aside from the selection and training of fire fighting crews we are evaluating the usage of communication means like an integrated microphone-loudspeaker device, of protective nomex suits and of improved illumination. Also the incorporation of small flaps in container walls are being investigated which allow the depletion of fire extiguishers into the container. However, all these means have to be considered as preliminary, as we do not know yet what the FAA will exactly request for.

FIRE-SENSIBLE DESIGN

The best known example of fire retardant design is **the sealing of the lavatory waste compartments**. Avoidance of gaps, self-closing flaps and other means of fire containment will avoid fire from spreading out even in case there is no automatic extinguisher or this extinguisher fails. Due to wear and tear a periodic inspection of this area is necessary to ensure an equal quality of this condition.

Another example for a solution by design is the Airbus A310 **floor panel** which could not be made from phenolic based material due to insufficient mechanical properties: therefore epoxy was used and the panel wrapped by an aluminim layer.

Designing in a fireproof manner also means the **prevention of dirt accumulation** or uncontrolled paper waste. We are for instance still concerned about the accumulation of clothes and carpet residues in the air return grills, though in two burn tests this material proved self-extinguishing. Despite these results we are requesting from the airframe manufacturers that air return grills or other such openings must be designed that way that there will be no accumulation of dirt or that at least these spots shall be easily cleanable by simple means like vacuum cleaning. "Easily cleanable" means that nocomponent must be removed or disassembled.

Last not least the fire blocking of cushions can be seen under this category, but I will come back to that subject a little bit later.

MATERIAL SELECTION

A new step towards more fire safety is the new rule, commonly known as the **100/100-respectively 65/65 heat** release rule with the new addition of a smoke emission limit.

For us at Lufthansa, this rule was of course new, but the **approach** was not. Years ago we were confronted with something similar, namely the **ATS1000.001** of Airbus Industrie. For us, the ATS1000 was a big step towards cabin safety. Thus, we introduced it into our BFE requirements, even for Boeing and Douglas airplanes, at an early stage. We exempted carpets and floor covering; in the first time, because there was no material available - the ATS-carpets had all the tendency to shrink - , later on we learnt that share of the floor coverings to unsurvivable conditions was neglectible. This has been proved by the full scale fire test in Germany and - if you wish - by the new rule which does not apply to carpets.

The new rule does also not apply to curtains, and maybe there are good reasons. However, for my feeling, the Bunsen burner test is not sufficient. Consequently, we have replaced wool curtains by those of Trevira CS which melts away and thus gives no fuel for a fire.

Let us come to the question: How is the situation regarding new **fire-resistant materials?**

There a sandwich panels available which have average and peak heat release figures between 20 and 40 kW which, in combination with special adhesives and LHR (low heat release) decor foils, still result in OSU testing values well below 65/65. These materials are being used by our interior furniture vendors. Also the paint industry can supply us with 65/65 material.

As far as thermoplasts are concerned, we have begun with the procurement of advanced materials like polyetherimide and polyethersulfone beginning with smaller cabin components like mini-containers and advertizing racks. Some concern constitute the yellowish color of the "Ultem" material which excludes some desired appearances. Furthermore, there is not yet enough knowledge about mechanical properties under operation conditions and resistance against widely used cleaning agents. In this connection, I may remind of the brittleness problems that occured when cleaning polycarbonate surfaces. In any case: we still have to gain more experience.

A special case are **passenger seats**. Passenger seats are installed in a large quantity in the cabin and can therefore contribute to a fire at a great extent. Beside the cushions and fairings, which consist of an organic material, the seats themselves can be made partly or in whole from composites instead of aluminum alloys. This can be advantageous for weight and comfort, but can be seen negatively for smoke and gas emission. I personally would hesitate to introduce such seats, although the regulations exempt seats from heat release limits. But why may we carry tons of plastic materials as seats whereas similar material as panels are not allowed?

By the way, we have some experience with all-composite seats (3 DC10 of our charter subsidiary) and had to learn that after machanical failures bringing these seats to the same strength as conventional seats the manufacturer had to add considerable weight, so that this advantage had been nullified. But I agree that for some components the new material is better.

One widely neglegted aspect is the **repair process** of new materials. In the beginning of A310 operation the only means of quick repairing damaged panels was by laying up epoxy resin patches. Very soon the question came up: to what extent can repairs like that be done without interfering with the ATS1000? There was no answer available; fortunately, one company came up with a quick repair kit, consisting of a Tedlar covered glass phenolic laminate and heat activated adhesive, which we use very frequently especially in cargo compartments, so that all panels even after a couple of repairs still comply with the ATS. Our shop experts are additionally experimenting with low-pressure phenolic processes, which have less limitations with respect to the emission of phenolic and formaldehyde. As far as the heat release rule is concerned we are together with the industry investigating the possibilities of economic repairs. We have found out that using very low heat releasing foils on low heat releasing sandwiches we can repair by just bonding another foil onto the damaged existing one and still are below the limiting values.

One of the most spectacular and - in my opinion - most effective rule was the requirement of **seat cushion fireblocking**. This change has been done in all our airplanes , has been finished - yet we cannot lean back in our chairs feeling we have completely performed our task. To begin with, our measures only make sense, if we really consider the **intent of the** rule and not only the compliance with the kerosene burner test. In a test series we initiated at Hoechst facilities, it was found out that different materials, the test cushions of which resulted in similar weight losses, behaved very different when tested in normal cushion size and shape. In other words: test cushions of defined dimensions had weight losses less than 10 percent, but normal cushions of the same material had losses up to 40 percent! Of course, we do not accept cushions like that although we would comply with the regulation.

A question that is put again and again is: do we prefer a **textile fireblocker** around a conventional **foam cushion or a foam material which is fire retardant in itself?** In my opinion a textile cover is an interim solution until there is a really good foam on the market. On one hand, a textile fire blocker needs more attention: the type of the yarn, the position and kind of the seams influence the burn test results considerably. The layer has to be checked frequently for wear caused by contact with hydrolocks, belt attachments etc. Replacing a foam cushion needs special attention and probably trained personel, which is higher on the payroll: if the fireblocking pocket is not closed carefully and completely, the safety effect will be questionable. In the last months we had a lot of collapsed cushions and we are presently trying to identify the cause. Whether the build-up of an athmosphere of moisture under the layer in connection with the pressure of the passenger's weight weakens the material (as one cushion manufacturer ascertains) or the local thickness of the foam is insufficient has not yet been determined.

Today there are a couple of foam products available which comply with FAR 25.853c. We have been flying "Metzeler" foam for more than one year without greater problems; this had been preceeded by two inflight tests of 3 months each, the second one of which was successful. These tests are standard procedure at Lufthansa to make sure that the comfort level is accepted by our passengers, that there is no early collapsing of the foam and that the cushions withstand the handling by maintenance personell (e.g. velcro must not be torn off). Despite of this good result, we prefer and expect the development of fire retardant cold molded foam - the Metzeler foam is a cut foam - because of easier dress-covering and lower price. Though there are some products onthe market, we are not yet satisfied: one reason is the afore mentioned phenomenon that the behavior of the original size cushions in the kerosene burner test is not acceptable - at least for us. Another problem is still the relatively high weight.

If we use a foam without fireblocker it is essential that a method is established that guarantees the **same material composition of each production batch as the test specimen material**. To cover possible tolerances we have specified a maximum weight loss of 8,5 percent.

Before I leave this subject, let me add two recommendations: firstly, for future developments the FAA should think about modifying the rule and give more tolerance to lightweight seat cushions. Light cushions are not only more economical, but also constitute less fuel for fires. Unfortunately, lighter systems have less fire resistance and thus tend to fail the kerosene burner test more likely, although they might be better for the cabin fire safety. The second recommendation is: the kerosene burner test is expensive, aside from the still bad correlation between the various laboratories. Could not it be possible to develop a secondary simple, small-scale test method which can select between the "good" materials and the "bad" ones?

In the summary of my report I stressed the importance of **influencing the manufacturers towards a fireharder cabin**. One kind of manufacturers is the airplane company, another kind are the vendors of the buyer furnished equipment. Due to the close cooperation between the AIA (Aerospace Industry Association) and the authorities the airplane manufacturer is the first one to be familiarized with the authorities intentions, and the way of information goes normally from the airframe manufacturer to the airline. But sometimes that does not work as far as the hardware is concerned. Of course, the frame manufacturer is interested to create a safe airplane; however he also has to watch soaring costs, because the market usually does not permit to transfer all these costs to the buyer. Furthermore, due to the size of the company the time involved for changes is normally very long. Thus, there are cases, in which we have to put some pressure on an airframe manufacturer. And we did so, in order to get 65/65-material rather than 100/100 material as early as possible and well ahead of the compliance date. If you think of the quantity of part numbers, now doubling into a 65/65 variant and a 100/100 variant for the same part, you will understand. Unfortunately, we were not very successful so that the results is a 100/100 SFE cabin with 65/65 BFE installations - a situation that does not make us happy.

Before I continue, let me give a short explanation, how we at Lufthansa use to come to our cabins. The airplanes we buy are usually empty: the cabin merely consists of floor panels, sidewall- and ceiling panels, overhead bins and lavatories. All the rest has to befurnished by ourselves. We have to buy from various vendors and have to determine how we want it. The approach can be made either, firstly, by designing the interior components ourselves or, secondly, by specifying exactly what we want to get and to leave the design work to the manufacturer or, thirdly, buy material as available and as is. We have decided for the second way.

The vehicle of the **specification** enables us to define exactly which state of the material technology with regard of fire safety we request for, regardless of less stringent rules. As an example I remind of the described processing of the Airbus Industrie specification ATS 1000.

VENDOR SUPPORT

Let us come to the question: How can airline engineers help manufacturers?

The first and most important step is: **to tell them exactly what the airline really wants** and what not. Surprisingly, the vendors often do not know the intentions of their customers. I remember when one seat cushion producer came up with the question whether we would accept o n e fireproof side of the cushion - namely that one which is located towards the kerosene burner. This would not only comply with the rule but also save a lot of weight - we were told - and there would be representatives of some other carriers who are at least willing to think it over. Of course, this was not accepted at all. However, I do not blame this manufacturer, because in the beginning of the fireblocker activities there was a lot of uncertainty about how to comply with the new rule. So it was our turn to carefully explain what we expect from the new material, how we rate safety versus price, weight, comfort and maintainability.

Similarly, when we extended the - at that time only at Airbus customers well-known - ATS 1000 to DC10-seats, the US seat manufacturer could not believe that we willingly added considerable costs for the expensive polycarbonate in lieu of the cheaper ABS and tried to convince us to follow the more "economical" solution. Today, it is a rare exception if an airline accepts or even specifies ABS for seats. I may not exclude that for future seats, we even go further and specify flammability requirements achieved by materials like polyetherimude or polyethersulfone, although the authorities possibly do not intend to impose further flammability rules on seats in addition to the fireblocking requirement.

Every now and then we conclude that our local manufacturers must get a wider-spread background and a "thrust of motivation". We then arrange meetings between them and experts from industry or authorities. These meetings were in the past considered successful, our vendors have learnt to understand the intention ("what is behind") of rules or test procedures, the characteristics of advanced materials and so forth.

When the vendors have understood the intentions it is more easy to strictly fix the requirements, maybe in extreme cases also on a "do-it-or-leave-it" basis. But sometimes one has to extend his help. Let us take a relatively small component - e.g. a time table rack - which shall be changed from polycarbonate to polyethersulfone. The manufacturer needs just a couple of square meters of the new raw material - and will not get it because of the small quantity. Thus, we as an airline have to purchase a larger amount and distribute it to several component manufacturers - hoping that all of them can use it and that all of them learn quickly how to work on it.

FINAL REMARK

Let me finish with an encouraging remark. During the recent years authorities and R & D groups have come up with unusually many safety activities which, on the other hand, resulted in a lot of work and measures - sometimes also in confusion. But we all in the aviation world live from safety, have our part in responsibility for our passengers, our crews and for those who could be involved in incidents or accidents. Thus, all upcoming activities in this field cannot be discouraging, but stimulating!

CHARACTERISTICS OF TRANSPORT AIRCRAFT FIRES MEASURED BY FULL-SCALE TESTS

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SUMMARY

This paper discusses full-scale transport aircraft cabin fire tests conducted in the United States under postcrash fire conditions. The logic behind the development of fire test scenarios is described, including a comparison of fire involvement by external fuel fire penetration through an opening or by fuselage burnthrough. Early full-scale tests in the 1960's and 1970's that furnished data on the characteristics of cabin fires are briefly described. Past test activities addressing facets of the fuselage burnthrough problem are also discussed. The impact of environmental factors (such as wind, door opening configuration, and fuselage orientation) on fire penetration through openings and the resulting cabin hazards is discussed on the basis of past test activities. The majority of the data presented in the paper are from a recent full-scale test to determine fire/hazard progression in a postcrash cabin fire environment with emphasis on post-flashover conditions, to examine factors affecting occupant survivability, and to evaluate the performance of a protective breathing equipment filter. The paper often discusses and cites past studies addressing important cabin fire characteristics and concepts, such as flashover, stratification, and survivability.

INTRODUCTION

Full-scale fire tests are required in any credible activity to improve fire safety in a man-made enclosure, whether that enclosure be a transportation vehicle, building or house. A full-scale fire test may be defined as a realistic experiment, conducted at a 1:1 scale ratio between enclosure and test article, to simulate a fire scenario that has occurred in the past or is likely to occur. The essential elements of a full-scale fire test are a test article, an ignition source, instrumentation, and a means of simulating and/or controlling ambient conditions or adjacent structures affecting the test results (e.g., ventilation, wind, etc.). Although the test article, ignition source, and ambient controls vary considerably depending on the specific type of enclosure being tested, the instrumentation employed is fairly common for all applications. The purpose of the bulk of the instrumentation is to record the life-threatening conditions created by the fire inside the enclosure as a function of time in order to describe and understand the results of the experiment and allow for the development of meaningful conclusions and recommendations. The environmental conditions often monitored include temperature, heat flux, smoke density, and various gas concentrations, including asphyxiants, irritants, carbon dioxide, and oxygen.

Why are full-scale fire tests important? Basically because full-scale fire tests furnish extensive data that usually cannot be obtained in a reduced scale setting or by theoretical calculations with the same degree of confidence with respect to the validity of the results. The objective of a full-scale fire test is usually for one or more of the following reasons:

1. To characterize the fire environment in order to better define or understand the problem;

2. To evaluate or demonstrate the performance of a fire safety improvement (also may require a baseline test to determine the degree of improvement or benefit);

3. To furnish data in support of studies to derive fire safety design requirements or to determine the degree of correlation with small-scale test results or physical/theoretical modeling predictions.

Perhaps the most difficult and expensive type of full-scale fire testing of a man-made enclosure is the aircraft passenger cabin subjected to a postcrash fuel fire. Briefly consider the size of an aircraft cabin, the cost of interior furnishing materials, and the problems associated with employing a large fuel fire as an ignition source. To properly simulate the geometry of a wide-body cabin for fire testing, as representative of the larger commercial transports, requires a test article of 15-20 feet in diameter and a minimal length of approximately 100 feet. The cost of furnishing a representative cabin section is enormous due to the quality and complexity of aircraft interior materials; e.g., the cost of a "typical" sidewall composite panel is on the order of several thousand dollars. Employing a fuel fire as an ignition source creates problems associated with flame control if conducted outdoors and safety and pollution if done inside a building. Until the establishment of a dedicated full-scale fire test facility at the Federal Aviation Administration (FAA) Technical Center in 1980, the number of full-scale aircraft fire tests and the application of the results as a basis for design improvements was rather limited.

AIRCRAFT FIRE SCENARIOS

Fire fatalities in transport aircraft accidents occur either as the result of fire developing in-flight or as a consequence of crash fire. Until recent years, the FAA research, engineering and development (R, E & D) program to improve cabin fire safety has mainly focused on the postcrash fire problem, simply because all fire fatalities involving United States carriers over the past 15 years have resulted from postcrash fire. This paper will concentrate on full-scale fire tests under post-crash fire conditions.

Fatal in-flight fires occur far less frequently than postcrash fires. However, a number of catastrophic in-flight fires have occurred in United States built aircraft operated by foreign carriers; e.g., Varig (1973), Saudia (1980), and Air Canada (1983). A common characteristic of these accidents and fatal in-flight fires, in general, is that the origin of the fire was in a hidden or inaccessible area. In recent years, FAA has placed greater stress on in-flight fire safety as evidenced by current R, E & D activities dealing with hidden fire protection, enhanced emergency smoke venting, a computerized fire detection/advisory system, and electrical wiring arc tracking characteristics (1).

Postcrash fires are usually initiated by the ignition of jet fuel released by parts of the fuel system damaged by the crash. One may expect that the intensity of the fuel fire and potential fuel fire hazards to aircraft occupants will increase as the severity of the crash increases. In this regard, Horeff has ranked six classes of postcrash fire for hazard severity, based on assessment of the likelihood of impact survivability (ability to survive crash trauma) and the number of occurrences in actual aircraft accident experience (2). For example, the most severe case was major fuel spill fires due to wing/partial wing separation and the least severe case was non-fuel spill fires due to ignition by friction. Because of the potential severe fuel fire hazards in accidents with major fuel spillage, FAA has supported R, E & D programs for anti-misting kerosene and fuel system crashworthiness that aim at minimizing or eliminating the fuel fire hazard. However, irrespective of the likelihood of success of these inherently complex concepts, other factors in the postcrash fire scenario may be of greater importance than the intensity of the fuel fire is to occupant survival. One such important factor is the integrity of the fuselage in that area which is adjacent to the fuel fire. Two conditions are possible: (1) a crash rupture or emergency exit opening, or (2) an intact fuselage. Based on a consideration of past accidents, experimental studies, and fuselage design, it is apparent that a fuselage rupture or opening represents the worst case condition and provides the most significant opportunity for fire to enter the cabin. By contrast, ignition and significant involvement of the cabin interior materials by the burnthrough mode is expected much later in time than when direct fire penetration through an opening occurs.

Because fatal aircraft accidents involving fire are fairly infrequent and dissimilar to one another, it becomes difficult to describe a "typical" accident. However, one can hypothesize a realistic accident scenario where burning interior materials control the probability of escape. In order to be representative of past accidents, the fire originates as a pool of burning fuel, adjacent and external to the fuselage. The fuel fire must be relatively large, perhaps on the order of 50-100 square feet, in order to be realistic. If the primary concern is with the dangers of burning interior materials, the fuel fire by itself must not preclude escape. Therefore, the fuselage must be relatively intact along the length adjacent to the fuel fire to prevent direct exposure of escaping occupants. An opening in the fuselage the size of an emergency exit door allows for the ignition of cabin interior materials by the adjacent fuel fire. In order to evaluate the role and performance of interior materials, ambient conditions surrounding the fuselage are selected to prevent or minimize combustion products generated by the fuel fire from entering the cabin. The fire scenario described above was developed by FAA for utilization with a C-133 wide-body test article to evaluate cabin interior materials (3). Full-scale fire test series were conducted to evaluate the effectiveness of seat cushion fire blocking layers (4) and fireworthy interior composite panels (5), and to develop low heat release test requirements for interior panels (6). The test results were invaluable in the development of improved laboratory fire test standards issued in recent years by FAA for seat cushions (7) and interior panels (8,9).

As briefly discussed earlier, ignition of interior materials by an external fuel fire by the mode of fuselage burnthrough is expected to occur much later in time than when fuel fire penetration occurs directly through a fuselage opening. This clearly appears to be the case for wide-body transports; e.g., B-747, DC-10, and L-1011. The fuselage walls of these aircraft (comprised of aluminum skin and heavy structural elements, a thick blanket of thermal-acoustical insulation, and a honeycomb composite interior panel) are an effective fire barrier and will resist burnthrough for several minutes. The burnthrough resistance of a wide-body fuselage was evidenced during the Continental DC-10 accident at Los Angeles in 1978 (10). In this accident a large fuel fire burned for 2 to 3 minutes before extinguishment by the crash fire rescue service. Over this interval the cabin furnishings were spared of fire although windows showed evidence of melting and interior panel seams were slightly heat/flame damaged. It is likely that had the fire burned longer the initial sustained flame penetration would have been through the windows. For standard body aircraft (e.g., B-727, B-737, DC-9, etc.) it is expected that fuselage burnthrough may occur earlier because of the presence of aluminum sidewall panels in many of these airplanes. Aluminum sheet is far less burnthrough resistant than honeycomb composite panels. However, reported accident findings do not present a consistent behavior. In the B-737 accident at Calgary in 1984, fire erupted due to failure of the left engine and ignition of fuel released from the damaged nearby fuel tank (10). Fire was observed immediately when the engine failed and intensified as the airplane was gradually brought to a halt almost 2 minutes later. Yet, the 119 passengers and crewmembers were able to evacuate in an estimated 2-3 minutes, although portions of the cabin filled quickly with smoke when exits were opened and windows melted through somewhat shortly after evacuation commenced. Fire penetration, initially through melted windows and later through the separated aft section, the latter which reportedly occurred after completion of evacuation caused the interior to be eventually gutted. By contrast, in the B-737 accident at Manchester in 1985, which had a similar fire scenario as the Calgary accident, 55 occupants perished primarily from inhalation of toxic gases from the cabin fire. At Manchester it is believed that fire penetrated into the cabin very quickly by melting through the lower fuselage skin and entering by way of the baseboard air return grills. Wind conditions reportedly caused the flames to be drawn into the cabin. Also of relevance to fuselage burnthrough resistance is a 727 ramp fire at Anchorage in 1987. A large fuel fire erupted on the ground adjacent to this airplane when it was inadvertently towed into a loading walkway, causing a fuel tank to be punctured and fuel spillage. Although a large portion of the fuselage skin was melted away, fire did not spread into the cabin. In this incident, the 727 fuselage acted as an effective fire barrier and prevented fire penetration into the cabin.

EARLY FULL-SCALE FIRE TESTS

The earliest full-scale aircraft fire tests provided a foundation for the development of a permanent full-scale test capability at the FAA Technical Center. The following is a brief description of these early tests and some significant results.

The first FAA aircraft fire tests were performed in the early 1960's in five C-97 aircraft under similar postcrash fire conditions (11). The tests were unique to this day in that jet fuel was continuously poured fore and aft of the wing on each side of the C-97, resulting in a fire which grew in size. Since the main objectives were to examine the capabilities of helicopter downwash and ground fire-fighting equipment in postcrash fire rescue operations, the aircraft was void of interior materials. A major conclusion of relevance to this paper was that "the fuselage broken open from impact or with openings next to fire areas offers a much more hazardous condition than the relatively closed fuselage."

FAA's first airplane fire tests to examine the combustion characteristics of cabin materials were conducted in the mid-1960's in a DC-7 fuselage (12). In situ fire tests at different cabin locations determined the relative ease with which the various materials would ignite and burn. In the last two tests the fire was allowed to burn out of control. Both tests culminated in a flash fire which grew from a relatively small fire that appeared harmless. The flash fire propagated at a calculated rate of 68 feet per minute. Up to the time of the sudden occurrence of the flash fire, ambient temperature and carbon monoxide concentration inside the cabin continued to remain low compared to human survival limits.

The Air Line Pilots Association (ALPA) conducted two tests in 1966 to determine if survival time could be extended during a cabin fire by using high expansion foam to completely fill the occupied portions of the cabin interior (13). The test articles were AJ-2P patrol bombers, fitted with a cabin mockup section almost 15 feet long. The fire source was 20 gallons of jet fuel placed in a 3-foot by 5-foot pan adjacent to the fuselage on the upwind side. Although the second test revealed serious drawbacks with the high expansion foam system, the first test provided useful baseline data. It was determined that the initial burnthrough of the 0.035-inch skin occurred at 1:03, which is somewhat longer but consistent with aluminum skin melting times measured in full-scale tests by Geyer using much larger fuel fires (14). Cabin light transmission measurements indicated "extreme stratification of smoke density" throughout the test and sudden cabin flashover at 7:40; both phenomena have been consistently observed in FAA full-scale fire tests in the C-133 wide-body test article.

In 1967-68, the Aerospace Industries Association (AIA) conducted an extensive Crashworthiness Development Program to find ways to increase passenger survivability following an aircraft accident (15). One aspect of the program was to examine the increase in postcrash fire survivability provided by improved cabin materials. The aft 24 feet of a 727 fuselage was subjected to a 30- by 30-inch fuel fire inserted halfway into a 3-square-foot opening in the fuselage, simulating a crash rupture. The AIA tests were conducted outdoors, as were the earlier full-scale tests described previously, which caused changes in the fuel fire behavior between tests due to differences in ambient wind conditions. A wind barrier surrounding the fuel pan was ineffective in providing a repeatable fire condition. The main concern was whether the ambient winds would force fuel flames to penetrate into the fuselage opening, and whether the degree of flame penetration would be reasonably invariant over the test duration and consistent between tests. The degree of flame penetration into the cabin and the resulting level of heat/flame exposure of interior materials has a significant effect on the rate of fire spread in the cabin. Isolation from fluctuating ambient wind conditions was a prime consideration in the decision by FAA to establish a permanent full-scale fire test facility.

Notwithstanding the problems associated with fluctuating winds, the AIA tests produced a number of important findings. Again, as observed in tests by other organizations, flashover and stratification were dominant characteristics. Also, when the fuselage was furnished with present in-service materials, flashover occurred earlier and when ceiling temperatures were lower as compared to the tests with improved materials.

In the early 1970's the National Aeronautics and Space Administration (NASA) ran tests in a 15-foot 737 fuselage section to examine the benefits of advanced fire resistant materials developed by the space program (16,17). To circumvent the outdoor problems associated with variable winds, the 737 test article was closed and a fan was employed to provide a longitudinal air flow. The ignition source was a 1- by 1-foot pan containing one quart of jet fuel placed beneath an outboard seat. The reduction in cabin visibility caused by the smoke produced by the burning fuel was significant and surprising, considering the relatively small quantity used. The results indicated that the advanced materials decomposed rather than ignited when subjected to the small ignition source, they did not support fire propagation, and they did not produce a flash fire (17).

FUSELAGE BURNTHROUGH TESTS

Over the past 20 years, a number of test activities have addressed facets of the fuselage burnthrough problem. However, because none of these activities dealt with the problem in a comprehensive manner, the FAA recently initiated a test program, as outlined later, to attempt to determine the mechanism and time framework for fire penetration into a cabin and ignition of interior materials. The following is a brief description of past studies related to fuselage burnthrough.

Geyer subjected aluminum sheets, mounted to a stainless-steel-covered 707 fuselage, to an adjacent 2500-square-foot fuel fire and recorded the increase in skin temperature as a function of time (14). Two types of alloys and four skin thicknesses (0.016, 0.020, 0.040, and 0.090 inch) were tested. The large fire pit provided relatively complete fire envelopment of the fuselage and maximum fire exposure. In conjunction with the experimental effort, a mathematical model was formulated which permits calculation of the temperature increase with time of the aluminum skin of an aircraft fuselage when exposed to fire (18). The model considers the aircraft skin backed by a layer of thermal-acoustical insulation and takes into account heat gain by radiation and convection and heat loss by radiation and conduction. Reasonably good agreement was obtained between the experimental and theoretical temperature-time profiles (14), illustrating that the mathematical model may be used as a predictive tool. As an example, the model predicted that a 0.040-inch aluminum alloy sheet under maximum fuel fire exposure would melt in 30 seconds, assuming the melting temperature of aluminum alloy at 1200 °F. Another test series employing 300-square-foot fire pits at three different distances from the test article exhibited slower temperature rises of the aircraft skin, which resulted from the different fire pit locations and the poor fire coverage caused by variable wind conditions on the relatively narrow fires (30 feet long by 10 feet deep). Thus, careful consideration must be given to fuel fire size, distance of fuel fire from fuselage, ambient wind conditions, and possibly other factors when attempting to apply the mathematical model to analyze the outcome of an actual aircraft accident.

Sarkos exposed a 28-foot titanium fuselage to a 400-square-foot fuel fire to determine the improvement in cabin conditions resulting from a burnthrough-proof fuselage (19). Not surprisingly, a flash fire occurred at 1:55, attributed to the ignition of combustible pyrolysis gases from room temperature vulcanizing (RTV) silicone pressure sealant, used extensively on the titanium skin, and from the silicone binder employed in the thermal-acoustical insulation. Small-scale fire tests with 2-foot-square panels, matching the cross-section of the titanium fuselage, corroborated the role of the silicone sealant and binder in creating a flaming ignition source and combustible gases that could yield a flash fire (20). The titanium fuselage test results illustrated the potential pyrolysis and ignition of materials adjacent to fire barriers at elevated temperature.

NASA demonstrated the ability of a passenger cabin surrounded by a burnthrough-resistant shell to protect passengers over a prolonged period from a severe external fuel fire (21). Basically, the protective shell consisted of a 2 1/2-inch layer of isocyanurate foam, an ablative foam that converts to a stable char when subjected to heat. To prove the concept, a C-47 fuselage section was divided into two compartments, with one compartment essentially protected with the isocyanurate foam attached to the inner fuselage skin and the other compartment fitted with typical aircraft insulation, and surrounded by a massive fuel fire (5000 gallons). The results indicated that the unprotected compartment was destroyed in about 2 minutes, while the protected section remained largely intact and provided a survivable environment for about 12 minutes. The test was regarded as a first step, recognizing that many problems, such as window protection, weight penalty, and various installation and service considerations, would have to be solved before such a system could be considered.

As discussed earlier, the best information available indicates that in at least two aircraft postcrash fire accidents (DC-10, Los Angeles, 1978 and B-737, Calgary, 1984) the initial or incipient burnthrough of the fuselage was through the windows. A contemporary window system consists of an outer pressure-holding pane and an inner fail-safe pane, both constructed of stretched acrylic, and a thin anacoustic pane attached to the interior panel, constructed of polycarbonate or cast acrylic. It has been observed during experiments that window failure occurs when the stretched acrylic panels shrink and fall out, allowing the fuel fire flames to penetrate into the cabin through the window opening.

NASA has developed a high-char-yield epoxy trimethoxyboroxine transparency that resists burnthrough (22). After an analysis of various options, it was decided that the most practical way to use the epoxy window as a fire barrier in a contemporary window system was as the inner fail-safe pane. To determine the improvement in burnthrough resistance provided by a window system containing an epoxy inner pane, a series of four tests were conducted by FAA in the C-133 wide-body test article (23). In each test the behavior of the acrylic and epoxy window systems were evaluated side by side, mounted on a DC-10 fuselage skin section, when subjected to an 8- by 10-foot fuel fire. The main difference between each test was in the type of insulation and sidewall materials mounted on the cabin side of the test section. It was determined that, on the average, the contemporary acrylic window system failed in about 3 minutes, whereas the improved epoxy window system provided about 1 minute of additional protection. This approach was not pursued further when it was established that the epoxy pane did not exhibit adequate impact resistance to suggest its used as a replacement for stretched acrylic.

The conventional fiberglass insulation and honeycomb composite sidewall panels in contemporary commercial airplanes provide some degree of resistance against burnthrough and ignition of interior materials by a fuel fire. This was clearly evidenced in the DC-10 accident (Los Angeles, 1978) and the 727 incident (Anchorage, 1987) where major portions of the aluminum skin were melted away but the cabin interior was not set afire before extinguishment of the external fuel fire. To better understand and quantitate the fuselage burnthrough problem, FAA is conducting a full-scale test program using surplus aircraft fuselages subjected to a 400-square-foot fuel fire. Basically, the fuel fire is set adjacent to an intact fuselage section instrumented with thermocouples, heat flux transducers, and cameras to attempt to determine penetration locations, firepaths, and important event times. The last of three tests was completed in a compartmentalized test article in a wheels-up configuration; i.e., test article resting on ground. The preliminary findings are as follows:

1. The aluminum fuselage skin melted in about 1 minute.
2. The fiberglass insulation acted as a fire barrier in areas where the fuselage skin melted away and prevented any heat damage to the sidewall panels.
3. Earliest penetration of small flame into the fuselage was at door edge areas (however, no sustained burning was observed).
4. Smoke obscuration inside the cabin, apparently due to pyrolysis of materials adjacent to the heated fuselage, occurs much earlier than significant flame penetration.

Currently, preparation for an additional series of tests with the landing gear deployed is under way with completion planned by spring 1989.

POOL FIRE IMPACT ON AIRCRAFT FUSELAGE

Consider the condition of a large external fuel fire adjacent to a fuselage opening. For the case of minimal flame entry into the opening, the primary impact of the fuel fire on the fuselage interior is high levels of radiant heating confined to the immediate vicinity of the fuselage opening. Experimental and theoretical studies have analyzed this case for a Type A door opening in the fuselage. Using various diameter fuselage models and pool fire sizes, the maximum thermal radiation through the opening was established (24). A maximum value of 1.8 Btu/ft^2-sec was measured at the fuselage symmetry plane at an elevation of one-half the door height. By treating the fuel fire as a radiating body at 1874 $^{\circ}$F, the theoretical thermal radiation profiles inside the fuselage were computed (24) and are shown in figure 1. For example, thermal radiation to the floor varies from 14 Btu/ft^2-sec at the door to near zero at the symmetry plane, indicating the magnitude of the extreme gradients in radiant heating. Therefore, because of the fire resistance of aircraft interior materials, under the conditions of minimal flame entry into the fuselage opening, the fire will be confined for a period of time predominantly to those materials immediately adjacent to the fuselage opening. Also, very little of the thermal radiation from the fuel fire is directly absorbed by the cabin air.

The factors that greatly affect the case of flame entry into the fuselage opening are wind conditions, door opening configuration, and fuselage orientation. The worst case is when the fuel fire is upwind of the fuselage and there are openings on the downwind side of the fuselage. In this case, full-scale tests in a DC-7 fuselage (25) and 1/4-scale model tests (26) have shown a rapid development of nonsurvivable thermal conditions within the fuselage. The results were due entirely to the fuel fire effects since both test articles were devoid of interior materials. On the other hand, if no downwind doors are open, but instead there are additional doors open on the upwind side but not exposed to the fire, the hazard development in the cabin will be greatly retarded. The results of full-scale tests (25) for these two cases are shown in figure 2. Also shown is the case with all doors closed, which matches the upwind-door-only-open case until the absence of ventilation through a door opening causes the temperature to increase at a faster rate. Another case is when the pool fire is downwind of the fuselage. For this scenario the hazard development within the cabin will be primarily from radiation in a manner similar to the pattern described in figure 1.

In order to examine survivability when wind conditions cause significant flame penetration into the fuselage, a number of tests were conducted in the C-133 test article without interior materials (27). The tests were conducted outdoors and under wind conditions that forced the fuel fire flame into the test article. Two doors were employed, one adjacent to the fuel fire and the other 60 feet away on the same side of the fuselage. Generally, the fuel fire hazards inside the fuselage accumulated more rapidly as the wind speed increased. On the basis of measurements taken at a height of 5 feet 6 inches, and at a location 30 feet away from the fire, it was concluded that both elevated temperature and smoke obscuration were greater deterrents to survivability than was carbon monoxide. At this measurement location, the concentration of carbon monoxide never reached 100 ppm under severe wind conditions that caused temperatures to exceed human survival limits and smoke to totally obscure visibility. Thus, it appears that for those accident scenarios in which fuel fire hazards are injected into the cabin, the main early threat to occupants, before burning interior materials become a factor, will be elevated temperatures and reduced visibility from smoke.

POSTCRASH CABIN FIRE CHARACTERISTICS

The cabin hazard characteristics of a postcrash fire dominated by burning interior materials in a wide-body aircraft have been reported previously using a C-133 test article (3,4,5,6). A realistic scenario was conceived and developed, consisting of an intact fuselage with an opening adjacent to an external fuel fire under quiescent wind conditions, that creates cabin conditions in which survivability is controlled by burning materials and not by burning jet fuel (3). The remainder of this paper describes a recent and final C-133 test, employing more extensive cabin furnishings and interior panels, to examine several aspects of postcrash fire survivability not heretofore studied.

Objectives: The objectives of the test were as follows:

1. Determine fire/hazard progression in postcrash fire environment with emphasis on post-flashover conditions.

2. Examine factors affecting survivability.

3. Evaluate performance of "generic" protective breathing equipment (PBE) filter.

Experimental Approach: The overall experimental arrangement is shown in figure 3. The forward cabin was completely furnished over a length of 45 feet, in contrast to previous tests where only a small section surrounding the fire door was furnished with up to three rows of seats. In this test there were 14 rows of seats, in a double-triple-double seating configuration, and a single triple seat in front of the galley, for a total of 101 seats. Surplus aircraft seats protected with fire blocking layers were used. The carpet was 90/10 wool/nylon. The sidewalls and stowage bins were surplus assemblies constructed of epoxy-fiberglass honeycomb panels. The ceiling was composed of flat sheets of epoxy-fiberglass and epoxy-Kevlar™ honeycomb panels.

There were a number of other features that differed from past tests. The test was conducted for 12 minutes, as compared to 1-5 minutes in previous tests that were terminated shortly after flashover, in order to examine post-flashover survivability. The ceramic insulation that protected the fuselage roof in the vicinity of the fire door was removed to allow for possible fire burnout in this area with potential venting consequences on the cabin environment. Finally, to enhance realism a small number of carry-ons were placed in stowage bins and beneath seats.

Instrumentation generally consisted of temperature and heat flux sensors in the forward, furnished cabin and gas, smoke, and temperature collection/measuring devices in the rear, unfurnished cabin. The instrumentation has been described previously (3,4). An interesting refinement for this test was a gas sampling line switching arrangement for the continuous analyzers (CO, CO_2 and O_2) at stations 650 and 880 that allowed for changing to a lower sampling location when the analyzer became saturated. PBE filter performance in terms of possible clogging and gas removal (primarily CO) was also measured in the rear cabin. Filter clogging was determined by measuring the pressure drop across six filters at low, medium and high air flow rates at two elevations located slightly aft of the galley (28). Gas removal effectiveness was determined by mounting a filter on a box connected to a breathing machine and continuously measuring the concentrations of CO, CO_2 and O_2 inside the box (29). The box represented the air space inside a smoke hood when donned by an individual.

Test Results: To summarize, survivability was dominated by cabin flashover and extreme fire hazard gradients such that the fire hazards decreased fore to aft and from ceiling to floor. Furnishing the test section more extensively with interior materials had no observable effect on the outcome; i.e., the fire characteristics were similar to previous tests. Over the 12-minute test duration the cabin fire did not burn through the fuselage roof area where the ceramic insulation had been removed. Intense cabin flaming, triggered by the flashover, persisted for about 1 minute and appeared to self-extinguish when oxygen levels diminished substantially. The most notable observations after the test were that the entire ceiling was consumed by fire, as were the outboard seats in the immediate vicinity of the fire door. For the remaining seats the most striking observation was that the dress cover of the seat back cushion was largely burned away but that the fire-blocked foam was still present.

The thermal characteristics of the flashover were measured by thermocouples placed slightly above the center seat top at rows 5, 7, 9 and 15 (row 4 was at the fire door). As shown in figure 4, it appears as if the onset of flashover occurred at 210 seconds and, based on the separation between the rising portion of the profiles, propagated at about 60 feet per minute, or at a rate of one seat row about every 3 seconds. Before flashover, the seat top temperature was near ambient value. The flashover caused peak temperatures of 1600 °F to 1900 °F. The trailing edge of the profile indicates self-extinguishment of the cabin fire and gradual cooling of the interior.

The intensity and duration of flaming combustion in the upper cabin caused by flashover was measured by total heat flux transducers, located at the center seat top of rows 1, 4 and 13, pointing toward the ceiling (figure 5). The data indicate that total cabin fire involvement continued for approximately 1 minute and that the intensity was considerably greater near the fire door but tapered off toward the front and rear of the furnished cabin.

Pronounced stratification of cabin fire hazards was evidenced by measurements and visual observation. Even on the symmetry plane at station 880, in the aft cabin across from the exit door opening, the temperature varied considerably from floor to ceiling (figure 6). For example, the peak temperature at the ceiling exceeded 900 °F, while at one foot above the floor the temperature was about 125 °F. Heat stratification occurred before and after flashover.

Based on light transmissometer measurements on the symmetry plane at station 880, at elevations of 5 feet 6 inches, 3 feet 6 inches, and 1 foot 6 inches, the sudden reduction in visibility caused by smoke created by the flashover was evidenced (figure 7). The data indicate that the smoke descended downward at a rate of 8 feet per minute and, at a given elevation, the percentage light transmission from smoke accumulation changed from 100 to zero in 15 seconds. Visibility reduction due to smoke preceded in time any apparent impairment to occupants from elevated temperature or toxic gases.

Gas concentration profiles on the symmetry plane at station 880, at elevati inches, 3 feet 6 inches, and 1 foot 6 inches, are plotted for CO_2, O_2 and CO in respectively. As discussed earlier, the data are in segments because the gas an to sampling lines located lower in the cabin when the readings saturated. Analy the graphs indicate a rapid increase in CO_2 and CO concentrations and a correspo concentration because of flashover in the forward cabin. Significant stratifica gases was evident throughout the test. Gas concentrations and O_2 depletion were more than half of the upper cabin. Only in the lower several feet of the cabin w concentrations low enough to perhaps allow for escape over a short period of time cabin the primary threat to survival appears to be CO, due to the relatively high and moderate temperature rise.

Systems,"

11-8

Hydrogen fluoride (HF) and hydrogen chloride (HCl) profiles at station 880, [illegible] feet 6 inches and 1 foot 6 inches, are shown in figure 11. The trends are very similar for these water-soluble acid gases as exhibited by the dry gases CO and CO_2; i.e., the acid gases were generated as a result of flashover and the acid gases are also significantly stratified.

At station 880 the temperature profiles shown in figure 6 were analyzed to determine the thermal threat to survivability. The fractional effective dose (FED) concept introduced previously (3) was employed to compute whether incapacitation would occur as a result of elevated temperatures. The thermal FED profiles shown in figure 12 indicate that at 4 feet and below, survival may be possible from the thermal threat alone. To generalize, the temperature measurements taken throughout the cabin indicate that the thermal threat decreases the farther away you are from the fire and the closer you are to the floor.

The cabin hazards data suggest that survival may be possible in a post-flashover environment near the floor in a crawling position and close to an exit door opening where fresh outside air is entering the cabin. To examine this hypothesis, CO and O_2 concentration measurements were taken just inboard of the aft exit door opening at an elevation of 1 foot 6 inches (figure 13). The fluctuating nature of the curves suggests a delicate exchange at this location between combustion gas exhaust and fresh air intake. An FED analysis of the CO profile indicates that incapacitation would occur at about 560 seconds, assuming a negligible effect from the lowered oxygen concentration (approximately 18 percent), any other toxic gases, and any elevated temperatures. This time of incapacitation is about 6 minutes after the onset of flashover. One may conclude that there is a survival zone surrounding an exit door opening wherein survival is possible in a crawling position for several minutes in a post-flashover cabin environment.

The function of a PBE filter is to remove toxic gases and smoke particulates from a combustion environment in order to furnish breathable air to the wearer. One potential problem is clogging from massive deposition of smoke particulates. To examine this effect the pressure drop was measured across filters drawing air at three different flow rates, representative of a range of inhalation rates, placed at 5 feet 6 inches and 3 feet 6 inches, at station 880. As shown in figure 14, a rapid increase in pressure drop occurred immediately following flashover because of the high loading of smoke particulates. However, the results are inconclusive since the pressure gauges could not be read after the initial increase because of smoke obscuration. Nevertheless, the data indicate a potential problem that requires further study.

The other aspect of PBE filter performance examined was effectiveness in removal of CO, which is generally considered the most hazardous toxic gas produced by a fire. Figure 15 presents the results with the breathing machine/box arrangement briefly discussed earlier (28). The high concentrations of CO measured downstream of the filter indicate that the filter was apparently saturated by the extremely high concentrations of CO produced by cabin flashover, allowing large quantities of CO to pass through. Thus, the particular filter evaluated appears unable to cope with the high levels of CO produced by flashover. Whether PBE, in general, can and should be effective in a post-flashover cabin environment is a broader issue that needs to be addressed.

Another recognized problem with filter-type PBE is that this type of equipment was not designed for use in a fire environment with oxygen depletion. Measurements of O_2 downstream of the filter with the breathing machine/box arrangement illustrate the obvious; i.e., oxygen depletion in the cabin environment will be experienced downstream of the filter, but only after a lag time of 30-60 seconds, caused apparently by the effects of the initial volume of fresh air beneath the PBE hood and the O_2 concentration in exhaled air.

ADDITIONAL WORK

Full-scale tests provide the essential data needed to understand the characteristics of postcrash cabin fires. Current FAA test activities will broaden this data base and, hopefully, improve our understanding of the postcrash fire environment. As summarized in the paper, full-scale tests are being conducted to determine the mechanisms and time framework for fuselage burnthrough by an external fuel fire. A new, comprehensive full-scale test activity is also underway to evaluate the effectiveness of an onboard cabin water mist fire suppression system. Tests are planned in both standard-body and wide-body test articles. Fire scenarios will include an external fire adjacent to a fuselage opening, as studied previously by FAA, and a new scenario consisting of cabin fire penetration by floor burnthrough. Wind will be simulated and varied for each scenarios. Thus, the water mist test program will provide data comparisons that have received little attention in the past; i.e., the effects of fuselage volume (standard- versus wide-body cabin) and fire scenario (immediate versus delayed flame penetration, quiescent versus finite wind).

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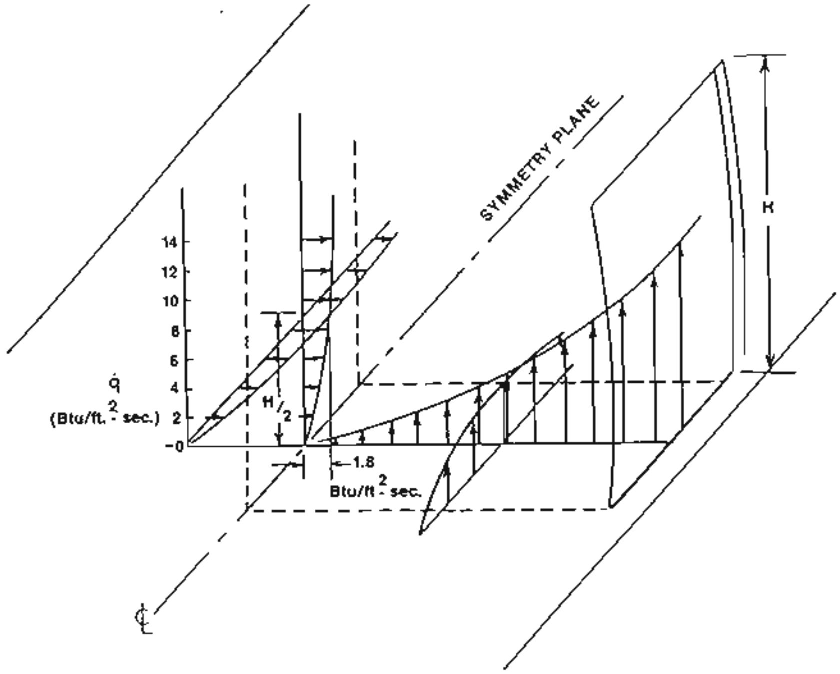

FIGURE 1. THEORETICAL THERMAL RADIATION PROFILES

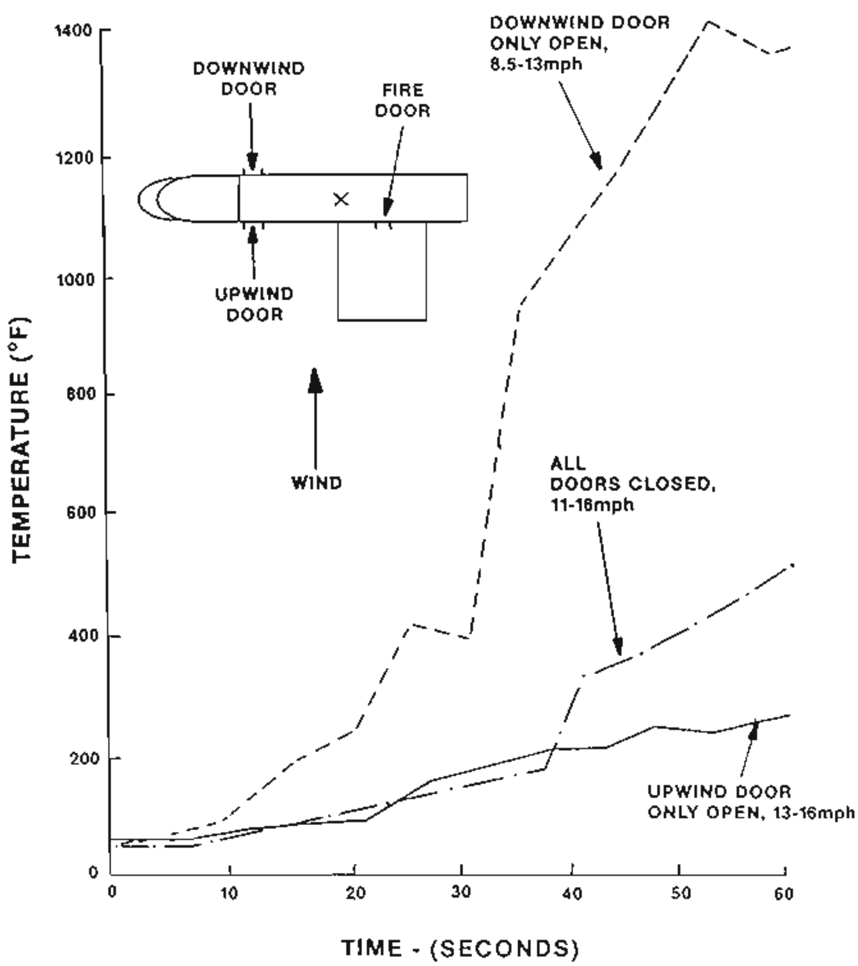

FIGURE 2. EFFECT OF WIND AND DOOR OPENINGS ON CEILING TEMPERATURE

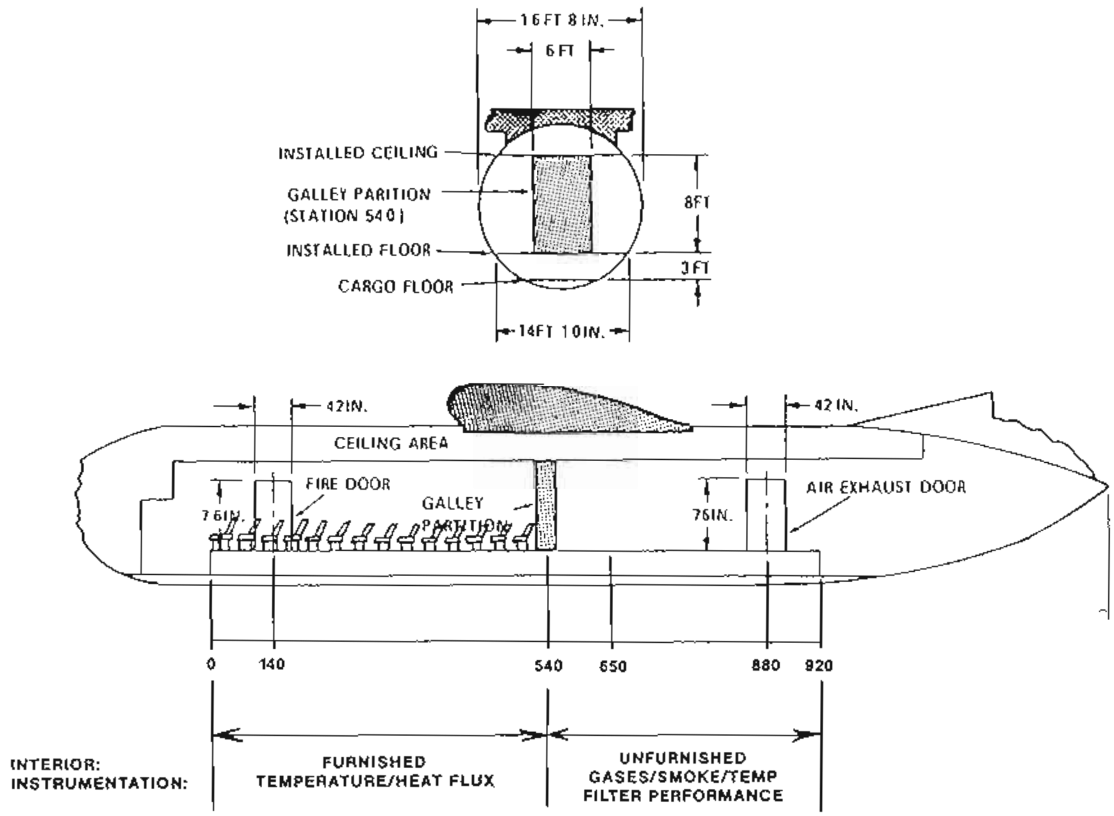

FIGURE 3. FULLY-FURNISHED FULL-SCALE TEST ARRANGEMENT

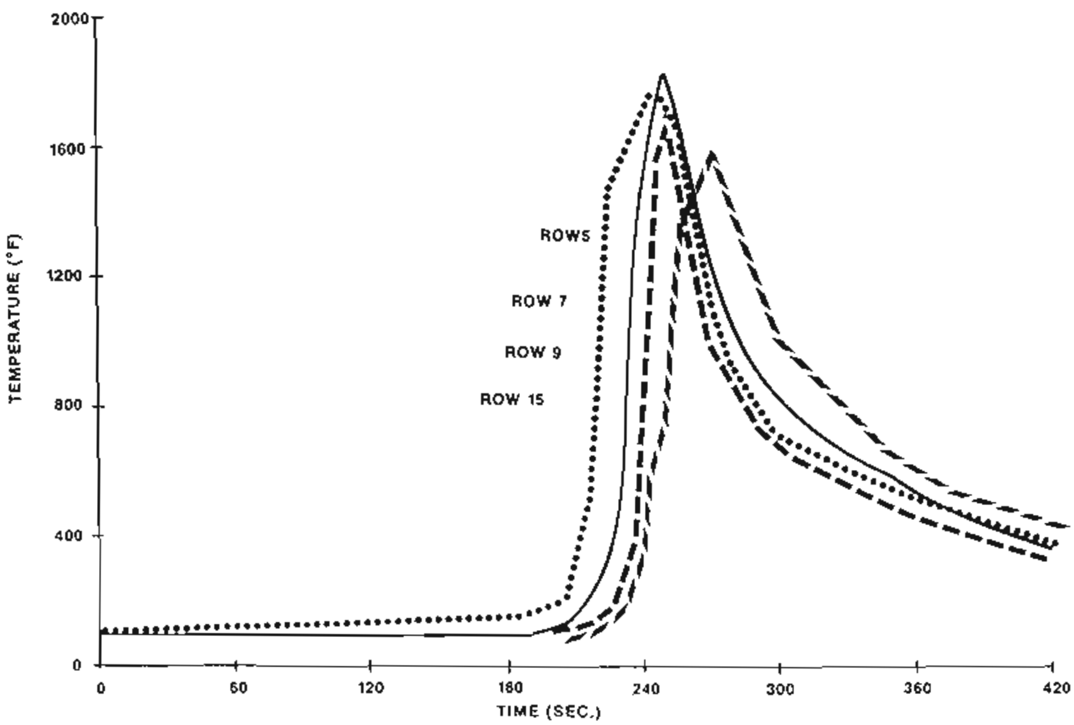

FIGURE 4. SEAT TOP TEMPERATURES

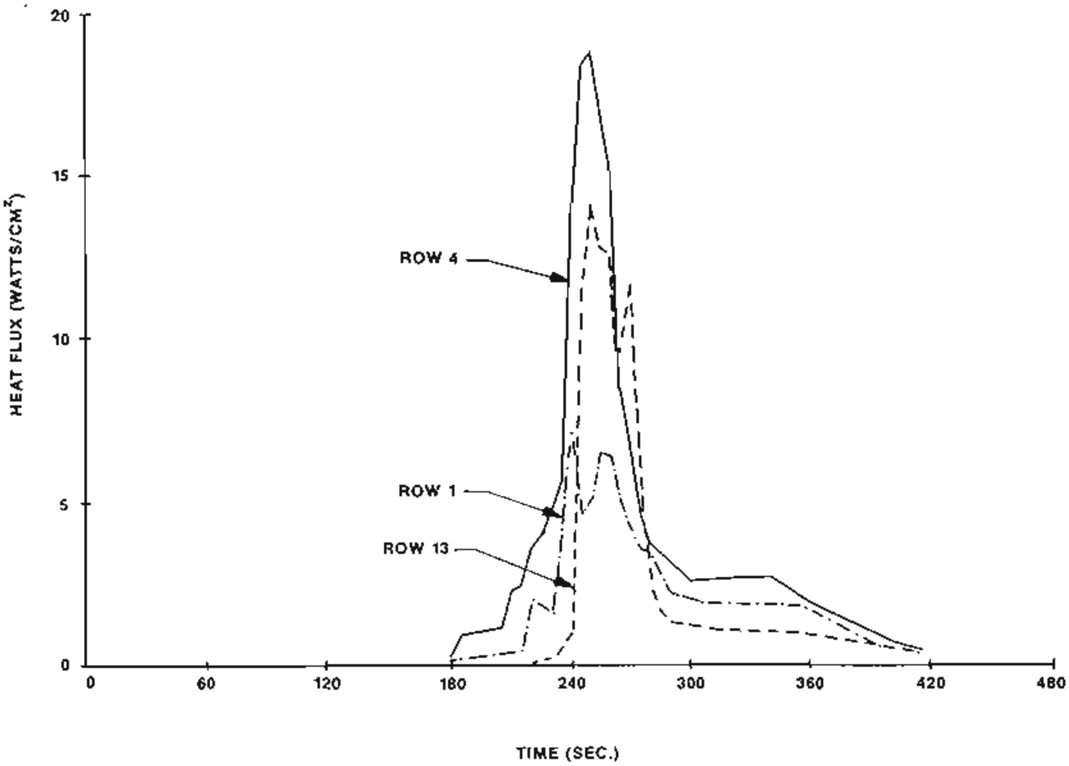

FIGURE 5. UPPER CABIN HEAT FLUX MEASURED AT SEAT TOP

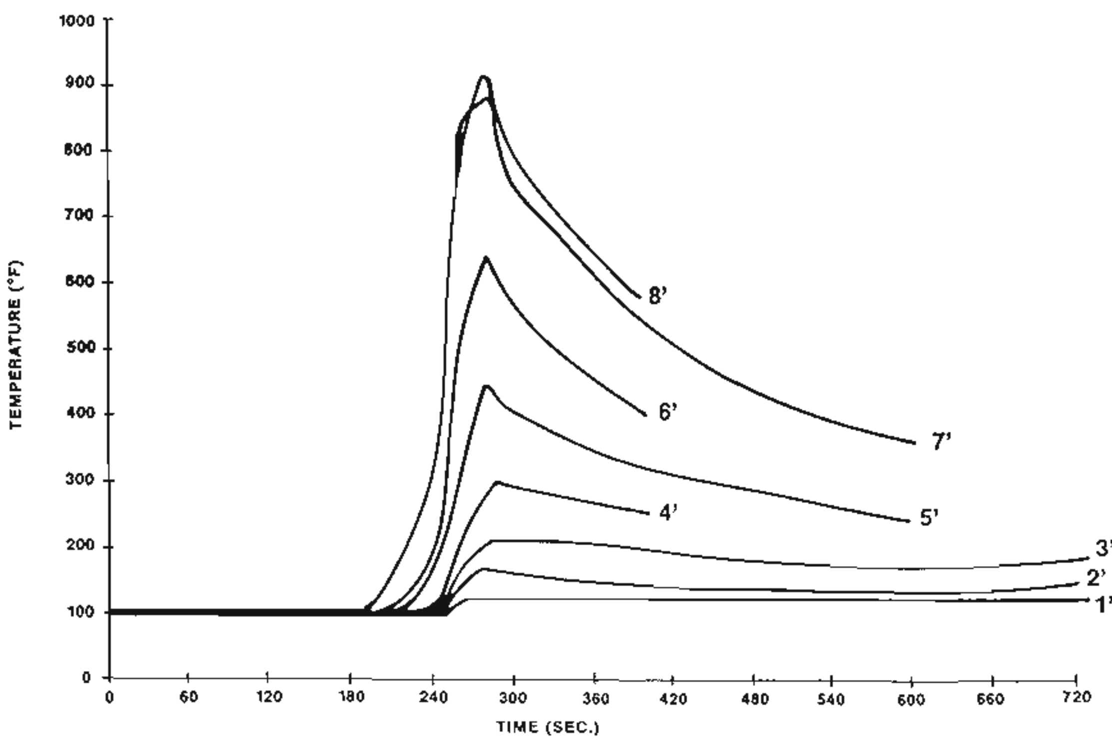

FIGURE 6. TEMPERATURES AT STATION 880

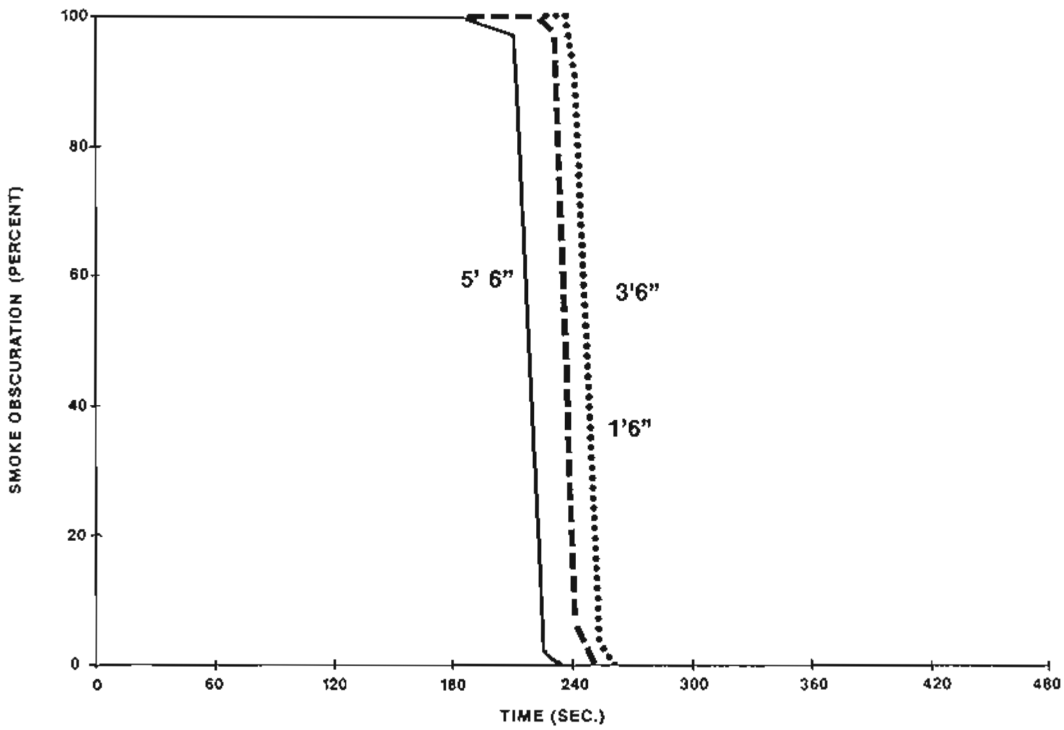

FIGURE 7. SMOKE LIGHT TRANSMISSIONS AT STATION 880

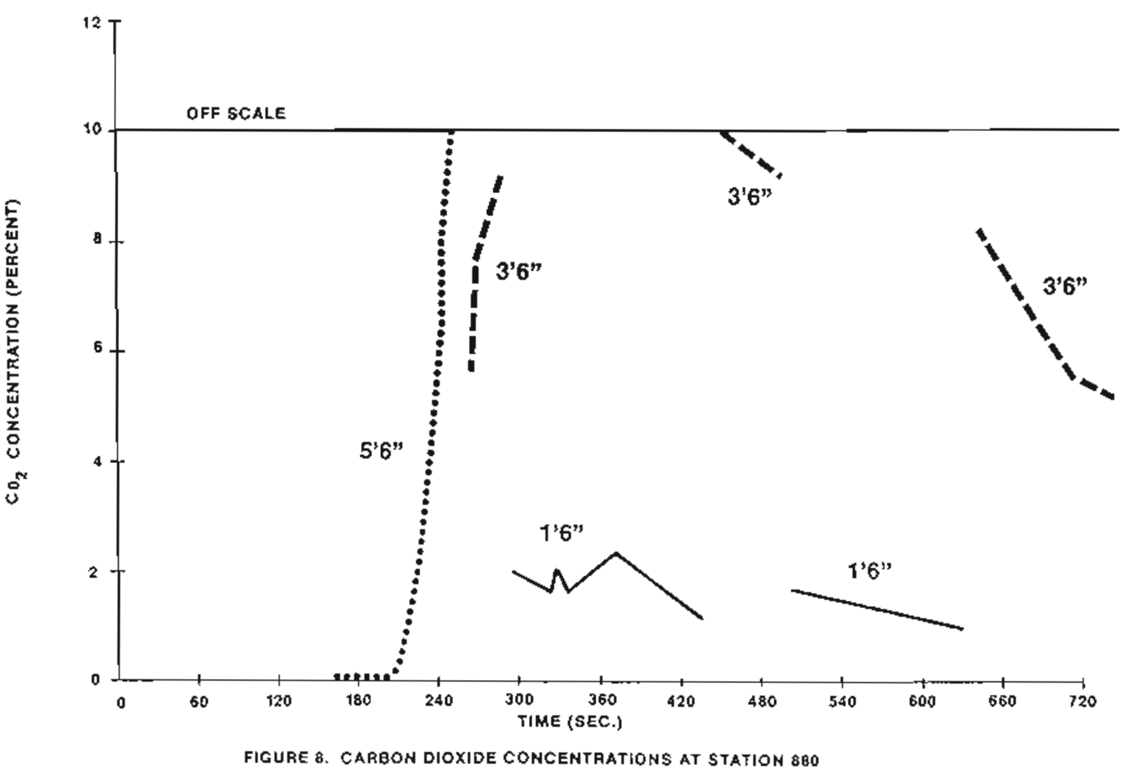

FIGURE 8. CARBON DIOXIDE CONCENTRATIONS AT STATION 880

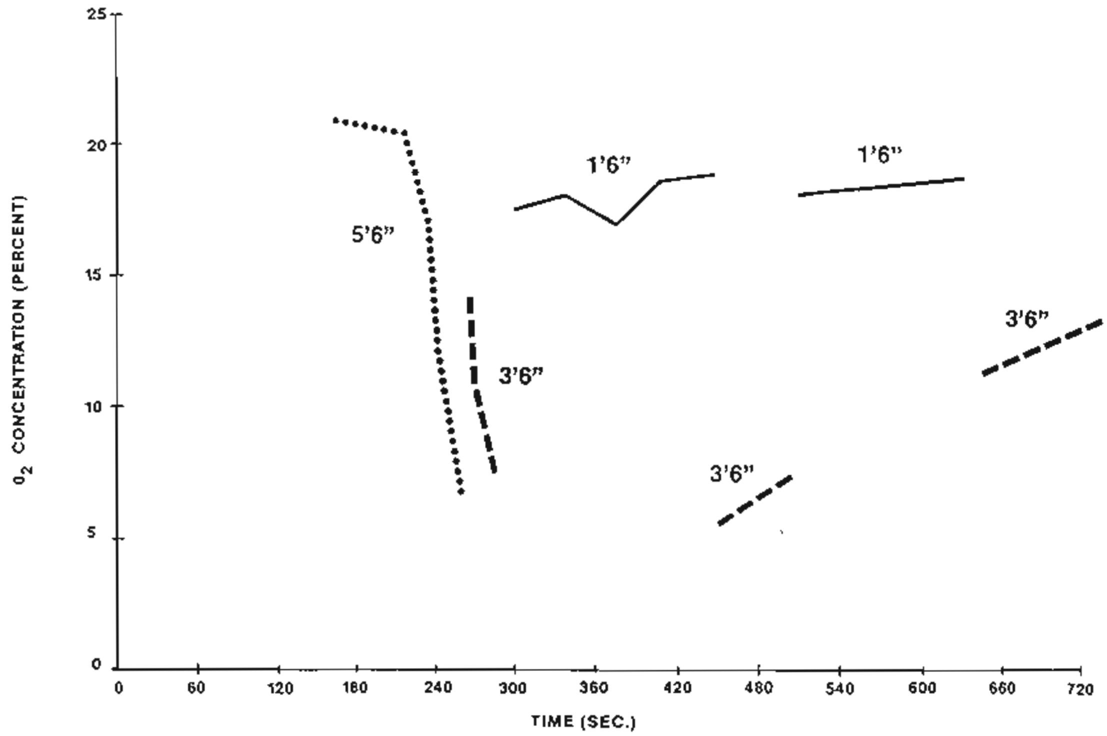

FIGURE 9. OXYGEN CONCENTRATIONS AT STATION 880

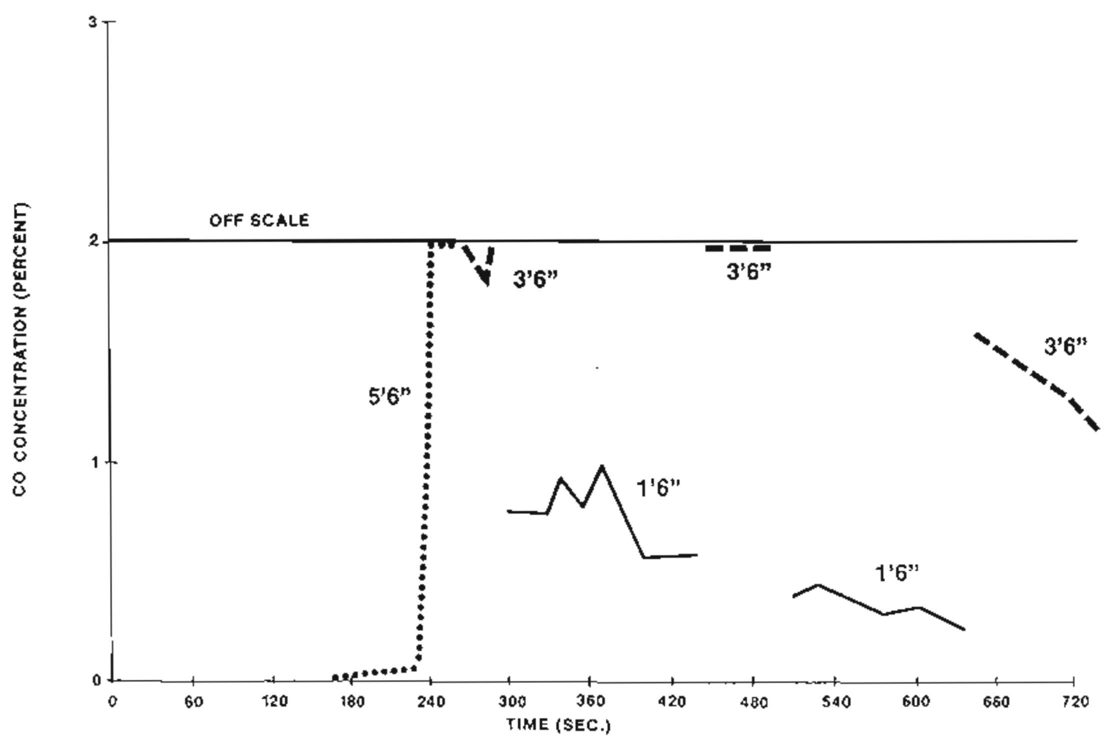

FIGURE 10. CARBON MONOXIDE CONCENTRATIONS AT STATION 880

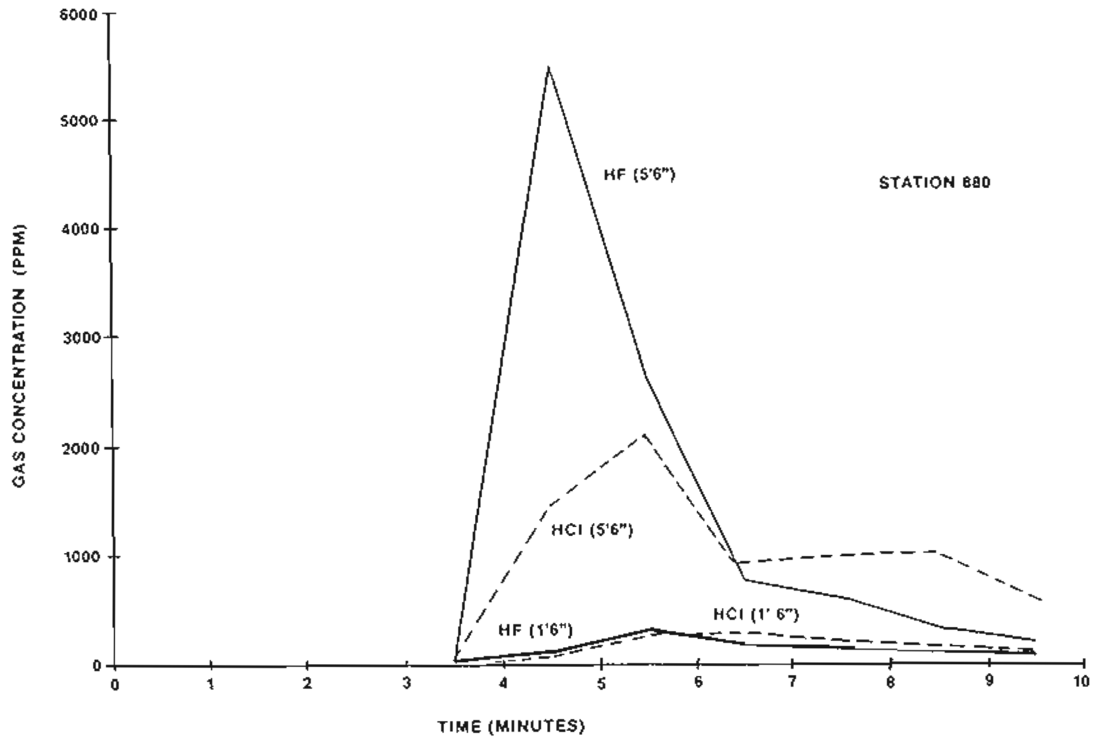

FIGURE 11. ACID GAS CONCENTRATIONS AT STATION 880

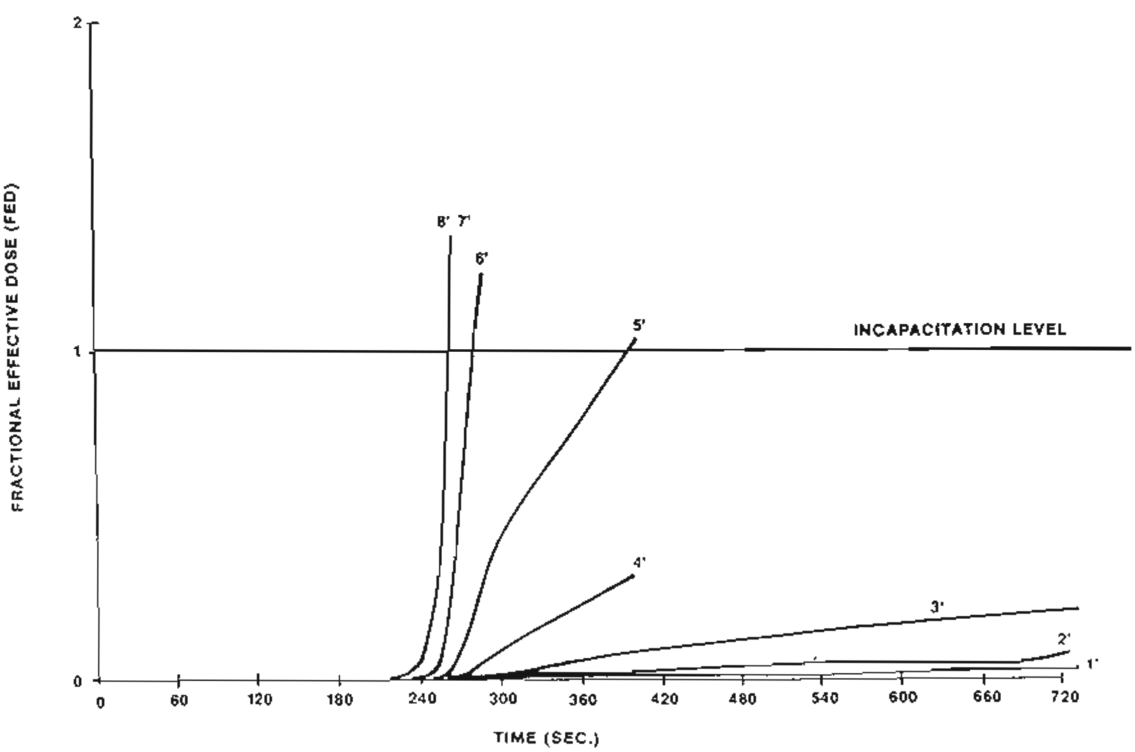

FIGURE 12. THERMAL FRACTIONAL EFFECTIVE DOSES AT STATION 880

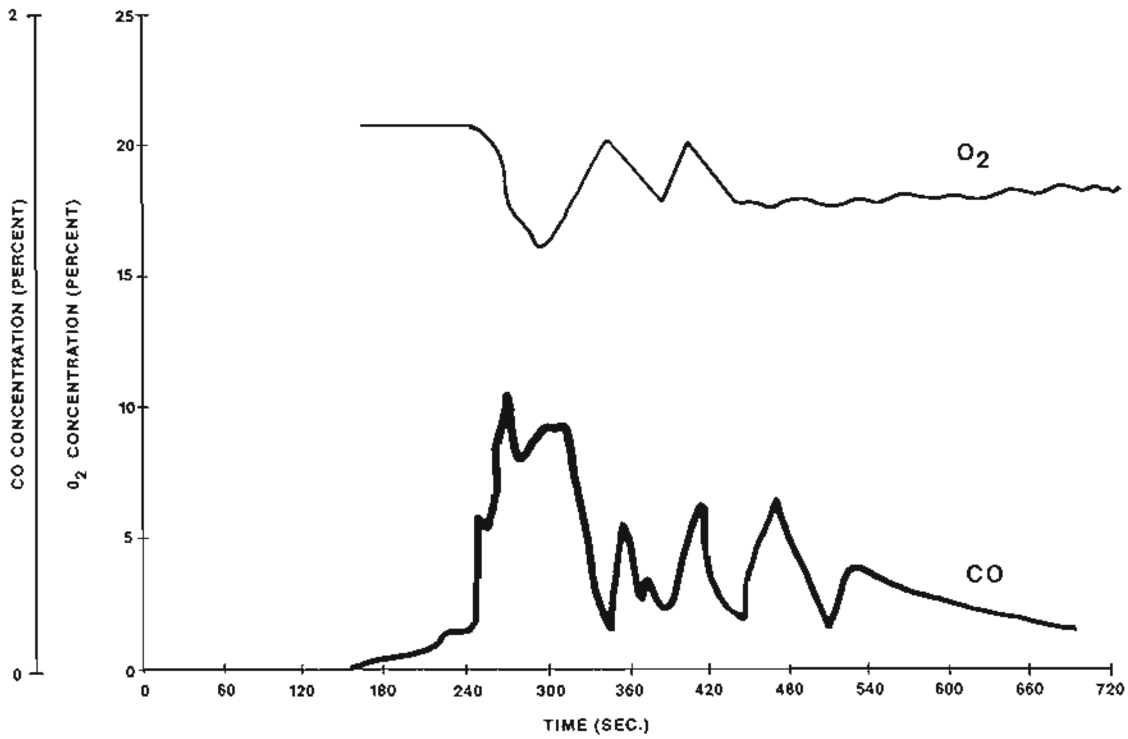

FIGURE 13. CARBON MONOXIDE & OXYGEN CONCENTRATIONS NEAR EXIT DOOR OPENING

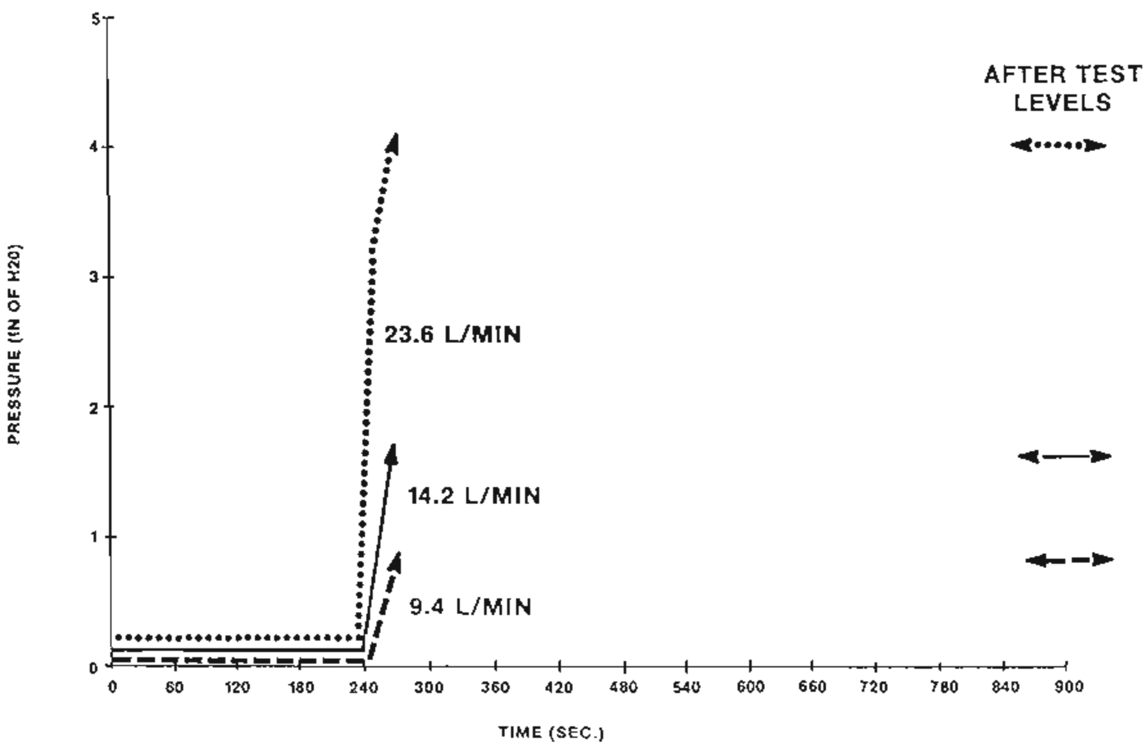

FIGURE 14. PRESSURE DROP ACROSS MASK FILTERS

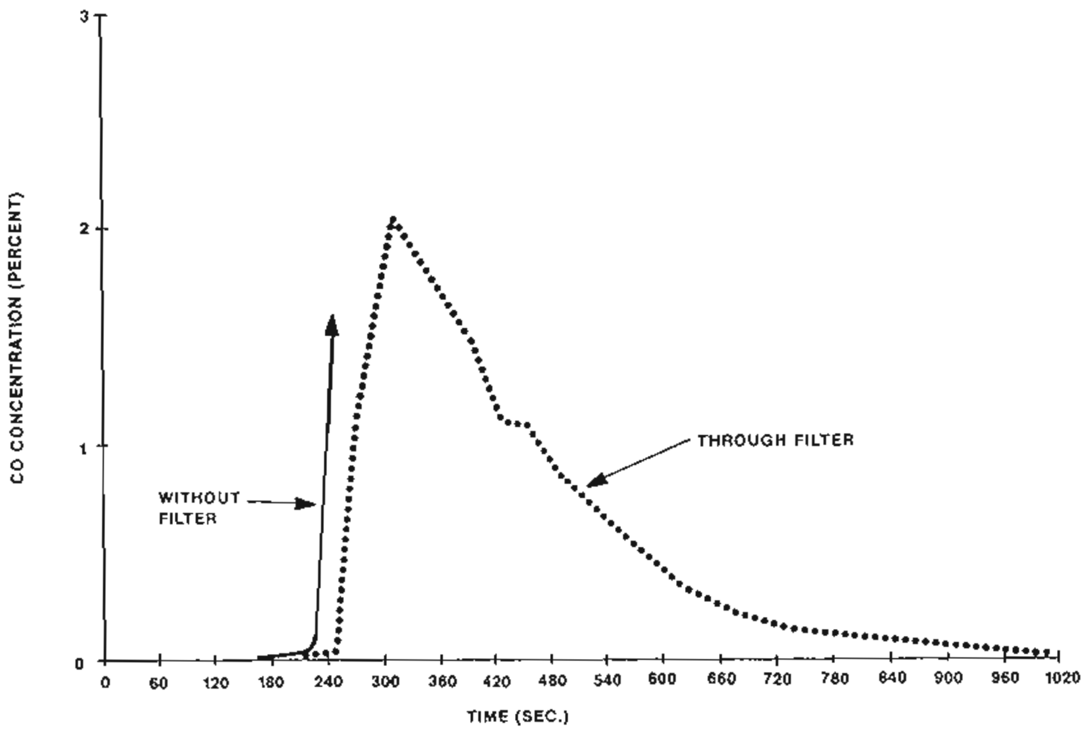

FIGURE 15. REMOVAL OF CARBON MONOXIDE BY MASK FILTER

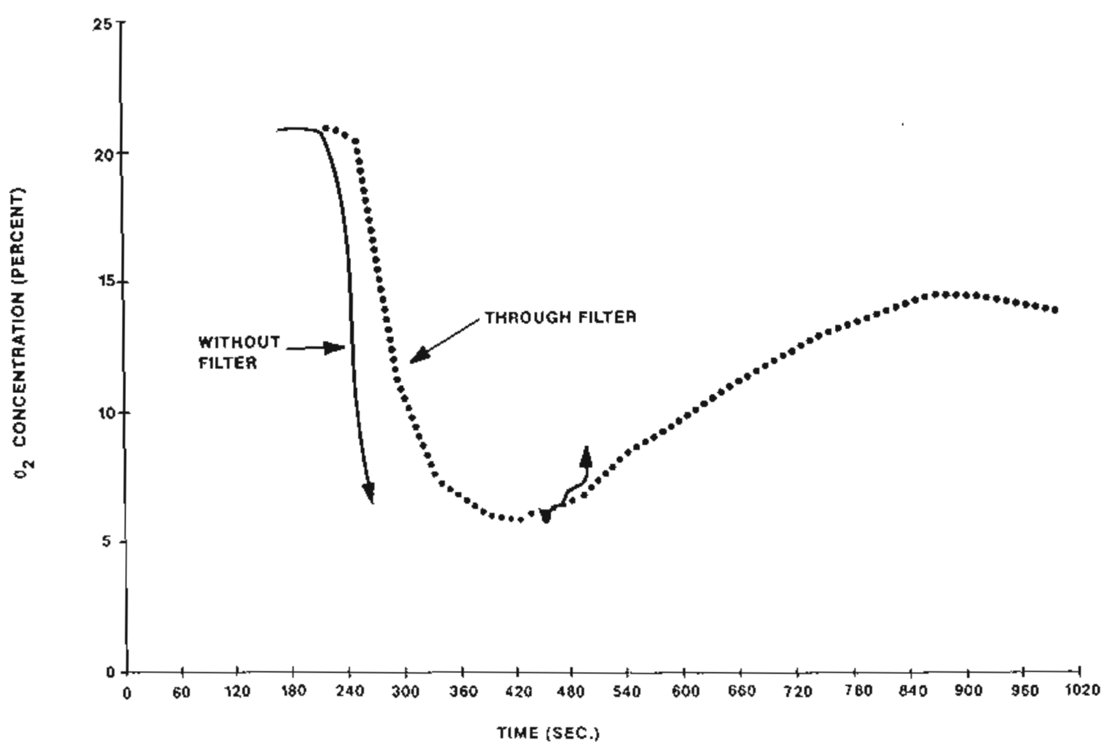

FIGURE 16. OXYGEN CONCENTRATION UPSTREAM & DOWNSTREAM OF MASK FILTER

AIRCRAFT INTERNAL FIRES

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SUMMARY

With modern day appliances and equipment a well trained fire service unit should be able to effectively deal with any external fire that may occur at a survivable aircraft accident situation.

Incidents that have occurred during recent years show that we still require to find a positive approach to what is loosely referred to as the internal fire. New legislation does call for higher fire resistance standards but there will always be the requirement for fire service personnel to deal with this type of problem. A number of attempts have been made to address this problem by using various methods to inject either water or halon gas. Whilst these attempts are a possible way forward they have inherent problems.

The fire service are faced with a situation over which they have no control and cannot alter in any way. These are - response time, the possible need to deal with an external fire first, passengers evacuating and thereby using exits and denying access or exits that have been left open by escaping passengers and will allow any exterior fire to enter.

At the present time the United Kingdom are testing a system that does address these problems. It is really two systems in one, firstly to allow onboard water to be used through the cabin area at very low consumption rates activated immediately on impact. Secondly, the ability for external services to connect to the system without entering the fuselage and thereby maintain the water sprays whilst evacuation continues or rescue actions take place.

1. INTRODUCTION

Over the last twenty years we have witnessed great improvements in the equipment and appliances that are available to the Aerodrome Fire Service to enable them to carry out their duties. These have come about in a number of ways, larger amounts of fire fighting media that can be carried in the mobile mode, large appliances with vastly improved acceleration, large output monitors and therefore greater application rates as well as improved fire fighting foams and complimentary media such as the halons and improved powders.

Equally as important we have witnessed a change in attitude of Civil Aviation Management in some parts of the world. They now recognise and appreciate that the fire service do have an effective part to play and can be instrumental in saving many lives at a major aircraft accident as well as preventing a minor incident developing into a major one.

Because of these developments I believe that we have reached the stage where any well equipped, well trained aerodrome fire service unit should be able to intervene and effectively deal with any external fire situation that may occur at a survivable aircraft accident situation, particularly if they are following the minimum standards as laid down by the International Civil Aviation Organisation.

Unfortunately it must be said that there has not been the same improvements with regard to the internal fire situation. Whilst there has been some international legislation to improve the fire resistance of aircraft internal materials, and some equipment manufacturers as well as individual aerodrome brigades have attempted to overcome the problem in their own way it still remains and will do so for the foreseeable future. It is sad to say that the majority of aerodromes still have to deal with this type of incident with the same outdated methods that they have had to use for the past two or three decades because they have no practical alternative.

It is the intention of this paper to briefly review the problem and discuss the equipment available both present and future with their assocaited advantages or disadvantages.

2. THE PROBLEM

The fire service are faced with a situation that can develop through a number of parameters over which initially they have no control and cannot alter in any way. Broadly they can be described as follows.

i The products of combustion or physical fire within the fuselage.

ii The necessity to deal with an exterior fire and at the same time to safeguard the fuselage and the people within it.

iii Application of Media to the interior of the fuselage.

iv Entry into the fuselage for fire fighting or to rescue incapacitated passengers.

v Response time

Any one of these parameters can happen individually or as a combination of events and it is not unusual for all to happen simultaneously.

2.1 Passengers that are trying to escape from an aircraft may in their confused state open exits without being aware that there is an adjacent external fire. If this does happen then experience shows that the exit is never replaced and there is a ready opening which will allow smoke and combustion products or even fire itself into the fuselage which will quickly have an effect on the passengers and may even be the source required to start the internal furnishings burning.

Modern civil aircraft whilst structurally strong are constructed from some material which have a relatively poor resistance to fire and will start to decompose at temperature as low as 600°C. This is a low temperature when measured against fire, consequently if the fuselage suffers from flame contact or even severe radiated heat, fire break through can occur and the exterior fire has direct access to the aircraft interior.

We can do nothing with regard to the passenger participation aspect as to restrict them in anyway would be unacceptable to the traveling public. Therefore our only way of combating this area is by fire hardening the fuselage and increasing the fire resistance of individual interior materials. This is an area which is outside the expertise of the operational fire service and is dealt with more fully at a later stage by more qualified speakers but suffice to say that the spray/mist system which is at present being evaluated and tested and will be discussed later in this paper has already shown the ability to achieve this.

2.2 The exterior fire may be of such dimensions or intensity that it is necessary to deal with this before any entry can be made into the fuselage. The purpose being to safeguard the people in the aircraft and to create a path which would enable them to evacuate the aircraft safely. This therefore commits possible limited manpower and resources which may otherwise have been used to advantage inside the aircraft.

It has long been suggested that we require a dedicated crew and appliance for the internal fire. Whilst this may initially appear to be the answer it must be remembered that manpower is the most expensive item of any fire service and if they are working to a limited budget then other areas of the service must suffer. They are also resticted by the lack of equipment designed especially for the task of the aircraft internal fire. They may also experience some delay in entering the aircraft due to passengers evacuating through available entry points. There is no doubt that the extra men and media would be an advantage, the way in which they should be used would need careful consideration.

2.3 To deal successfully with any fire the extinguishing media must be applied directly to the fire. Failure to do this means that a large percentage of it has been wasted and in the case of limited supplies on an airfield may mean the difference between successful extinguishment or failure and the loss of life. This means thatthe media must be applied inside the fuselage, the means of doing this at the moment are very restricted. They consist of conventional spray branches which are taken inside the fuselage or "spray pierces" which are driven through the skin from outside and then connected to a pumping appliance. Whilst these piercers enable water to be delivered to the interior without actually entering the fuselage there are a number of drawbacks.

The spear must be introduced above seat level, but below luggage rack level. Failure to do this means that the water spray is either trapped between two seat rows or in the luggage bin. Even on a narrow bodied aircraft this gives a height problem and means the firemen must work from a ladder and it is not easy to gain sufficient purchase to pierce the skin manually. This can be overcome by using a powered tool to cut a hole first but can be very time consuming.

There may be no indication where the seat of the fire is situated so the whole of the fuselage interior would need to be covered. On a 737 type aircraft this would take a minimum 4 sprays (each one gives about 20ft coverage) this would be outside any realistic time span to aid the people in the aircraft. It would of course take more sprays and a great deal more time for the same effect to be achieved in a wide bodied aircraft.

Again this would mean a dedicated water supply, but more important, sufficient manpower to enter the spears through the fuselage and to run the necessary hose.

A ground fire may preclude immediate access to the skin of the aircraft and thereby delay the entry of water.

One vehicle manufacturer has attempted to overcome some of these problems by making the water spears mechanically operated by the means of an extended hydraulic arm which will make the necessary entry into the fuselage and allow water to be pumped through the arm and into the fuselage. Bearing in mind that a minimum of four sprays would be needed this in turn means that four extra vehicles would be needed with the additional manpower requirements. This method would not overcome the problem of the external fire stopping these vehicles from getting close enough to the fuselage so that they could operate their extending arms successfully. There may be a number of other reasons why they cannot get close enough even if the fire has been dealt with, this could be wreckage, fuel spillage, disturbance of the foam blanket that has been laid in fighting the fire or even escaping passengers that are still in the close proximity to the fuselage.

Experimental work has also taken place in the United States of America using the same basic principle of extending arms from vehicles, but in their work instead of using water for the interior fire they have used halon gas and this work is well documented. It is not the purpose of this paper to discuss the relative merits or disadvantages of using a gas versus water. However it must be pointed out that whilst a halon may well extinguish the fire it will do nothing to improve the atmosphere within the fuselage. As will be discussed later water spray does have the advantage of "cleaning" the atmosphere to create a more breathable condition for people who are delayed in evacuation or trapped inside the fuselage.

2.4 Entry into the fuselage must take place as quickly as possible if the object of putting water on to the seat of the interior fire is to be achieved. This however depends entirely on the situation on arrival. As already discussed the external fire may prevent this, but even if this is not a problem then evacuating passengers may well be. If all available entry points are being used by passengers to exit the aircraft then fire service personnel must wait until this has been cleared as to try and force their way in would disrupt the evacuation and in any case it is nearly an impossible task to try and stop people in this situation. If the aircraft is still on its undercarriage there would be the additional problem of escape slides to overcome and although this is not a difficult task it is time consuming. Firemen entering a smoke logged fuselage should be equipped with self contained breathing apparatus and whilst this is done at a large number of airports it is by no means standard procedure throughout the world.

3. WATER SPRAY SYSTEM

The idea of using water spray systems in aircraft is not new by any means. Over the years a number of studies have been made. The last meaningful one was sponsored by the Federal Aviation Administration (FAA) in 1983 and came to the conclusion that a water based system would offer a broad protection base unfortunately this study did not result in any known work to develop the concept. When thinking about this type of system it always appears to be developed along the same lines as a structural sprinkler system that is with highlocalised flow rates with the primary purpose of extinguishing an established fire which has the inherent problems of large amounts of water required with consequencial weight factors which are not conducive to aircraft operations.

One alternative which is showing promise is a low flow rate internal spray system developed by Safety (Aircraft and Vehicles) Equipment Ltd (SAVE). Spray nozzles installed in the cabin ceiling can fill the cabin and the dead space above the ceiling with a heavy water mist. Because of the low flow rate requirement of the system a significant level of protection can be provided by water carried onboard. This system concept also provides for the incorporation of exterior couplings accessible to the airfield fire and rescue services which allows much higher flow rates to be supplied from the fire appliance. This combined system would allow for the first time protection inside the fuselage from the moment it is required therefore overcoming the problem of reponse time and also allowing the fire and rescue services to attack the internal fire immediately on arrival without having to make entry into the fuselage thereby overcoming many of the problems discussed earlier. This new spray mist concept has been developed using an unfurnished and fire hardened VC10 fuselage and demonstrated using a fully furnished Trident aircraft. The UK CAA has carried out a review of world wide accidents involving fire deaths over the period 1966 to 1985 and has concluded that the benefit attributable to the carriage of an onboard cabin fire suppression capability such as a water spray system is likely to be substantial. It therefore concludes that the concept is sufficiently promising to be the subject of further investigation in particular to define more precisely the likely benefit, to establish its efectiveness in wide body aircraft and to optimize the system and to determine whether additives would be desireable to enhance toxic gases absorption. The CAA envisages that this further work would be carried out on an international basis and has therefore initiated discussions with the FAA and other authorities with a view to entering a collaborative programme.

To enhance the chances of survival in a ground fire emergency two basic options are available, to increase the evacuation rate from the aircraft or to extend the time for which survivable conditions exist within the cabin. A water spray system would be expected to achieve the latter of these two options. Firstly the "onboard" system distributes water carried on the aircraft and would have sufficient quantity to be self sufficient for the first minutes of the emergency. Secondly, the "Tender" system uses water provided by the fire and rescue services and consists simply of suitable ground connections to the distribution system.

From work already carried out the "onboard" system appears to have the potential to:

i fire harden the fuselage structure to an extent that penetration of an external fire through the skin of an aircraft in to the cabin can be delayed,

ii limit fire propagation within the cabin by the absorption of radiant and convective heat from either an internal or external fire and as a result prevent the occurrence of a flash fire,

iii reduce the threat to life by the "washing" of the cabin atmosphere thus limiting the buildup of toxic gases and solid particulate from the fire that would have an adverse effect upon both sight and breathing.

The Tender system used on fire service arrival has the potential to enable the fire and rescue services to extinguish an internal cabin fire, enter the cabin and assist in the removal of any remaining passengers.

Considering these objectives in more detail, the benefit of fire hardening could be substantial. Provided there is no structural break-up, a fuselage which resists fire penetration will also prevent the ingress of smoke and toxic fumes from an external fire. To achieve this, water would need to be sprayed onto all internal surfaces of the fuselage skin to maintain skin temperature below their melting point, this would not appear to be very practicable or worthwhile in those areas where cabin insulation is installed. In any case, above floor level the thermal and acoustic insulation will tend to act as a secondary fire barrier once the skin is penetrated. The most likely areas where water could be effectively applied tends to be in the below floor and keel areas and, fortuitously, these are probably the areas at greatest risk to an initial fire threat. However, some degree of protection would be afforded to this underfloor region through the effects of drainage from an above floor system, but this may not be sufficient to fire harden the skin in all circumstances. Whether or not it would be worthwhile to provide sprays in such areas or whether reliance could be placed upon the draining of water from an above floor system would need to be established.

For a water spray system to absorb effectively radiant and convective heat, the water spray needs to be fine and evenly distributed. It must not however, be so fine that it cannot penetrate powerful convective gas flows generated within a fire, nor must it be so fine as to adversely affect vision, ie fog. To "wash out" solid particulate generated by the fire, the water droplets must be small in diameter and large in number so as to bombard the smoke, carrying the solid to the floor. The same is true for the absorption of the water-soluble toxic gases. The effectiveness of this "wash out" is also dependent upon a homogenous water spray distribution throughout the cabin. There must be no regions within the cabin or above the cabin ceiling through which hot smoke and toxic gases can migrate forward or aft.

Clearly, for an onboard system, it would be important for the water spray pattern to be optimised to mimimise the amount of water that must be carried as this bears directly upon the weight of the system and thus on the aircraft's operating cost. On the other hand, a "Tender" system is not so constrained and is only limited by the ability of the fire service rescue personnel being able to reach the aircraft with a suitable water carrying appliance. If the Tender system is to have a capability of extinguishing a cabin fire, water flow rates would need to condiserably exceed those of the on-board system. This could be achieved by dual flow rate nozzles.

Although the on-board and tender systems have been considered separately in the above discussion, they are complementary in purpose and could readily be integrated into a single installation. The bulk of the testing has been performed in a combined system.

All research effors have been directed towards the ground use of the on-board system only and the preliminary benefit is based upon assumption. Whether or not the system could be used in flight is at present unknown. If it could be shown that such use was unlikely to be catastrophic, its use could be considered at least as a "last ditch" measure. It is open to question whether design precautions should be taken in respect of other systems (eg, electrical supplies, avionics) to facilitate such use.

4. TESTS

The initial test scenario was a fire within the cabin of a VC10 aircraft hulk arising from a fire penetrating the fuselage, entering the cabin through the aircraft floor and immediately attacking the aircraft seating. Tests not only confirmed the rapid fire-kill capability of the tender system but indicated the extent to which an on-board system could limit fire development and maintain survivable cabin temperatures throughout the test.

Following discussions with the FAA, a second scenario was evaluated. An opening equivalent to a Type A exit was cut in the side of the fuselage and fire hardened locally with steel sheeting. An external pool fire was simulated using a 10ft x 8ft tray of burning kerosene immediately outside the fuselage opening. Seats were arranged inside the fuselage with the most forward seat row aligned with the exit centreline. Here again results showed that, while the on-board system was in use, little or no fire development occurred within the fuselage and that fire damage was limited to the exposed outboard edges of the seat armrest and cushion and seat back upholstery. Throughout such tests the cabin environment remained survivable without any form of respiratory protection. The facility also provided the opportunity to refine the nozzle design and to develop guide-lines for their spacing.

Having reviewed the results of these tests, it was decided that a programme of tests in a fully furnished aircraft was then needed using a fire scenario similar to that which existed in the tragic accident to the B737-200 aircraft at Manchester in August 1985.

Proof of Concept

The CAA collaborated with SAVE in a series of tests to confirm the effectiveness of the system in the case of a pooled fuel fire and a fully furnished aircraft. Use was made of a Trident 2 aircraft at the CAA's Fire Service Training School at Tees-side. Three tests were carried out with, in each case, a substantial fire under the rear of the aircraft aft of the wing (comparable in position and intensity to the fire at Manchester) which was allowed to burn for approximately three minutes before external fire fighting commenced. In all cases the cabin spray system was switched on when smoke entered the cabin, (for a production installation this water would be carried on board).

i In the first test the aircraft was intact at the start with the rear baggage hold full of baggage. The fuselage skin below cabin floor level (baggage hold) was substantially destroyed, and there was considerable damage to the structure behind the rear pressure bulkhead. The fire did not penetrate the cabin, and temperatures throughout remained survivable.

ii In the second test, with crudely repaired skin, the baggage hold was again filled but the fire rapidly destroyed the repairs so that the protection provided by the baggage was quickly lost. As a result the cabin floor above the baggage hold was severely damaged with only the upper skin of the "sandwich" construction floor remaining intact. Again, there was no fire penetration of the cabin, and temperatures remained survivable. Fire damage aft of the rear pressure bulkhead was such that the tailcone and empennage fell to the ground.

iii In the third test, the spray was removed from the toilets and the area of the last four rows of seats. The fire thus gained entry to this part of the cabin very rapidly indeed, and it was totally destroyed. The water spray kept the fire at bay such that the sprayed part of the cabin suffered no fire damage whatever and the temperature remained survivable.

In summary, not only did the spray system keep the cabin temperature survivable in the face of a fully developed fire in the cabin, but it also provided a degree of protection against fire penetration through aircraft structure which was wetted on the inside.

However, significant levels of carbon monoxide were measured in the cabin in all three tests, and further work is needed to assess its origin, extent and significance to evacuating passengers.

5. SYSTEM DESIGN FEATURES

Although a fully functional airborne standard has yet to be designed and developed, there is nothing anticipated in the cabin water spray system concept which would introduce technologies or design practices not already included in other aircraft systems. In this section some of the more significant design features are discussed.

On Board System

An on board system could be expected to consist of:

i water supply of adequate duration,

ii

iii distribution system,

iv means to inject the water into the required fuselage zones, and

v means to "arm" and a means to initiate the system.

The installation would need to take into account environmental factors such as temperatures and the inertia forces that can exist in an otherwise survivable crash in which a fire ensues.

Water Supply

The quantity of water that would be required to be carried would depend on system design duration, (ie, how long it would be able to afford protection while passengers and crew evacuate the aircraft) and on system flow-rates.

Duration

Each aircraft type before certification must be shown to be capable of evacuation of a full passenger load, using half the exits, in less than ninety seconds. This is a design condition and assumes an orderly evacuation. There is no implication that, in all circumstances, an aircraft can always be evacuated within this time limit. In reality an evacuation may take from as little as thirty seconds to as much as five minutes, depending upon the particular circumstances of the accident. Where fire is involved, conditions within the cabin are likely to become unsurvivable within five minutes unless some means is introduced to delay the fire development. However, the tests have shown that a spray system can be expected to delay both the fire threat and the deterioration of conditions in the cabin. A system duration of three minutes would afford survivable cabin environment for some time beyond the system operating period and possibly as much as five minutes. It is suggested therefore that a three minute minimum design duration would be appropriate for the on-board water spray system. This operating duration has been used for all full scale tests so far performed. This also corresponds to the internationally agreed maximum time for the fire rescue services to reach an accident on the airfield. In this regard it is relevant that a major proportion or survivable fire accidents do, in fact, occur on airfields.

Flowrate

The system development tests conducted by SAVE in the VC10 test fuselage in 1987 suggest that, for a narrow bodied aircraft, a flowrate of about 0.2 gallons of water per foot-run of cabin per minute is needed. For an aircraft the size of a Boeing 737 aircraft this equates to approximately 15gallons/minute (45 gallons for a three minute system).

NOTE: For the same spray density a wide bodied aircraft could be expected to require considerably more, say 0.35 gallons per foot which would be equivalent to about 145 gallons for a three minute system. However, tests would be necessary to substantiate this crude estimate.

Although it would be attractive from weight considerations to make as much use as possible of drinkable (potable) water already carried on the aircraft, this could create practical difficulties. Firstly, there is a risk of contamination of the drinking water and secondly there would be the need to ensure that there is always a minimum reserve retained for the water spray system.

On current aircraft, potable water is often largely depleted by the time the aircraft arrives at its destination and would therefore be unavailable in a post landing accident. It would therefore seem to be essential to have dedicated water supply to provide a specific minimum period. Means for interconnecting this to the potable supply could, for accidents at takeoff, provide extended duration, ie the potable water would be a bonus when available.

The number of storage tanks required for a specifice aircraft would need to take into account the system redundancy philosophy. The likelihood of a major fuselage break suggests that at least two storage tanks would be necessary, one located towards each end of the fuselage.

Material used in the construction of the tank would need to take into account considerations such as impact resistance, affects of fire and the range of working pressures.

Pumping System

Whatever means is used to "atomise" the water into a suitable spray, some form of pumping/power system would be required. The power for such a system could be derived from a number of sources but the most likely would seem to be either electrical or pneumatic. Whatever the power source, it would have to be independent of the failure of any normal aircraft power sources or supplies, and one of the simpler ways of achieving this independence would appear to be a stored gas pneumatic system that pressurizes the storage cylinder.

It could perhaps utilize components currently used to deploy inflatable escape slides, ie a rapid discharge, high pressure, gaseous, dry nitrogen system. The system would also need to include appropriate non-return, pressure-regulating and relief valves.

Distribution System

Ensuring that the water spray is fed to all the required regions of the fuselage and at the same time minimizing system water loss in the event of structural damage to the fuselage in a survivable accident, would require check valves, restrictors, frangible self closing couplings etc. From the recent trials, it is clear that distribution within the cabin would be unlikely to be achieved using a single manifold except perhaps for the smaller aircraft cabin having a simple internal profile. In most cases it can be expected that at least three main distribution manifolds would be needed, one on the aircraft centre line and one on each side of the fuselage, somewhere near the interface between the side wall and the overhead stowage/passenger service units. Further lines feeding roof and below-floor area may well be necessary.

6. CONTROL

How the system would be controlled will require very careful consideration. It seems likely that the on-board system would always be armed for take-off and landing but disarmed forother phases of flight. This action would probably be performed manually by the flight crew but could perhaps be linked automatically to, say, flight altitude above the ground. However, this would be dependent upon appropriate signals, electrical supplies etc being available in the circumstance which might eventaully precipitate use of the system. Any automatic arming means would almost certainly require a manual override device:

i to cover the failure of the automatics, and

ii to allow the crew the "last ditch" capability of initiating the system to combat an uncontrolled in-flight fire.

System initiation also presents problems. Should it be "manual or automatic"? It is conceivable that thermal, UV or IR sensors could be located in the fuselage skin which automatically initiate the system. It is important, however, that the system is not initiated by fires which are not a direct threat to the fuselage or its occupants as a transient torching flame which may result from a "wet start", or a localised wheel brake fire or even solar heating or sunlight. For these reasons a manual control seems less likely to result in unnecessary system operation. It is also most likely to be "crash survivable". But this raises the question of who would be responsible.

It may be argued that the flight-crew, with their more intensive training, would be less likely to overreact to a situation and would therefore, be less likely to prematurely initiate the system. On the other hand they may be unaware of the extent of the fire near the rear of the fuselage or, in a crash, they may have been incapacitated. The cabin crew may be in a much better position to assess the fire threat and initiate the system in a timely manner. They would however, need training.

On balance preference appears to be for a control system which is manually armed and initiated, a system in which the "arming" is performed by the flight crew and is capable of being initiated by both the flight crew and the cabin crew. The location for the controls for use by cabin attendants would be near to those cabin attendant stations which are adjacent to floor level exits.

Even the production of an "arming" feature, the system may operate when it is not needed either as a result of failure, or overreaction of a crew member. Either way it may be desirable to provide a "dump" function which would stop the system discharge into the cabin so limiting the cabin damage and the possible hazard to essential electrical and avionic systems.

Environmental Factors

To date, all tests have been conducted using water without any additives such as "antifreeze". Glycols and similar agents can depress the freezing temperature to a level where it would be unnecessary to drain the system during cold overnight soak conditions. However, such agents can produce toxic thermal breakdown products which could represent an unacceptable hazard. Facilities for draining the system overnight, therefore, likely to be required.

As with potable water systems the water tanks and controls may need thermal protection in flight, particularly in long-haul flights with extended periods at high altitude.

7. TENDER SYSTEM

A viable tender system presupposes that a suitable water supply is readily transportable to the aircraft by the fire rescue services, and dedicated specifically to this particular purpose. The air frame part of a "tender system" would need to be able to handle the high flow rates needed to extinguish an established fire and could be expected to consist of:

i ground vehicle connections accessible in likely fire scenarios, and

ii a distribution and spray nozzle system.

Ground Connections

The number and location of the tender connections for such a system would vary from aircraft to aircraft. They would need to be readily accessible to the fire service vehicles used in this role and should be located where at least one would be clear of any likely ground fire and remain clear throughout the emergency. Accessibility should not be adversely affected with any or all of the landing gear collapsed.

With these constraints in mind the most likely locations would be at each end of the fuselage, on each side and just below the cabin floor. Wing tip connections could be considered but, with the length of pipework feeding from wing tip to the fuselage, this would be vunerable to damage and would represent a substantial weight penalty. Wing tips on large aircraft can also be a long way above the ground.

The type of connection used would need to be standardised and would have to cope with flow rates of up to say 200 gallons per minute. To be realistic, standardisation would have to be internationaaly agreed as would the provisioning of appropriate and adequate water supplies at each airport.

Distribution and Spray System

The distribution system, its redundancy and crash integrity would be very similar to the on-board system discussed above. The spray nozzles would need to be able to cope with the higher water flow rates. Where both on-board and tender systems were installed much of the distribution system could be common to both systems, particularly where nozzles were utilised which could operate at both high and low rates.

8. COSTS

The cost implications can be broadly divided into the following areas installations costs, maintenance costs and loss of payload due to the weight of the system. It is difficult to quantify exact costs at this time but estimates have been made on certain assumed factors. These are, narrow bodied aircraft installed cost £80,000, maintenance £5,000, annual operating cost £8,000. Wide bodied aircraft £110,00, maintenance £8,000,annual operating cost £12,000. It must be emphasised that these figures are crude estimates and may well change as the system develops.

9. REMAINING CONCERNS

Effectiveness in Wide Bodied Aircraft

All testing so far has been conducted in a narrow bodied VC10 and a Trident II aircraft. There has been no assessment in a wide bodied aircraft.

Whilst no major problems are foreseen, it may be necessary to increase the number of spray distribution manifolds to ensure complete coverage of the cabin interior including loft spaces and particularly where multiple overhead stowages could result in potential dead spaces.

Ceiling height may also influence spray penetration. A slight increase in droplet diameter may be necessary to ensure good droplet penetration to floor level.

Further practical fire tests in a wide bodied fuselage are necessary to determine optimum droplet size and distribution.

Carbon Monoxide

Whilst water in the form of a spray has the potential to absorb much of the water soluble products of combustion, its ability to absorb carbon monoxide (CO) is minimal. In fact it has been suggested that the addition of moisture to the combustion process may potentiate the production of CO and hydrogen (H_2) through the reaction between the water and the hot carbonaceous products of combustion.

Additives could be introduced into the water spray which may well reduce the total CO yield but they, in turn, may create other hazardous thermal breakdown products. Further tests are necesssary to determine whether such additives would be worthwhile.

Effects on Egress

In the tests so far performed, the reduction in visibility has been slight and is therefore unlikely to affect aircraft egress rates. However, wet floor surfaces and escape routes may have an effect which needs to be evaluated. Further trials may be necessary to quantify such effects, including that of drenching of the cabin occupants.

10. GENERAL

The work carried out so far would indicate that an effective water spray system installed in an aircraft would overcome a large number of problems which now face the fire service when dealing with an internal fire situation but most importantly would extend the available evacuation time and give the capability of water being applied to the interior of the aircraft before the arrival of the fire service.

Although the systems have been described separately to achieve the maximum utilisation they should be considered as a package and complementary to one another.

Work is now progressing both in the UK and the USA to further the work particularly in regard to wide bodied aircraft. It is also to include a dis-benefit study which will compare it with other suggested safety methods and the problems associated with the inadvertent discharge whilst the aircraft is in flight.

IGNITABILITY OF JET-A FUEL VAPORS IN AIRCRAFT FUEL TANKS

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SUMMARY

Ignitability criteria for fuel vapors in aircraft wing tanks were analyzed. The effects of ambient temperature, tank pressurization, and ventilation on the flammability of the ullage gas mixtures have been demonstrated using the ULLAGE computer code. It was shown that in the absence of tank inerting, flammable mixtures are most likely to form at some point during all transport and fighter missions considered. The relative ignitability of ullage vapor mixtures versus the propane-air mixture called for in Military Standard 1757A was analyzed for a lightning strike scenario, for spark ignition and hot surface ignition modes. It was shown that the military standard is not always a conservative evaluation of the ullage ignition hazard. A procedure to determine when the ullage is more readily ignitable than the mixture specified by the Military Standard 1757A has been recommended.

INTRODUCTION

Ignition of fuel vapors in a fuel tank ullage poses potential catastrophic consequences. Therefore, the ignitability of ullage mixtures is an important part of the overall aircraft vulnerability evaluation program.

The five steps required for deterministic evaluation of the hazard posed by the ignition of the ullage vapors are outlined in Figure 1. Since three elements are required for combustion to take place: fuel, oxidizer and the ignition source, the first step of the evaluation is to calculate the state of the ullage, i.e., the pressure, temperature, concentrations of the fuel vapor, oxygen and inert gases. A convenient solution to this problem has been provided by Seibold (1987) in the form of a computer code capable of predicting the state of the ullage versus time for input mission profiles.

The second step is to determine if and when the ullage state will become combustible. Flammability limits for jet fuels are effected by changes in ullage pressure, temperature and oxygen concentrations. Other mechanisms, such as fuel mist combustion, cool flames, and diffusion flames should also be considered in this assessment.

If the ullage mixture can reach combustible proportions, the next step (step III) is to hypothesize various ignition scenarios and to determine associated realistic ignition strengths. The term "ignition strength" is a nebulous word used deliberately here which could denote the energy of the spark for a spark ignition mode, or the surface temperature for a hot surface ignition scenario. A review of various ignition scenarios was given by Kuchta (1975).

Step IV is to calculate the minimum ignition strength requirements for the ullage mixtures determined in step I for each of the combustion modes determined to be possible in step II, and for each of the ignition scenarios considered in step III.

Finally, in step V the minimum required ignition strength is compared with the credible available ignition strength and a decision is made as to whether combustion will take place. If combustion is possible, the corresponding peak pressure may be calculated to assess the damage potential. Generally, however, even mild deflagrations are detrimental to the structural integrity of the aircraft fuel tanks, and the accepted practice is not to allow the possibility of ignition.

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While this type of "lumped" approach is technically viable and may be cost effective in the short term, the data obtained would apply only to a specific tank design under the conditions tested. Therefore, for each new design or each new set of operating conditions, additional testing is required. This can become prohibitively expensive or dangerous when ignitability is to be ascertained for in-flight conditions. Another shortcoming of the lumped approach is the fact that it is difficult to establish the importance of individual factors in determining the outcome of the test and to identify those factors that are most responsible for scatter in the results.

In this paper, the steps outlined in Figure 1 will be discussed using the lightning strike example. It will also be shown that the Military Standard 1757A may not always provide a truly conservative assessment of the actual ignition probability of the gases in ullage.

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Fuel tank ullage conditions were determined by running the ULLAGE computer code* (Seibold, 1987) for a number of transport and fighter airplane missions. The matrix of the computer runs given in Table I was selected to isolate the effects of mission day temperature, fuel tank pressure, and ventilation on the composition of the ullage mixture.

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The calculated average oxygen and fuel vapor fractions are plotted against each other in Figures 2 through 4. For the transport mission (Figure 2), the maxima for both fuel vapor and oxygen are reached nearly simultaneously around the time the airplane first attains its maximum cruising altitude. The peak oxygen and fuel vapor concentrations (Figures 3 and 4) for the fighter missions occur at different times corresponding approximately to the time the fighter plane first reaches high altitude, and the time of maximum fuel temperature, respectively. The calculated peak average oxygen and fuel vapor concentrations are also reported in Table I. In this table, the peak values denoted with the superscript "s" indicate that the ULLAGE program has predicted stratification in the ullage, and there is a variation of concentrations around this value.

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Combustion of the ullage gases may occur in various modes such as normal flames, cool flames, diffusion flames and heterogeneous combustion. The estimated flammability limits for normal flame propagation through Jet-A fuel vapor-oxygen and nitrogen mixtures are given in Figure 5. It must be emphasized here that the flammability limit curve given in Figure 5 is estimated based on only two data points: the lower flammability limit of 0.6 vol % and the upper flammability limit of 4.7% Jet-A fuel vapors in air reported in the CRC handbook of Aviation Fuel Properties. The other points making up the flammability curve were obtained by appropriately scaling the curves given in Zabetakis (1965) for paraffinic hydrocarbons. If the mixture at any point in the ullage at any time during the mission falls inside the peninsula shown in Figure 5, normal flame propagation is possible. Outside the peninsula, normal flame propagation is not possible, yet combustion may still occur in another mode. For example, below the lean limit heterogeneous combustion can occur, if fuel mist is generated in the ullage due to sloshing of fuel in the tank. Diffusion flames can

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IGNITABILITY OF JET-A FUEL VAPORS IN AIRCRAFT FUEL TANKS

by

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SUMMARY

Ignitability criteria for fuel vapors in aircraft wing tanks were analyzed. The effects of ambient temperature, tank pressurization, and ventilation on the flammability of the ullage gas mixtures have been demonstrated using the ULLAGE computer code. It was shown that in the absence of tank inerting, flammable mixtures are most likely to form at some point during all transport and fighter missions considered. The relative ignitability of ullage vapor mixtures versus the propane-air mixture called for in Military Standard 1757A was analyzed for a lightning strike scenario, for spark ignition and hot surface ignition modes. It was shown that the military standard is not always a conservative evaluation of the ullage ignition hazard. A procedure to determine when the ullage is more readily ignitable than the mixture specified by the Military Standard 1757A has been recommended.

INTRODUCTION

Ignition of fuel vapors in a fuel tank ullage poses potential catastrophic consequences. Therefore, the ignitability of ullage mixtures is an important part of the overall aircraft vulnerability evaluation program.

The five steps required for deterministic evaluation of the hazard posed by the ignition of the ullage vapors are outlined in Figure 1. Since three elements are required for combustion to take place: fuel, oxidizer and the ignition source, the first step of the evaluation is to calculate the state of the ullage, i.e., the pressure, temperature, concentrations of the fuel vapor, oxygen and inert gases. A convenient solution to this problem has been provided by Seibold (1987) in the form of a computer code capable of predicting the state of the ullage versus time for input mission profiles.

The second step is to determine if and when the ullage state will become combustible. Flammability limits for jet fuels are effected by changes in ullage pressure, temperature and oxygen concentrations. Other mechanisms, such as fuel mist combustion, cool flames, and diffusion flames should also be considered in this assessment.

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Minimum ignition energies of various hydrocarbon-air mixtures under atmospheric conditions are given in Figure 6. It is interesting that the minima of the energy curves for these various hydrocarbon compounds occur at nearly identical energy values. Note that the minima shift to richer than stoichiometric mixtures as the molecular weight of the fuel increases, apparently due to the decrease in the diffusivity of fuel vapors in air (Lewis and Von Elbe (1961)). The curves also flatten for higher molecular weights so that there is a wider range of mixtures for which the minimum ignition energy is close to the lowest value.

In order to extrapolate these curves to Jet Fuel A, the fuel concentrations at the lowest point of the minimum ignition energy curves are plotted against the molecular weight in Figure 7. As was pointed out above, Jet-A fuel vapors are likely to have a molecular weight around 140 Kg/kmol so that the lowest minimum ignition energy should occur at concentrations around twice stoichiometric and the same value is expected to be applicable between 1.8 to 2.2 times the stoichiometric.

The minimum ignition energy decreases with increasing oxygen mole fraction. Since the authors are not aware of published data on the effect of oxygen concentration on the minimum ignition energy of Jet-A fuel, the data for propane, given in Figure 8, were used as a rough estimate. Most of the data for 1 atmosphere, shown in Figure 8, fall on a straight line with a slope of ~2.5 when replotted on log-log scale. Therefore, the effect of oxygen concentration on the minimum ignition energy can be expressed as:

$$MIE = (MIE)_o \left(\frac{x_{O_2}/(1-x_v)}{0.209} \right)^{-2.5} \qquad (1)$$

where:

MIE = Minimum ignition energy in O_2 enriched air
$(MIE)_o$ = Minimum ignition energy in ordinary air
x_{O_2} = Oxygen mole fraction in the ullage
x_v = Fuel vapor mole fraction in the ullage.

The minimum ignition energy increases with decreasing pressure. The relationship of the minimum ignition energy at fuel tank pressure P_u, with that when the fuel tank pressure is atmospheric, P_o, is given by

$$MIE = (MIE)_o \, (P_u/P_o)^{-n} \qquad (2)$$

where n is approximately 2 for hydrocarbon type fuels (Kuchta, 1975).

Finally, the minimum ignition energy decreases with increasing mixture temperature. Kuchta (1975) recommends a factor of 2 decrease in minimum ignition energy for every 150°F temperature increase. However, the review of the data given in Barnett and Hibbard (1957) indicated that 150°F is appropriate for pentane, whereas for relatively heavier hydrocarbons of Jet-A vapors a 100°F (56°C) temperature increase is probably more realistic for representing the factor of 2 drop in the minimum ignition energy. The minimum ignition energy at a given ullage temperature T_u can be related to its standard value* at 537°R (298°K) with the equation

$$MIE = (MIE)_o \exp \left[\frac{537°R - T_u(°R)}{144°R} \right] \qquad (3)$$

In lieu of accurate correlations for the combined effects of these variables, the overall effect can be approximated as a product of the individual effects given in Equations 1 through 3. Examples of such calculations for two of the missions listed in Table 1 (cases 1 and 5) are given in Figure 9, where the ratio of the estimated minimum ignition energy of the ullage gas mixtures during flight to the minimum ignition energy of propane is plotted as a function of time into the mission.

The oxygen and fuel vapor concentrations needed for these calculations were taken from the output of the ULLAGE program as the average ullage concentrations. The effect of the hydrocarbon concentration was ignored recognizing the fact that the vapors in the ullage may be stratified.

The horizontal line passing through the middle of Figure 9 denotes the ullage gas mixtures with a minimum ignition energy equal to that of 1.2 times stoichiometric propane-air mixture. For all the points above this line, the Military Standard 1757A is conservative, whereas the points below the line correspond to an increased vulnerability that cannot be foreseen by the standard. As seen in Figure 9, at the beginning and the end of the mission (during low altitude flights), the Military Standard 1757A may be underestimating the ignition energy by a factor of 2 for the pressurized ullage case. The nonconservatism is less for the vented ullage.

It should be noted that the type of calculations made to obtain Figure 9 can also be used in an absolute (rather than relative) sense, if the actual value of the credible spark energy in the ullage is known. In that case the ullage mixtures during flight can be checked to see whether they will ignite at any time.

b) <u>Hot Surface Ignition Induced by a Lightning Strike</u>

Hot surface ignition could occur if the lightning strike were to heat up some high resistance current paths to an ignition temperature. The surface ignition mode is more complicated than the spark ignition since the details of the igniting surface (in addition to the state of the ullage) play a significant role in determining the ignition temperature. The hot surface ignition phenomenon has been studied in some detail for hydrocarbons (e.g., Laurendeau, 1982) as well as for aviation fuels and fluids (e.g., Clodfelter and Anderson, 1989).

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* This is an extrapolated value. Jet-A vapors at this temperature do not form a flammable mixture under atmospheric pressure.

The asymptotic limit of this ignition mode characterized by the autoignition temperature is the case for slow, uniform heating of the entire mixture until it ignites. The minimum autoignition temperature for Jet-A vapor-air mixtures was reported to be 435°F (224°C) by Kuchta (1975). For propane-air mixtures, however, the minimum autoignition temperature is much higher and is 871°F (466°C). This large difference in the autoignition temperatures is recognized by the Military Standard 1757A which calls for the use of temperature sensitive paints (rated for 450°F) for the hot spot testing. However, the minimum autoignition temperature of Jet-A vapors in air is expected to decrease with increasing mixture temperature, and oxygen mole fraction; and with decreasing pressure, so the military standard may become nonconservative during a mission, as in the case of spark ignition. However, an analysis similar to the spark ignition has not been performed for this possible yet less likely ignition mode.

CONCLUSIONS

Execution of the ULLAGE program using realistic mission profiles for transport and fighter airplanes fueled with Jet-A has shown that the fuel vapors in the ullage reached flammable proportions at some time during the flight for most of the missions (with non-inerted fuel tanks) considered. For missions where the ullage mixtures were not normally flammable, the average fuel vapor concentration at times exceeded 50% of the lower flammability limit, so that combustion may still be plausible, if there is sufficient stratification, or fuel mist is present. Therefore, when Jet-A is used as fuel either tank inerting must be considered, and/or great care must be exercised to eliminate all possible ignition sources in the ullage. This is particularly true for fighter aircraft missions on hot days because the ullage is flammable during most of the mission.

Parametric cases run to isolate the effects of various operational parameters on the ullage flammability have shown the following:

- Increased flight environment temperature has the effect of strongly increasing the fuel vapor concentration while slightly reducing the oxygen enrichment in the ullage;
- Pressurization of the ullage reduces the fuel vapor concentrations and oxygen enrichment substantially;
- The modest amount of tank ventilation considered in the analysis helps reduce the oxygen enrichment in the ullage while the slight reduction in the fuel vapor concentration occurs only in pressurized tank cases.

A deterministic methodology to evaluate the ullage ignition hazard has been outlined and recommended for use as more data become available on the characteristics of Jet-A fuel vapors. This procedure has been used to assess the relative ignitability of Jet A fuel vapors in the ullage under realistic flight conditions with respect to 1.2 times stoichiometric propane-air mixture under standard conditions as recommended by the Military Standard 1757A. The results have shown that the Military Standard 1757A is not always conservative. Until more data become available the method presented in this paper can be used to supplement the Military Standard 1757A as a screening tool to identify the windows of increased vulnerability.

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TABLE I

SUMMARY OF THE COMPUTER RUNS MADE USING PROGRAM ULLAGE

	INPUT			OUTPUT			
Case No.	Mission	Tank Pressurization	Tank Ventilation	Maximum Average Oxygen Vol %	Maximum Average Fuel Vapor Vol %	Percent Mission Time Elapsed Above: 50% LFL	100% LFL
0	Transport	No	No	29.3	0.61	53	1
1	Fighter/Hot Day	No	No	25.9^{s*}	24.2^{s}	100	94
2	Fighter/Cold Day	No	No	27.2^{s}	1.35^{s}	46	30
3	Fighter/Hot Day	No	Yes	23.7	24.2^{s}	100	94
4	Fighter/Cold Day	No	Yes	24.9	1.35^{s}	46	30
5	Fighter/Hot Day	Yes	No	21.5^{s}	4.59^{s}	94	65
6	Fighter/Cold Day	Yes	No	21.6^{s}	0.28^{s}	14	0
7	Fighter/Hot Day	Yes	Yes	21.2^{s}	3.62^{s}	94	63
8	Fighter/Cold Day	Yes	Yes	21.4^{s}	0.22^{s}	9	0

*Superscript s denotes that the mixture was predicted to be stratified by ULLAGE.

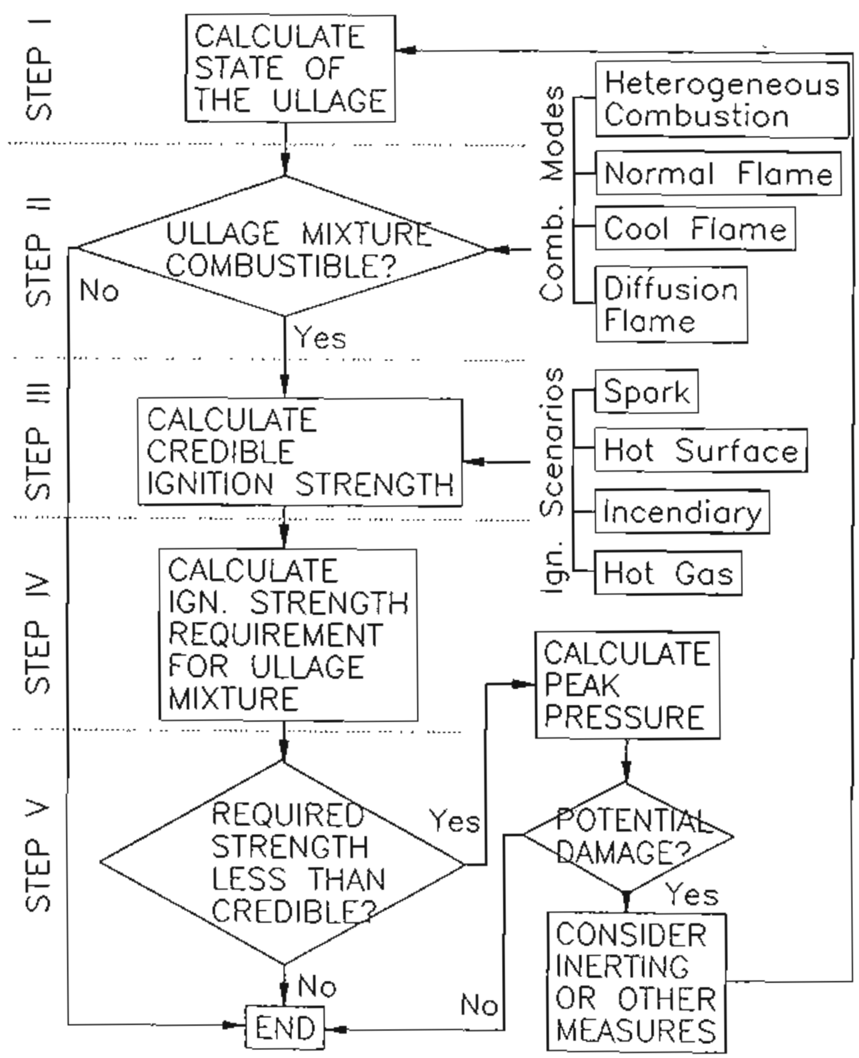


Figure 1. Steps involved in the deterministic evaluation of ullage ignition hazard.

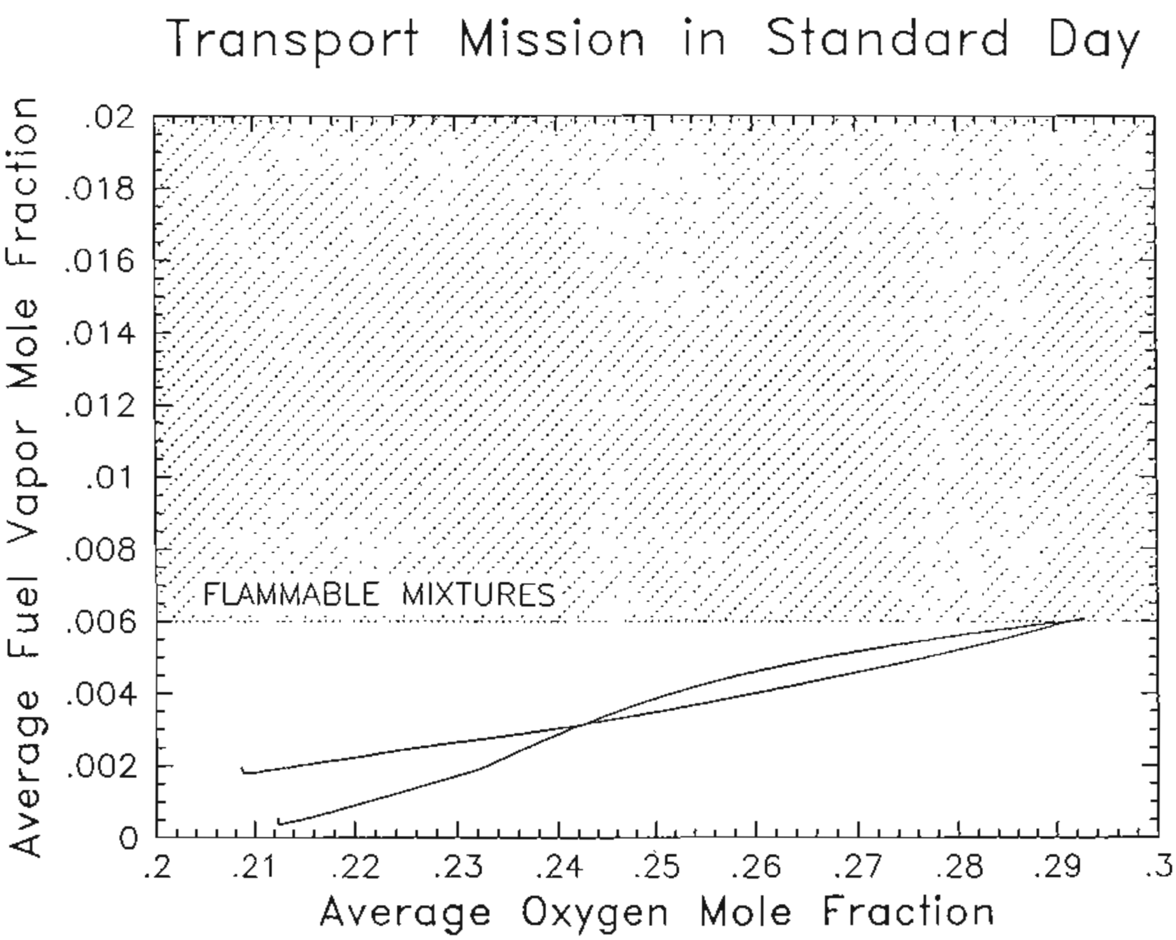


Figure 2. Variation of the average ullage composition during a transport mission.

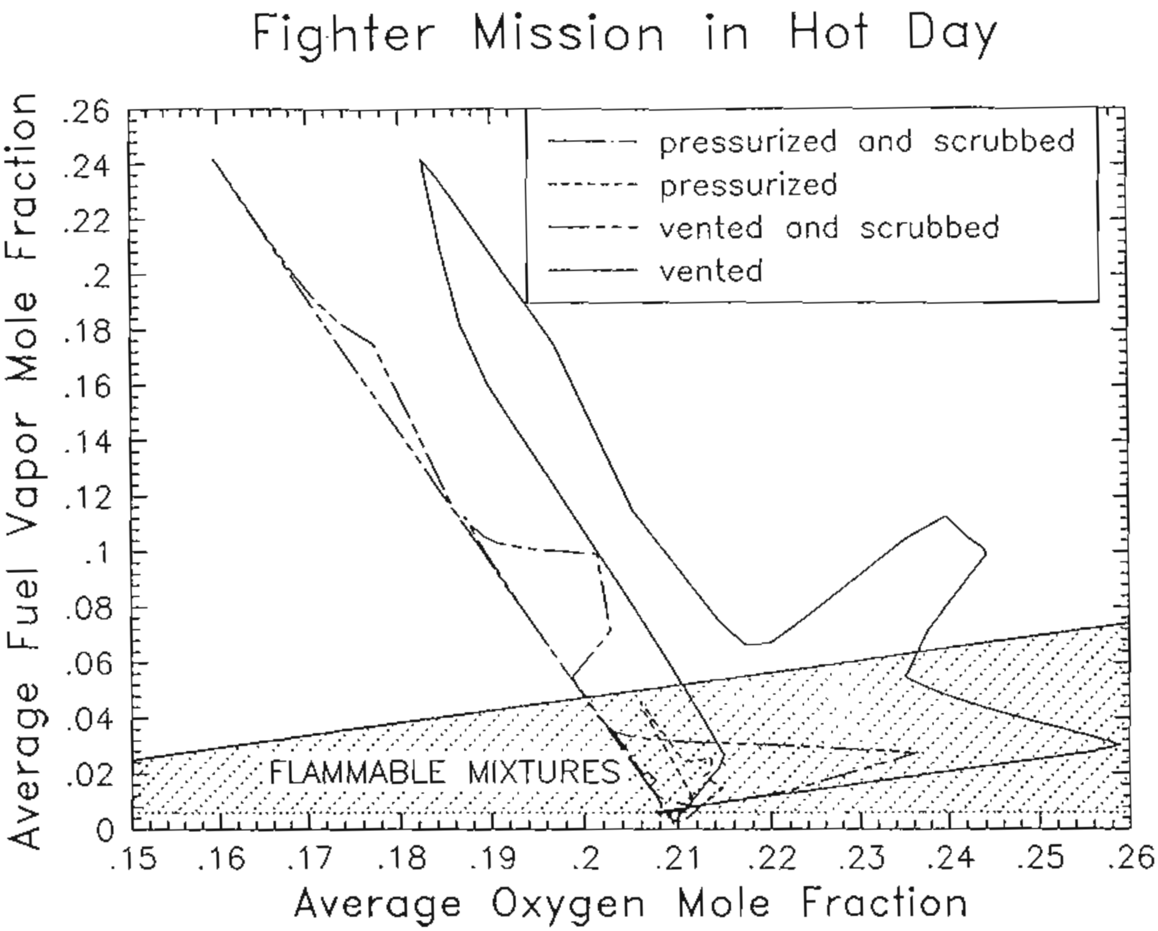
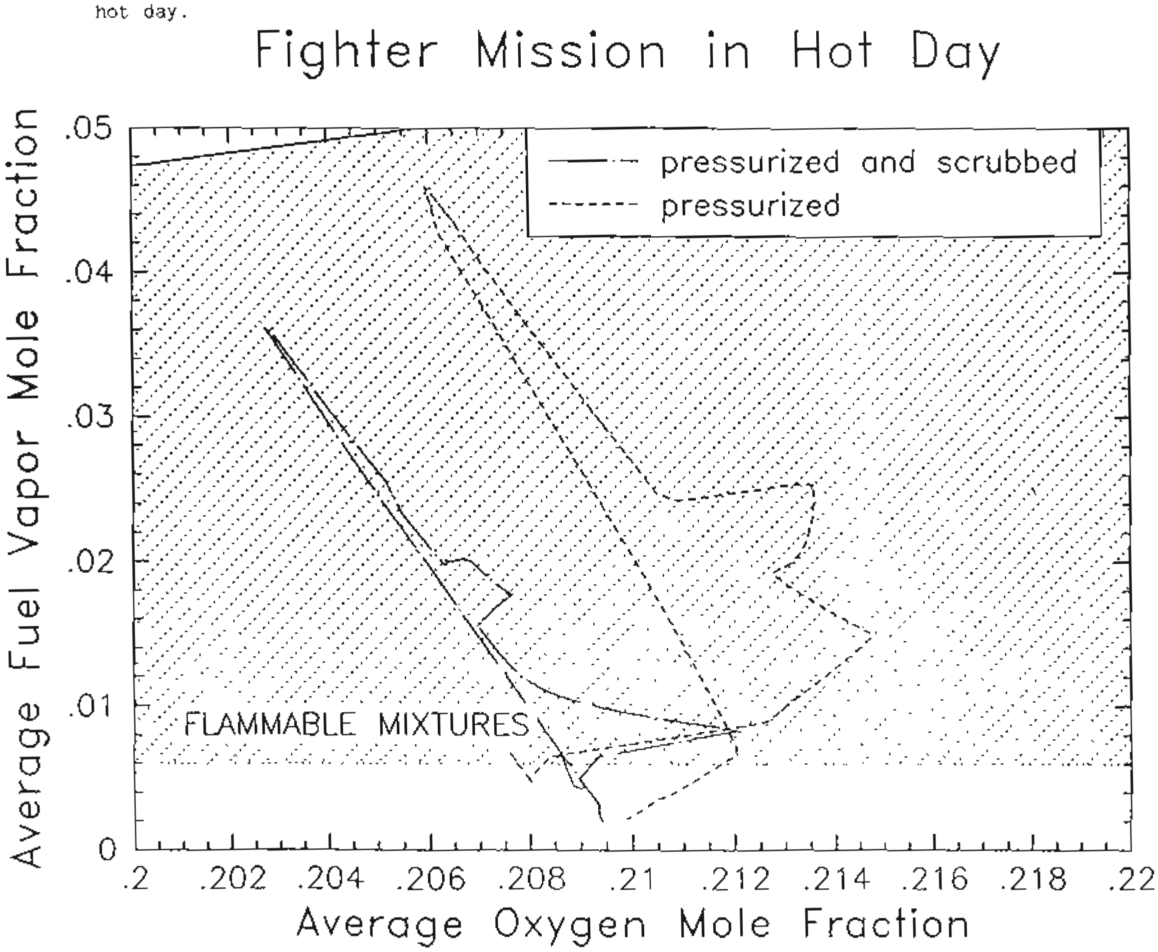


Figure 3a. Variation of the average ullage composition during various fighter missions on a prototypical hot day.



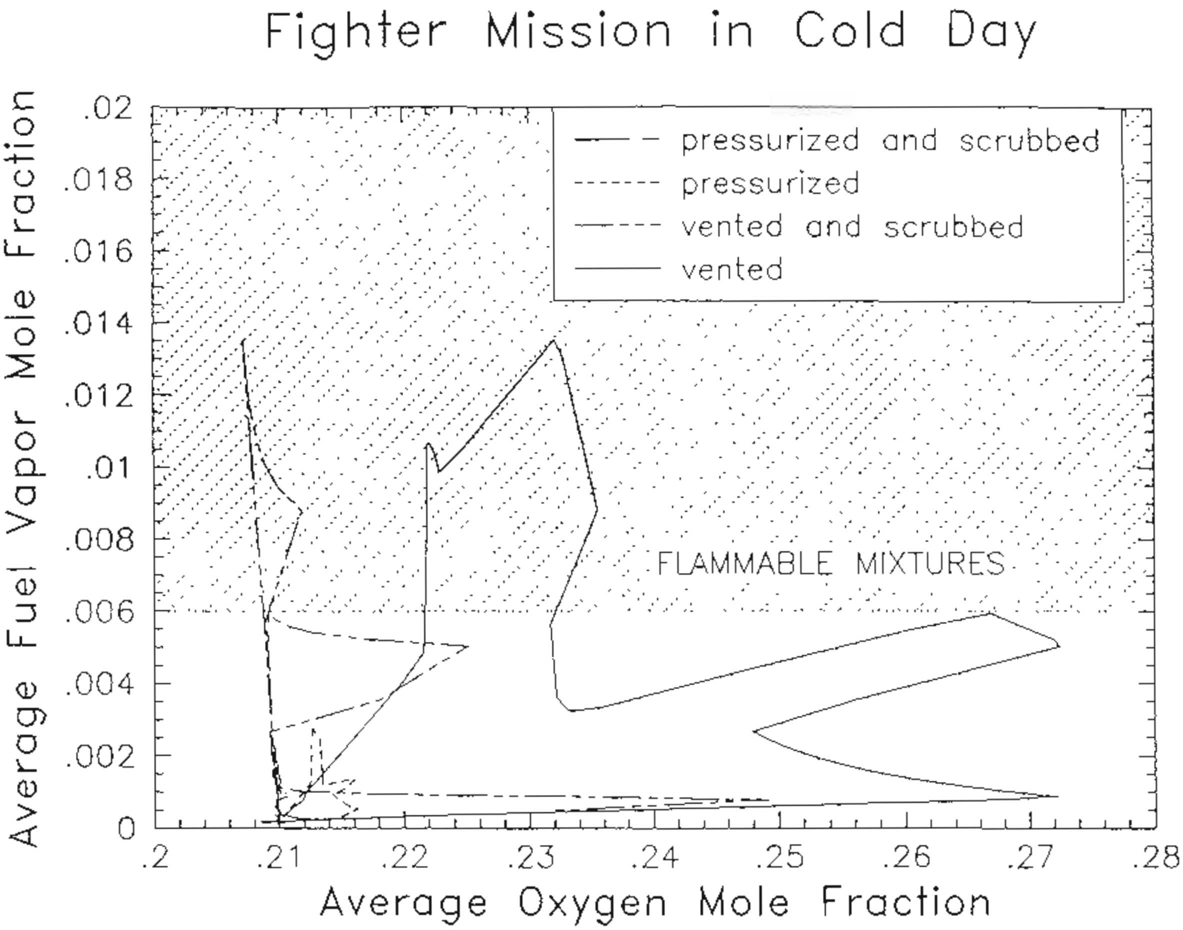


Figure 4. Variation of the average ullage composition during various fighter missions on a prototypical cold day.

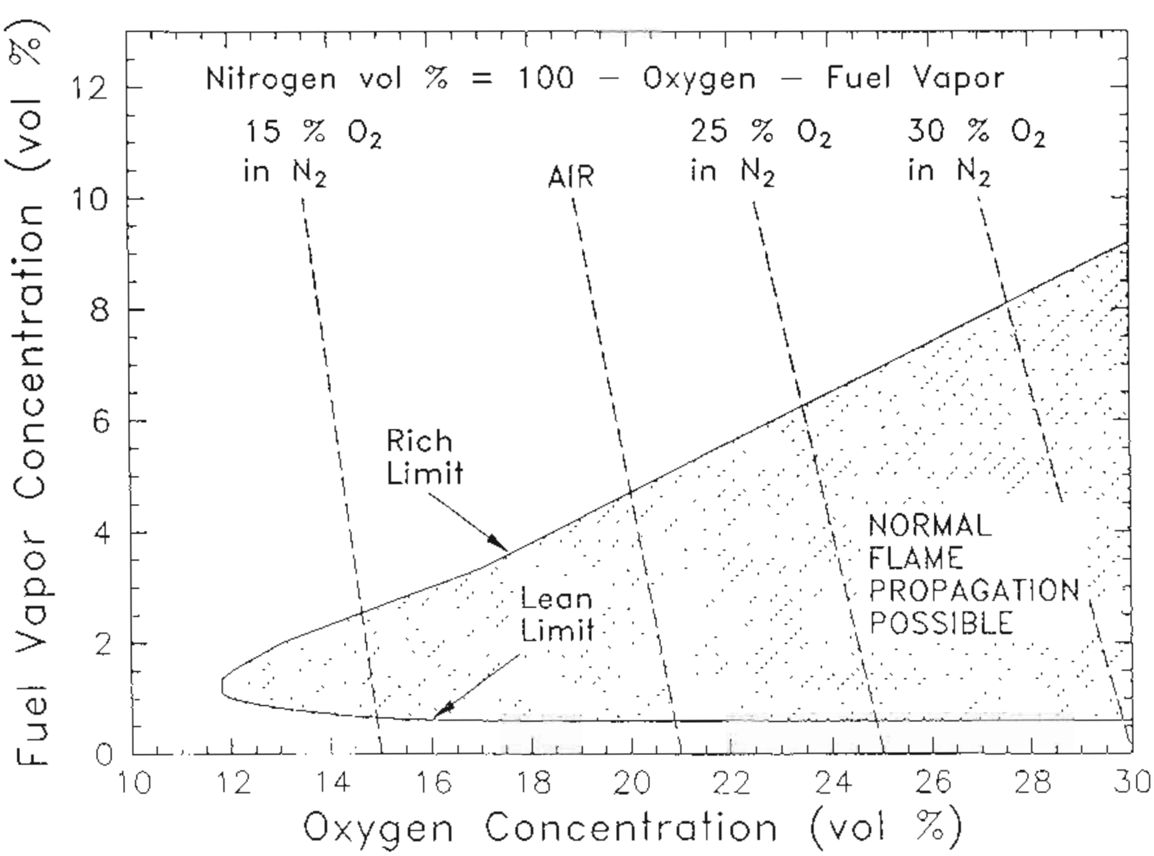


Figure 5. Estimated normal

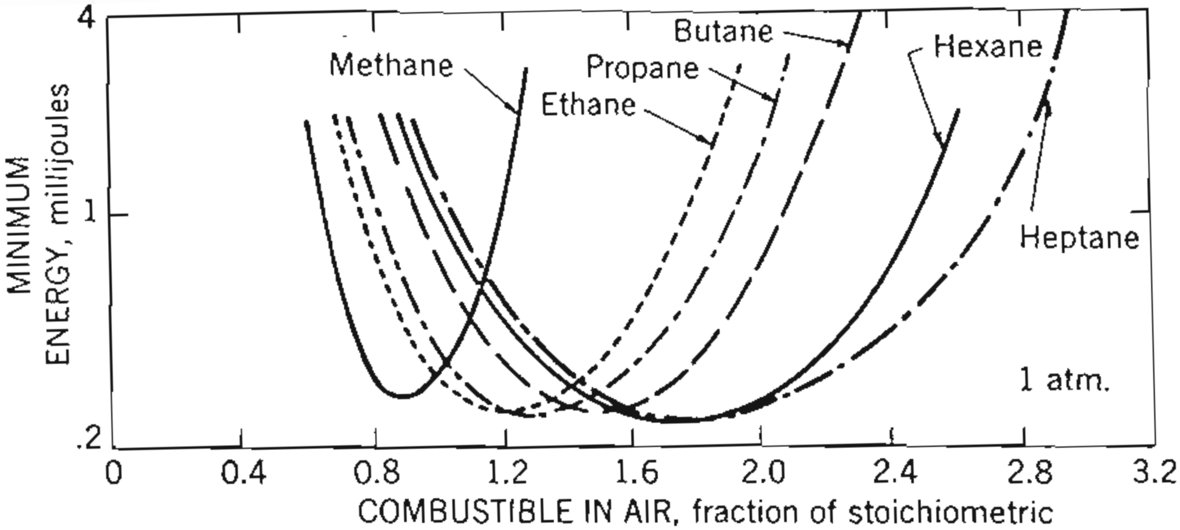


Figure 6. Spark ignition energy vs mixture composition for mixtures of various straight chain saturated hydrocarbons with air at 1 atmosphere. (Taken from Kuchta (1975).)

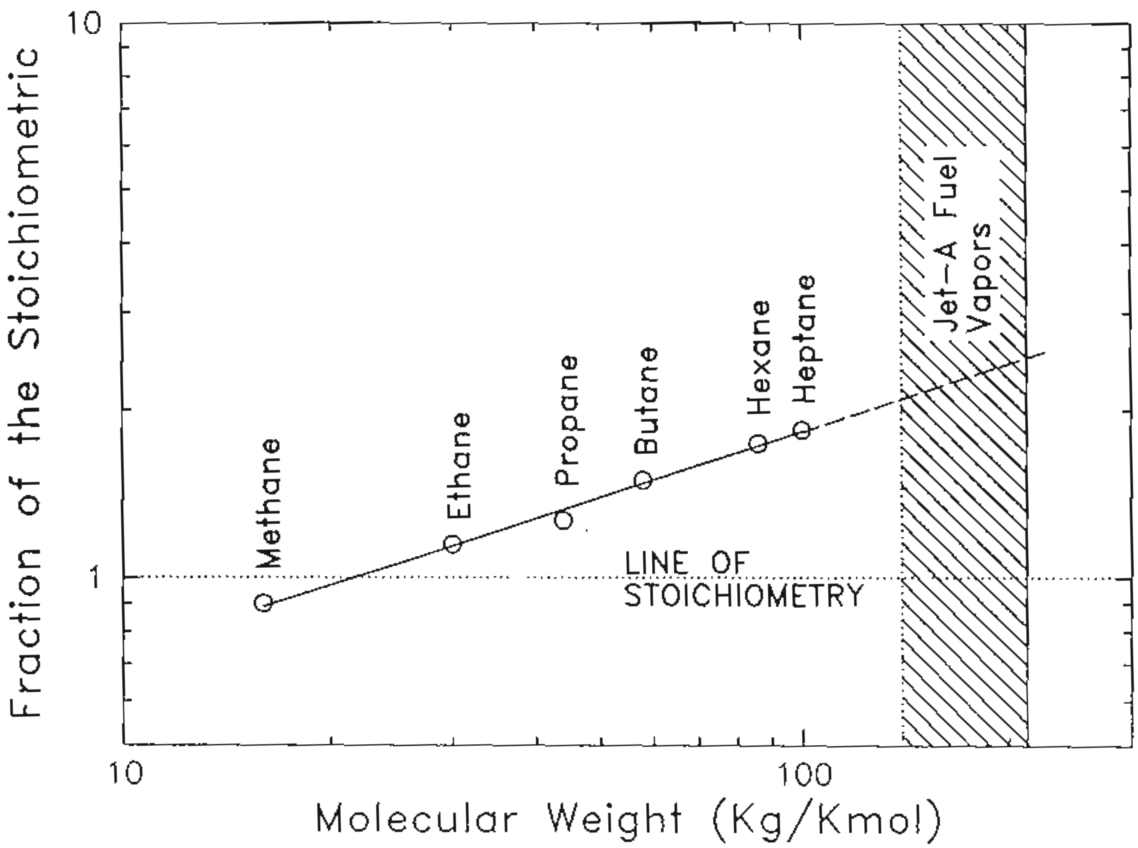


Figure 7. Variation of the fuel concentration corresponding to the minimum of the minimum ignition energy curves as a function of the molecular weight.

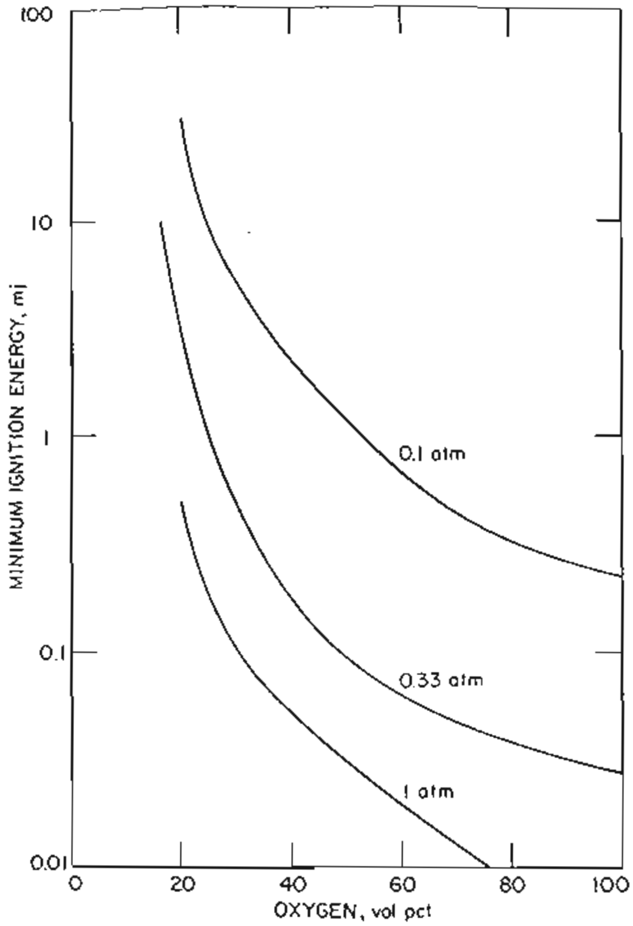


Figure 8. Minimum ignition energy of propane-oxygen-nitrogen mixtures as a function of oxygen concentration and mixture pressure. (Taken from Kuchta (1975).)

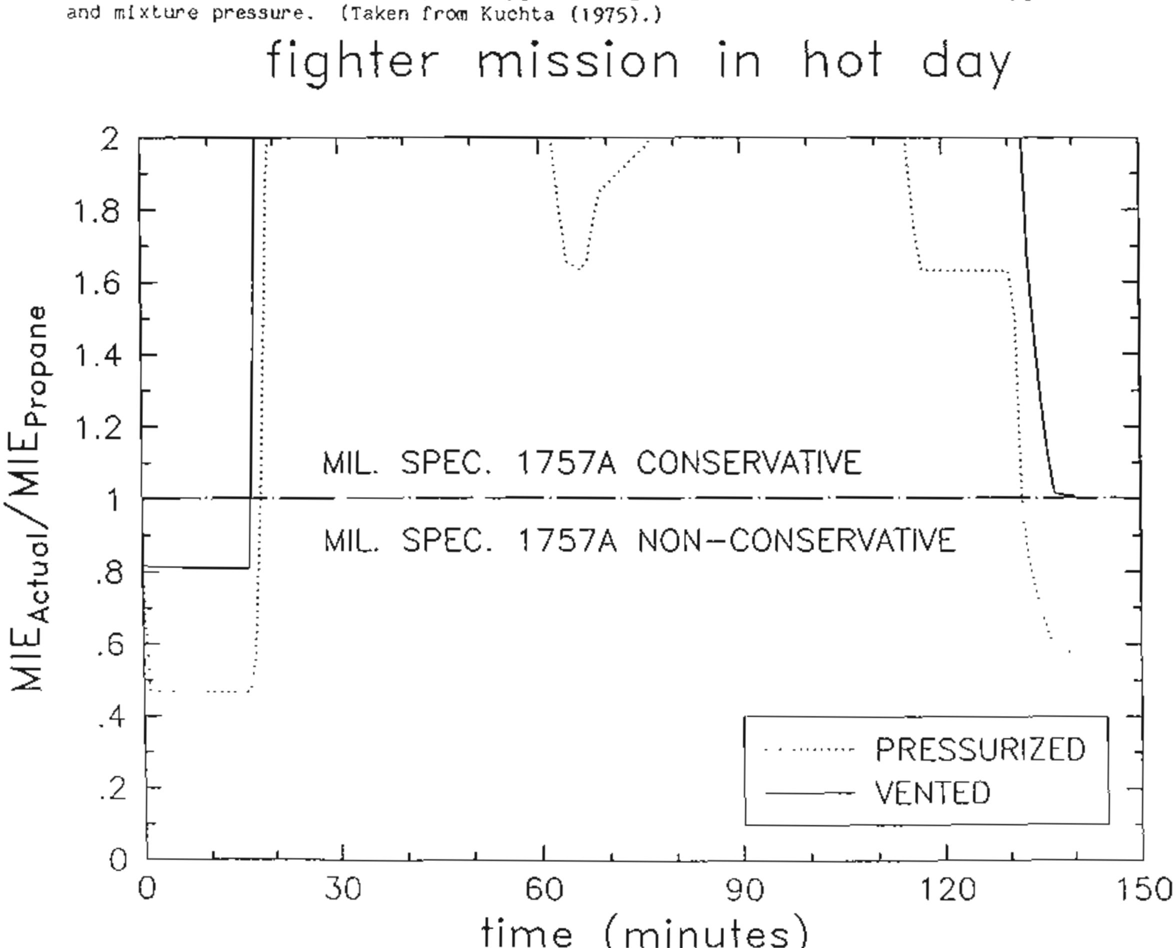


Figure 9. Ratio of the estimated minimum ignition energy of the ullage gas mixtures to the minimum ignition of propane plotted as a function of time for two of the fighter missions on a hot day (cases 1 and 5).

FIRE SAFETY APPLICATIONS FOR SPACECRAFT

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SUMMARY

This paper reviews fire safety for spacecraft by first describing current practices, many of which are adapted directly from aircraft. The paper then discusses current analyses and experimental knowledge in low-gravity combustion, with implications for fire safety. In orbiting spacecraft, the detection and suppression of flames are strongly affected by the large reduction in buoyant flows under low gravity. Generally, combustion intensity is reduced in low gravity. There are some notable exceptions, however, one example being the strong enhancement of flames by low-velocity ventilation flows in space. Finally, the paper examines the future requirements in fire safety, particularly the needs of long-duration space stations in fire prevention, detection, extinguishment, and atmospheric control. The goal of spacecraft fire-safety investigations is the establishment of trade-offs that promote maximum safety without hampering the useful human and scientific activities in space.

INTRODUCTION

Fire is regarded as one of the most serious threats to space travel, yet the spread of fire in space is not well understood. Efforts to prevent and control fires in space have, to a large extent, been based on techniques borrowed from aircraft practices. Indeed, fire potential in ground, launch, and recovery operations for space is analogous to that in ground servicing, takeoff, and landing operations for aircraft. Thus, present spacecraft fire safety has been promoted through strict control of materials and atmospheres and through fire detection and suppression methods optimized for reliability and mass and energy conservation.

For space missions of the near future, fire safety techniques must change from simple strategies borrowed from aircraft practices to specific methods for spacecraft, compatible with the requirements of complex, multi-mission operations. The next generation of human-crew spacecraft will be dominated by permanently orbiting platforms such as the prototype U.S.S.R. Mir or the planned U.S. Space Station Freedom. The future space stations will be clusters of living quarters, laboratories, satellite launch and recovery facilities, and industrial pilot plants, accommodating "passengers" who are scientists and observers, not astronauts. Fire-safety techniques will strive for simplicity, standardization, practicality, minimal impact on operations, and reasonable costs. The similarity of these objectives to present policies in the passenger-carrying airplane fleet is inescapable.

An AGARD symposium held 14 years ago summarized the progress in aviation fire safety at that time (Ref. 1). Some of the concerns discussed at the symposium are now interests common to spacecraft and aircraft, including the needs for better understanding of fundamental fire-safety principles, improvements in nonflammable materials, and the reduction of fire-generated smoke and toxic products. These specific concerns for spacecraft fire safety have been discussed in a symposium held in the United States, aimed at initiating studies applicable to the U.S. Space Station Freedom (Refs. 2 and 3).

This paper is a review and status report on current understanding and research directions in spacecraft fire safety. In addition to the aforementioned similarities to the aircraft environment, the paper discusses the unique attributes of space, the most obvious of which is the almost complete absence of the gravitational force. The behavior of flames in "microgravity" has a strong influence on fire initiation and control. The paper also surveys the application of low-gravity combustion knowledge to provide techniques of fire prevention, detection, extinguishment, and atmospheric control in spacecraft.

CURRENT SPACECRAFT FIRE-SAFETY PRACTICES

Fire Prevention in Space

Basic strategies. - Safety in human space travel has always been of paramount importance. The earliest space missions attempted to minimize fire hazards through stringent control of potential flammables and sources of ignition energy. Since space vehicles were relatively simple and their operating missions short in duration, the strategy of strict preclusion of fire-causing elements was thus practical to implement. For new generations of space missions, this approach of "complete exclusion" for fire safety is impractical. First, a lack of thorough understanding of fire behavior under space conditions undermines the confidence that hazards can be completely eliminated. Second and more important, regardless of the state of knowledge, space planners now concede that complete elimination of fire-causing elements is neither practical nor desirable if a space mission is to serve a variety of useful purposes in terms of passenger, scientific, or commercial accommodations (Refs. 3 and 4). Thus, total elimination of risk is impossible, and spacecraft fire safety becomes part of an optimum balance among safety, performance, cost, and schedule (Refs. 5 and 6).

Figure 1 represents a logical approach to spacecraft fire safety based on practical strategies. The goals of risk reduction are approached through the acceptability criteria, which include safety standards, material test limits, operational procedures, and other factors that limit the degree of risk. The information contributing to these acceptability decisions is provided by the identification and assessment of hazards and the formulation of tolerance standards to set a policy of risk limits.

Friedman and Sacksteder (Ref. 6) have further characterized the process of risk assessment by defining simple steps of prevention, response, and recovery, based in part on the analyses of Peercy and Raasch (Ref. 7). In brief, prevention is the original philosophy of fire safety through the strict exclusion of fire-causing elements. Where prevention is impractical, response, that is, the identification of the hazard and the limitation of the growth of an incipient fire through detection and suppression techniques is a lesser risk option than full-scale fire control. Recovery, on the other hand, is the highest-risk option of fighting an established fire, limiting damage, and restoring the original conditions. Spacecraft risk management, out of necessity, incorporates this entire range of risk assessment into fire-safety programs.

Material flammability and acceptance. - The first line of defense in spacecraft fire safety is in the limitation of materials, as far as practical, to those characterized as nonflammable. For U.S. spacecraft, the primary acceptance test is the upward flammability test, described in the NASA Handbook NHB 8060.1B (Ref. 8). The apparatus is sketched in Fig. 2. The sample material, a sheet or fabric for example, is mounted vertically and ignited at the bottom. To pass the test, the material either resists ignition or, if ignited, must not sustain a flame propagating more than a stated limit (15 cm at present). Furthermore, the ignited specimen must not drip sufficiently to ignite a sheet of paper mounted below the sample. Alternative acceptance tests are defined for flammability determination of such materials as wire insulation, sealants, greases, and liquids that are unsuitable for evaluation in the upward flammability test.

Cole (Ref. 9) notes that for confidence in the results of these tests, it is critical to test material samples representative of their end-use configuration in spacecraft and to test them in the same atmosphere as to be used in space. Since fire behavior is surely different in space than in normal gravity, the safety factors provided by the normal-gravity flammability test data are uncertain. In addition, one must realize that many essential items that will be used in spacecraft, items including some clothing, paper, and films, are inherently flammable. The acceptance of these materials into a space environment assumes that their potential hazards are reduced through limitations of quantity and requirements for specialized spacing, barriers, and storage.

Fire Detection Practices in Spacecraft

Detection of fire, or its precursor overheating, depends on the ability to recognize the abnormal departure in environmental conditions known as a "fire signature" through measurement of temperature, radiation, smoke-particle, or chemical-specie changes. Knowledge of low-gravity fire behavior leads one to expect that fire indicators in space are different from those in normal gravity, both in the nature of the signature and in the mode of transport of the signature to the detector sensor (Ref. 3).

Nevertheless, present fire detectors in spacecraft are adaptations of acceptable models used on aircraft. Aircraft fire detection techniques, a subject well reviewed in recent years (Refs. 10 to 12), incorporate several modes of detection, such as temperature sensing in engine nacelles and cargo areas, and radiation and smoke-particle detectors in cabin areas. The original spacecraft fire detectors were the human crew, who could sense and detect incipient fires. The complexity and varied missions of present spacecraft, however, make remote sensing necessary.

Figure 3 shows the fire-protection provisions in the U.S. Shuttle cabin, and the inset shows a typical detector. Nine ionization-type smoke detectors are installed in the instrument bays and crew decks of the Shuttle (Refs. 9 and 13). Similar fire protection is provided in the Spacelab, which is a European Space Agency laboratory chamber installed in the Shuttle payload bay in selected missions. The Shuttle smoke detector is identical in principle to conventional aircraft and commercial ionization smoke detectors, except for two additional features. The Shuttle smoke detector is provided with a built-in fan to assure a continuous flow of sampled atmosphere. The smoke detector also has a fine screen upstream of the ionization chamber to bypass larger particles and assure the entry of only submicrometer-sized particles into the chamber. Thus, the spacecraft smoke detector can monitor air quality regardless of location, since it maintains a continuous forced-convection flow through its sensing elements. The sampling screen is intended to reject large particles, most likely dust, to reduce the number of false alarms caused by these air-borne particles.

The present spacecraft fire detectors represent the best application of the state-of-the-art derived from aircraft and ground experience. The detectors are an outgrowth of prior investigations of several proposed techniques, including ultraviolet radiation, cloud chambers, quartz-crystal impact microbalances, and gas samplers, for smoke and fire detection (Ref. 6). While the modified ionization smoke detector represents an optimum in terms of reliability, maintenance, minimum mass and cost factors, it cannot be claimed to be the most effective for low-gravity performance. In fact, several questions for future space applications must be resolved, namely, (1) is the screened particle-size range most representative of smoke-particle densities generated in incipient space fires? (2) do the placement and internal flow performance of the detectors ensure early detection and rapid response times? and (3) how can the sensitivity and performance of the detector be checked and calibrated under space conditions?

Fire Extinguishment Practices in Spacecraft

In space, techniques for fire suppression may differ from those in normal-gravity situations both because of the unusual characteristics of low-gravity fires and because of the low-gravity influence on extinguishment delivery systems. As is the case for fire detection, present spacecraft fire extinguishers are adaptations of those used in aircraft cabin protection and employ mixed-phase extinguishants (foams) or, more commonly, pressurized gases (Refs. 10 and 14).

The early human-crew spacecraft had provisions for use of food-reconstitution water guns for emergency fire extinguishment (Ref. 9). The Skylab, the 1973-1974 U.S. prototype space station, was equipped with water/foam fire extinguishers. At present, the Shuttle fire extinguishers are pressurized gas cylinders, charged with bromotrifluoromethane (Halon 1301) (Fig. 4). Three fixed-position extinguisher cylinders protect the instrument bays, and these may be actuated remotely from the control deck. Additional portable fire extinguishers are available for fire fighting in the Shuttle cabin and also in Spacelab. These portable units can be used to suppress fires originating behind the instrument panels by inserting the extinguisher nozzles into ports in the panels.

The choice of Halon 1301 for fire protection in the Shuttle is based on the demonstrated effectiveness of this extinguishant (a small concentration extinguishes most fires) as well as on its inertness, at least in small concentrations. There are, however, recognized disadvantages in the use of Halon 1301, even for aircraft service (Refs. 12 and 14). The principal problem is that Halon 1301 extinguishes by inhibiting the chain-branching reactions of combustion and, in the process, generates hydrogen halides (HBr and HF). These gases are toxic and corrosive, and they can be difficult to remove in the recycling environmental control system. Furthermore, Halon 1301 is relatively ineffective on deep-seated or smoldering fires, which require cooling or smothering foams for suppression. The occurrence of smoldering fires may be reasonably probable in space, where the slow diffusion of oxygen into porous media favors smoldering rather than flaming combustion.

A number of common extinguishing agents have been suggested as alternatives to Halon 1301 in future spacecraft (Refs. 1 and 4), but each has disadvantages as well as advantages. A primary consideration in the selection of an extinguishing agent is the effect of the potential contamination of the spacecraft atmosphere by the agent and its reaction products. The provision for Halon 1301 onboard the U.S. Shuttle is justified in that, for a short-duration mission, the advantages of the Halon overcome its disadvantages. A discharge of the extinguishant during a mission would call for an immediate termination and return to earth within a few hours to minimize the toxic or corrosive effects (Ref. 13). This option is not available in future, permanent orbit missions, as in Freedom.

COMBUSTION AND FIRE IN SPACE

The Low-Gravity Environment

At the usual altitude of a few hundred kilometers for human-crew orbiting spacecraft, the Earth gravitational acceleration is little different from that at sea level (9.8 m/s^2). The condition of the spacecraft and its contents is that of free fall, where there is a balance of forces with a very low net acceleration force. Zero acceleration, or zero gravity, is approached only as a limit. In practice, accelerations due to unbalanced drag forces and other perturbations are slight, of the order of 10^{-7} to 10^{-4} times normal Earth gravity. For combustion research, this low-gravity environment is usually called microgravity.

The large temperature differences in flames cause density differences, which produce strong upward, buoyant flows in normal gravity. In low gravity, flame propagation is no longer preferentially "up," and diffusion, Stefan and other transport mechanisms, whose effects are overwhelmed by buoyancy in normal gravity, can strongly influence flame propagation. Transport of heat by radiation may become dominant, causing flame inhibition by cooling in some instances, causing fire propagation to adjacent surfaces in other instances. The transport of oxygen to a flame zone by diffusion alone may be slow and inefficient in low-gravity flames, altering the chemistry and kinetics of the combustion reaction. All these factors can strongly affect the ignition, spread, and nature of the reduced-gravity flame.

Thus, fire safety in orbiting spacecraft requires foremost an understanding of the behavior of combustion processes in low gravity, based on theoretical analyses and validating experimental data.

Brief History of Low-Gravity Combustion Research

The earliest low-gravity combustion experiments conducted with solid materials were performed aboard aircraft flying over parabolic flight paths to obtain short periods of low gravity (Ref. 15). Various polymeric materials, rubber compounds, paraffins, and paper were burned in low-pressure, pure-oxygen environments. Burning rates in low gravity were observed to be slow, but steady-state conditions were not achieved during the short test time.

Subsequent aircraft experiments (Ref. 16) were conducted to study the burning rates of cotton cloth strips under various oxygen-diluent atmospheres. Burning rates were observed to increase with increasing thermal conductivity of the inert diluent but were overall much lower in low gravity than in normal gravity Momentary slight accelerations were observed to increase the burning rates considerably, but again the effect could not be quantified because steady-state was not achieved.

A series of drop tower experiments were conducted in the early 1970's (Refs. 17 to 19) to examine the effects of oxygen concentration and pressure on the burning rates of cellulose acetate. These test results indicated that low-gravity flame-spread rates are nearly the same, or slightly lower, than normal-gravity spread rates and are a function of material thickness. The flame-spread rate of the thinnest materials is comparable to normal-gravity rates, but the rates of thick materials are considerably less than those in normal gravity.

The only on-orbit combustion experiments to date were direct continuations of the early aircraft tests. Aluminized mylar, nylon, neoprene-coated nylon fabric, polyurethane foam, paper, and Teflon fabric were studied aboard Skylab 4 in 1974 (Ref 20), in a 0.04-cubic meter spherical combustion apparatus (Fig. 5). In addition to tests of the burning rates of the materials noted, the Skylab experiments studied the spread of fire to adjacent materials as well as the extinguishment of the burning material through water sprays or venting to the vacuum of space. Qualitative results from these tests were recorded by a 16-mm color movie camera. Burning rates were observed in general to be much slower in low gravity than in normal gravity. Figure 6 shows the spherical flame generated by burning a polyurethane sample in low gravity. Fires were observed to spread from one material to another over a gap of 1.3 cm. In the venting tests, it was noted that air flow caused by evacuation of the atmosphere greatly intensifies the burning rates for a brief period of time before causing extinguishment in the near-vacuum. It was concluded from this observation that, unless the evacuation time is short, the enhanced combustion due to the air motion could do considerable damage before extinction occurred. Water extinguishment was successful in some cases. However, when the water spray was not carefully dispersed, the water was observed to scatter burning materials rather than extinguish them.

Based upon these simple low-gravity combustion tests, Kimzey observed that, because low-gravity burning rates are slower and show no tendency to increase with time as is usual in normal-gravity upward burning, normal-gravity flammability tests (Ref. 8) provide adequate, conservative standards for low-gravity material acceptance. Recently, the sufficiency of normal-gravity tests to characterize low-gravity flammability has been questioned. Of particular concern is the observation from the early tests that, if some convection is imposed on the burning material in low gravity (due to accelerations, venting, or air circulation), the burning rate intensifies considerably. The U.S. Shuttle and Space Station Freedom must have air circulation systems to provide a constant flow of air through the cabin; and, as an example, the Shuttle closed-loop air circulation system provides nominal air velocities between 8 and 20 cm/s throughout the crew cabin (Ref. 21). Thus, as the fire-detection systems and extinguishment systems are being designed for Freedom, further knowledge of the hazards of fire in space is essential.

In response to this renewed concern, a comprehensive, continuing experimental and model development program is being conducted to study the effects of oxygen concentration, material thickness, and flow on combustion of materials in low and partial-gravity environments. Figure 7 shows the evolution of experimental hardware to study solid-material flammability in low gravity. The airplane test package was the earliest apparatus (Ref. 15), which served as a model for the Skylab tests cited here. The drop-tower package is an apparatus currently in use at the U.S. NASA Lewis Research Center to study effects of atmospheres, inertants, and ventilation flow on paper combustion. The Solid Surface Combustion Experiment (Ref. 22) is a flight package designed for long-duration tests in the Shuttle, scheduled to fly at the earliest opportunity, probably in 1990.

Low-Gravity Combustion Parameters of Concern for Fire Safety

The modeling and experimental results to date have given an improved understanding of what factors are important in assessing the fire hazard in a low-gravity environment. To illustrate, typical normal and low-gravity flames in thin solid fuels are drawn schematically in Fig. 8. In general, the flames in low gravity are observed to be cooler and more diffuse than their normal-gravity counterparts. The flame is larger and establishes itself further from the fuel surface than normal-gravity flames. Large soot particles are seen to escape from the flame zone in low gravity, and the color of these radiant particles change as they cool, from orange to dull red to black (Ref. 23).

Material properties. - Material properties play an important role in the combustion process in low gravity. Materials that melt as they burn may boil at their surface, and the pulsating flame that results is due to the unsteady rate of vaporization from the boiling fuel. Nylon samples in the Skylab tests (Ref. 20) and nylon velcro in drop tower tests (Ref. 24) were observed to burn in this manner. The viscosity of the solid-fuel melt could also be a factor in the hazard of fire spread, because gaseous bubbles breaking through the liquid surface can propel molten and burning chunks of fuel into the gas phase to drift away until they impact on another (possibly flammable) surface. The expulsion of burning droplets of molten fuel has been observed in drop tower tests with nylon Velcro. Figure 9 shows a photograph of burning droplets leaving the flame zone of the burning material, along with a sketch interpreting the photograph. Droplet expulsion appears to be enhanced by a slow air motions past the sample, which also increase the overall burning rate considerably (Ref. 24).

Another material property which has been found to be important in low gravity combustion is the material thickness. In normal gravity, the flame-spread rate varies inversely with material thickness throughout the flammability region. In low gravity, the same relationship holds except near the extinction limit (minimum oxygen concentration) where the flame-spread rate for these flames decreases more strongly with increasing material thickness (Ref. 25). Further studies are needed, however, to quantify the thickness effect in low gravity more completely.

Atmospheric composition. - Inert gases such as nitrogen also have an important role in the burning process. It is known from normal-gravity testing that, for a constant partial pressure of oxygen, flammability decreases if the total pressure is increased by adding atmospheric diluent. This is because the combustion energy absorbed in heating the inert gas reduces the flame temperature. Therefore, although it has yet to be studied comprehensively in low gravity, inert pressurization with high heat-capacity gases appears to be an excellent candidate for fire prevention.

Inert gases also affect the combustion process by acting as a heat transfer medium from the flame to the fuel. Normal and low-gravity experiments have demonstrated that the thermal conductivity of the inert gas directly affects the burning rate; the higher the thermal conductivity, the faster the material will burn. Helium, for example, transfers heat very rapidly, and so materials in a helium-oxygen environment burn more quickly than the same materials in comparable nitrogen-oxygen environments. Thus it is desirable for further research in fire prevention, to consider diluents with a high heat capacity but a low thermal conductivity

Oxygen concentration in the environment has probably been the most studied parameter in low-gravity combustion research. The early tests focused on low-pressure, high-oxygen-concentration atmospheres because these atmospheres corresponded to the spacecraft practice at that time. U.S. human-crew spacecraft since the Apollo era have been designed for a low-oxygen concentration to reduce the fire hazard. The Shuttle currently uses standard sea-level air as its baseline atmosphere, although an elevated oxygen atmosphere is introduced in preparation for extravehicular activities.

Increasing oxygen concentration increases the burning rates of most, if not all, solid materials. Figure 10 shows how the flame-spread rate for paper changes as the oxygen concentration is increased (Ref. 25). For flames in high-oxygen concentrations far from the extinction limit, normal and low-gravity flame-spread rates are identical and linear with oxygen concentration; gravity plays no discernible role in the flame-spread process. Near the extinction limit, however, flame-spread rates decrease rapidly with decreasing oxygen concentration; and the low-gravity flame-spread rates are lower than the normal-gravity counterpart rates.

Radiation and extinction limits. - The data illustrated in Fig. 10 show the extinction limits in both normal gravity and low gravity. The cause of extinction is believed to be different for the two gravity situations. In normal gravity, flame extinction is usually caused by "blowoff," or the excessive gravity-induced convective removal of heat, usually due to buoyant flows. Blowoff occurs, for example, when you blow out a match. In low gravity, however, there are no gravity-induced convection flows, but the cooler flames are more sensitive to heat losses than normal-gravity flames. Experimental results suggest that radiative heat loss from the burning fuel surface, or quenching (i.e., rapid cooling), is the probable cause of extinction in low gravity (Ref. 23).

Convective heat transfer in low gravity is greatly reduced because of the elimination of buoyancy-induced flows, and conductive heat transfer appears to be reduced because flames are observed to be further from the fuel surface. Thus the relative importance of radiative heat transfer, either from the solid surface or from the flame zone, is greater. Radiative heat transfer can, as postulated above, cause flame extinction, or it can cause ignition of a fuel surface in the absence of convective cooling.

Ventilation and forced convection. - In the absence of buoyant flow, the dominant flow imposed upon a burning surface in spacecraft would be due to the ventilation system. The early low-gravity tests indicated that flow enhances combustion, and more recent quantitative tests have supported these early qualitative results (Refs. 23, 26, and 27). Figure 11 is a summary of the effect of air velocity on the flame-spread rate over paper. At near-quiescent conditions, attainable only at low gravity, the flame-spread rate is low. As the air velocity is increased in a direction counter to the flame spread, fresh oxygen is brought into the flame zone by forced convection; and the flame-spread rate increases rapidly with air velocity. On the other hand, at high air velocities typical of buoyancy-driven normal-gravity air velocities, the flame-spread rate decreases with increasing air velocity due to "blowoff," the convective cooling and dilution of the flame zone. The important concern for fire safety is in the range of intermediate velocities where flame-spread rates can be greater than the typical normal-gravity flame-spread rate. While the quantitative extent of this enhanced flame-spread-rate zone is not fully defined by experiments, it appears to lie within the range of typical spacecraft ventilation-air velocities.

Figure 12 describes the air-velocity effects as a flammability map for paper, which indicates the atmospheric conditions (oxygen concentration and flow velocity) over which the material will or will not burn. As is the case for flame-spread rates shown in Fig. 11, flammability increases (lower oxygen limits) at low air velocities, typical of low gravity, but decreases at high air velocities, typical of normal gravity with buoyant flow. Again, the maximum fire hazard for paper appears to be at intermediate forced-flow velocities attained in low gravity (in the range of current Shuttle ventilation velocities). Under these conditions, the material may burn at oxygen concentrations as low as 15 percent, which is below the measured downward-spread flammability limit in normal gravity with no forced convection.

Application of Low-Gravity Combustion Knowledge to Fire Safety

Much has been done since the Apollo era to improve the safety of spacecraft. The major improvement in the fire safety area has been to reduce the oxygen concentration from pure oxygen to that of sea-level air. Although humans can tolerate even lower oxygen atmospheres, reducing the oxygen concentration below that of air can adversely affect the mission usefulness, in terms of passengers, scientific, and commercial accommodation.

The reduction of oxygen concentration to that of air was an obvious improvement because this is the normal baseline atmosphere; and most, if not all, materials are more flammable in higher oxygen concentrations. Other fire-safety changes are not as feasible for adaptation. For example, the thicker the material the slower it burns, so it would seem to be logical to use potentially flammable materials in as thick a section as practical. However, this design concept is inconsistent with a common-sense approach of limiting the total quantity of flammable materials.

Actual low-gravity testing of all materials to fly in space is obviously not feasible at present. Current test methods reflect our understanding of flammability in normal gravity, but they fail to include some of the unique hazards associated with low gravity. These concerns include the enhanced low-gravity burning rate associated with forced-convection flows, the spread of fire by expulsion of hot particles from melting plastics, and the flammable, persistent aerosols created by spills of fluids or powders. In addition, some assessment of the potential for smoldering must be devised. Smoldering solids may burn undetected for hours or days, and even if flaming combustion never occurs, the build up of toxic products in the atmosphere is a serious danger to the environmental-control and life-support system.

Furthermore, investigation of the influence of low-gravity combustion processes on fire detection and fire extinguishment is needed for intelligent protection of the long-term habitation environments in space. Potential designs for fire detectors and fire extinguishers need to be tested in real low-gravity fire situations. Application of low-gravity combustion knowledge can also influence operational procedures to determine what improvements can be made to reduce the fire hazard while minimizing the inconvenience of safety regulations on the day-to-day activities of the crew.

FIRE SAFETY FOR FUTURE SPACECRAFT

The U.S. Space Station Freedom

Freedom, a permanent vehicle in low earth orbit, is a space station to be placed in operation in the next decade. Freedom is conceived as a cluster of elements devoted to satellite servicing, scientific and commercial space activities, and long-duration human habitation. The center of Freedom is the grouping of modules with interconnecting nodes and airlocks (Fig. 13). The main components are the habitation module for a crew of perhaps eight persons, the supply module, and three laboratory (and workshop) modules, with projects and personnel from several NATO nations and Japan, as well as the U.S.

The permanent installation and long-duration missions of Freedom will increase the probability of the occurrence of a fire. Since rescue and resupply flights cannot be immediately available, perhaps taking 30 days or longer to arrange, safety planning must assume that all fire controls and recovery supplies are contained within Freedom. In this respect, the interconnecting, "ladder" arrangement of the modules (Fig. 13) assures at least two paths of egress from each module, a haven for the crew in any node, and a means of closing off a damaged module without blocking access to any other module or node.

As stated earlier, the goal of fire safety in Freedom is the minimization of risk, rather than zero risk. That is, small tolerable threats are balanced against the constraints of practicality, operations, and economics (Refs. 5 and 6). A space station must accommodate living and recreational activities, as well as scientific and industrial operations, all of which require the possible introduction of flammable materials, heating and energetic operations with no satisfactory substitutes. The challenge to spacecraft fire-safety designs and techniques is obvious.

Submarine and Aircraft Analogies

Spacecraft fire-safety practices have been modeled on, and will continue to derive from, techniques and experiences established for the enclosed compartments of aircraft and submarines (Ref. 28). The submarine operates in a hostile external environment, supplies its own recycled atmosphere, and depends on self-contained fire detection and suppression systems. The spacecraft, however, has obvious differences because of its low-gravity exposure and the inability to extract oxygen from the surrounding atmosphere. (Submarines can generate oxygen from sea water.) In addition, submarines may surface for personnel evacuation if a fire becomes wide spread.

One set of submarine fire-protection investigations of interest for potential spacecraft application is that of fire-safe atmospheres. The small-scale combustion studies promoting low-oxygen atmospheres for fire prevention have already been discussed in a previous section. Gann et al. (Ref. 29) described simulation-chamber tests of nitrogen flooding for submarine fire fighting, where excess nitrogen lowers the oxygen content while retaining the oxygen partial pressure at tolerable levels for humans. An alternative approach, more suitable for spacecraft applications, is to maintain a constant total pressure with a reduced oxygen partial-pressure level based on minimum levels from high-altitude human experience. Allowable limits for low-oxygen atmospheres have been discussed by Horrigan (Ref. 30), and the fire-protection aspects have been presented in a spacecraft atmosphere selection forum summarized in Ref. 1. Another alternative method involves the substitution of a high molar-heat-capacity inert gas, such as CF_4 or SF_6, for nitrogen in the atmosphere (Ref. 31). The diluent will suppress combustion by lowering the flame temperature. Nevertheless, the use of fire-safe atmospheres on spacecraft must await the definition and implementation of long-duration testing of human responses and efficiency in the respective atmospheres. In any event, there are formidable structural and operational difficulties to the general adoption of atmospheres other than "air" in future spacecraft.

Of greater interest, however, is the use of inerting atmospheres in specific, uninhabited volumes, such as in electrical power cabinets. A promising source of an inerting atmosphere, already under investigation for military-aircraft fuel-tank inerting, is onboard inert-gas generation. This technique involves the removal of some of the atmospheric oxygen by molecular-sieve or permeable-membrane separators (Refs. 32 and 33). In spacecraft practice, an inert gas retaining 6 percent or greater oxygen concentration may be effectively fire-safe. In contrast to the once-through aircraft inerting system, the gases from the spacecraft inerting system would be recycled, and both the inert gas and the separated oxygen would be recovered and combined to regenerate part of the breathing atmosphere.

Research and Technology Trends

Fire prevention. - Adequate screening of materials for onboard use has been a long-time concern for both aircraft and spacecraft, and this concern has spurred the development of new plastic and composite materials with low-flammability characteristics. The principal acceptance test for NASA spacecraft materials, the upward propagation test (Fig. 2), has already been described in this paper. In low gravity, since flammability is often reduced for solid materials, the normal-gravity test may offer an adequate margin of safety for spacecraft acceptance. There may be exceptions to this supposition, however. For example, the low-gravity tests on Velcro specimens, already cited (Ref. 24), showed that the random expulsion of hot particles from burning plastics may create an additional ignition hazard in space. It has also been noted that low-gravity combustion may be greatly enhanced by even low levels of ventilation air flows. At present, however, the correlation of small-scale test results to the ventilation-flow environment of the Space Station Freedom, for example, is unknown. Thus, it is important to continue research on low-gravity combustion with the major objective of providing understanding of processes to establish safety levels for long-duration space station needs. In addition, fire-risk analyses for space must assume that, even if satisfactory assessments of low-gravity flammability are defined, some flammable materials will still have to be tolerated onboard Freedom because many useful human and scientific activities require hazardous materials and procedures. Fire-safety strategies will approach fire prevention through compartmental inerting, fire-safe storage, configuration controls, and material quantity and separation minimums. As the second line of defense, provisions for fire detection and extinguishment, which assume the probability of an incipient fire, become of great importance.

Fire detection. - Spacecraft specialists are aware that present fire-detection techniques, while adequate for the short-duration Shuttle missions, require considerably more knowledge and development for space-station applications. Obviously, one requirement is more information on expected fire signatures under low gravity. As noted earlier in this paper, studies show that low-gravity flames are generally cooler, sootier, and slower propagating than their normal-gravity counterparts, and these characteristics affect the techniques of detection. It appears that smoldering combustion may be possible in space, because the slow transport of oxygen into porous media (foams, waste containers) can promote this rather than flaming combustion. Smoldering combustion generates large smoke particles, and detectors would have to be tuned to recognize these particles as fire signatures. Finally, the transport of various fire signatures is also changed in low gravity. Since it is impractical to instrument space modules completely, a limited number of fire detectors must be judiciously placed to intercept the most probable pathways of fire-signature agents.

Placement of fire detectors planned for Space Station Freedom can take advantage of ventilation ducting for efficient monitoring of the atmosphere and potential fire radiation. The type and design of sensors are still under discussion, and it is likely that fire protection in Freedom will incorporate sensors of several generic types. Thus, the complete fire-detector system would include smoke, chemical, radiation, and overheat sensors, whose coverage could be augmented by extensions, such as rotating mirrors, fibers optics, or sampling tubes.

Adequate sensitivity of fire detectors is a problem common to ground and aircraft systems. Fire detectors must respond to minimum fire-signature thresholds yet reject extraneous signals that cause false alarms. An extensive survey of commercial experience cites a 14 to 1 ratio of false alarms from smoking, cooking, dust, and so on, to real alarms in smoke detectors (Ref. 34). Thus, promising approaches for high-sensitivity detector systems less prone to false alarms may incorporate multiple sensors with decision logic to define the alarm conditions with adjustable sensitivities (Refs. 6 and 12).

Fire extinguishment. - A parallel concern for spacecraft fire extinguishment arises from the evidence that the Halon 1301 fire extinguisher, while adequate for the short-duration Shuttle missions, requires considerable improvement or replacement for space-station applications. In long-duration spacecraft, the environmental problems with the use of Halons are of great concern. An ideal, substitute low-gravity extinguishant should be effective (minimum quantity required) for all anticipated fire scenarios, convenient for delivery to the fire, and readily removable, in both its original and reacted states, from the atmosphere.

Several types of extinguishing systems are being considered for future spacecraft. For example, deionized water and foam systems have been proposed for further study in recent review papers (Refs 1 and 4) Water is efficient as an extinguishant, creates no undesirable reaction products, and is readily removable from the atmosphere. The effective control and dispersement of water sprays in low gravity are formidable technology problems, however. A more practical approach employs gaseous extinguishers, and carbon dioxide is favored in the initial plan for Space Station Freedom. The strong advantage of carbon dioxide is that it is readily removable by any spacecraft environmental control system. Carbon dioxide is recognized, however, as a relatively inefficient extinguishant, and the large concentration required for effective fire suppression may be hazardous to the crew as an asphyxiant (Refs. 32 and 35). The same arguments may support or disqualify nitrogen as a fire extinguishant, although nitrogen is an ideal diluent for inerting of uninhabited compartments, a technique already discussed.

Venting to the vacuum of space is an ultimate fire-extinguishing method available to spacecraft. A difficult fire can be completely controlled by venting after the escape of the crew and sealing of the fire-stricken compartment. Venting need only proceed to a point where the retained oxygen partial pressure is low enough to suppress combustion, which makes later reconstitution of the atmosphere less demanding. The small-scale Skylab experiments of Kimzey (Ref. 15), cited in a previous section, showed that the air motion induced by venting can temporarily increase flame spread and may cause additional fire damage before the fire is extinguished.

Human factors. - The completely closed cycle and limited resupply capabilities in spacecraft atmospheres cause the threat of contamination to be greatly feared, even more so than in the closed-environment counterparts of submarines and aircraft. For Space Station Freedom, evaluation and selection of fire-control systems will depend strongly on internal environmental impacts. In summary, it is important to emphasize that the greatest danger from fire, its precursors (overheating, pyrolysis, and smoldering) and its extinguishment, lies in the toxicity of the products and not in the thermal effects or structural damage. Human responses, including safety enforcement, fire drills, escape modes, and rescue may be modeled to a great extent on practices established for aircraft. Important decisions in future spacecraft planning will be on the relative reliance on manual versus automated responses. As spacecraft and their missions become more complex, there is a greater need to invest in automatic systems for protection of unattended compartments and to insure rapid and predictable responses to emergencies. Nevertheless, strong arguments can be advanced to retain many human-detection options. The value of Space Station Freedom is increased if users are confident that irreplaceable projects are protected not only from fire effects but also from damage through inadvertent shutdown or false-alarm extinguishant release.

Fire-Safety Research in Space

As discussed earlier, analytical modeling and simulation-facility experiments are necessary and valuable for small-scale studies of microgravity combustion pertinent to fire-safety understanding. What is lacking, of course, is the capability to conduct low-gravity, long-duration tests on, for example, material flammability, smoldering, fire-signature identification, detector response and calibration, extinguishant delivery and effectiveness, and human response modes. The U.S. Shuttle incorporates the best available technology in its fire detection and suppression systems. These systems cannot be verified in true space conditions, but this lack is compensated by the extremely low probability of a fire during a short-duration mission and the ability to terminate a mission and return to earth promptly. The permanent habitation and long-duration mission of the Space Station Freedom, however, present more serious problems for the development of fire-protection systems, requiring some degree of in-space testing and verifying.

As a practical matter, development and demonstration of fire prevention, detection, and suppression policies and techniques for Freedom will need a compromise to simplify validations through effective use of analytical knowledge and small-scale simulation testing. There are hopes that some timely tests and demonstrations can be conducted in future Shuttle missions up to the time of the construction and assembly of Freedom in orbit

The Space Station Freedom itself is the ideal facility for long-duration fire-safety testing for space. The space-station laboratory modules are equipped with power, utilities, and standardized racks for mounting experiments to exploit the microgravity environment in the modules. One definition concept for installation in a Freedom laboratory module, shown in Fig. 14, consists of a combustion chamber to be mounted in one rack with associated data and power systems in an adjoining rack (Ref. 36). Such a facility, which is one of several under active design consideration by NASA, can accommodate multiple experiment functions, including investigations of ignition, flame spread, flammability, combustion products, and flame suppression.

CONCLUDING REMARKS

This paper is a review of the knowledge, techniques, and future trends in spacecraft fire safety. It is clear that aircraft fire-safety strategies and hardware serve as important models for corresponding measures in space. The overwhelming difference in space is the negligible gravitation body force, a situation that profoundly influences fires, their detection, and their control. Another operational difference affecting fire safety is that spacecraft of the future must be completely self-contained: the atmospheric, fire-fighting, and rescue resources are all maintained by the spacecraft logistic supplies.

For the present, the fire safety provisions in the U.S. Shuttle appear adequate for they are based on selected applications of proven techniques in ground and aircraft fire safety. What is lacking for continued safety in future long-duration missions is a better understanding of low-gravity combustion and its application to spacecraft fire safety. Analyses and small-scale experiments indicate that the lack of natural convection (absence of gravity-driven buoyancy) may generally inhibit combustion, producing cooler, less efficient flames. Special circumstances, in contrast, may increase fire dangers in space. The most important is the demonstrated enhancement of low-gravity combustion by low flow rates of ventilation. Regardless of the relative danger of fire in low gravity compared to normal gravity, it is clear that the unique characteristics of fires in space require innovative techniques in fire prevention, detection, and extinguishment.

Design and research are underway for the U.S. Space Station Freedom, a multipurpose space community, to be permanently placed in a low-earth orbit. For Freedom, it is necessary to devise reasonable material flammability acceptance policies, consistent with present knowledge of space behavior. Fire detection for this spacecraft must recognize the potential fire signatures in low gravity and devise systems of adequate sensitivity yet perceptive enough to reject false alarms, with added provision for in-flight checks and calibrations. Fire extinguishment for Freedom must be efficient, suitable for operation in low gravity and, above all, uncontaminating and removable from the closed atmospheric system. Crew training and escape modes must be devised to consider the probability of fires occurring in space and their spread and hazards in low gravity

Finally, spacecraft fire safety can no longer rely on strict rules, devised for short-term missions. Fire safety for future spacecraft, like Freedom, must be flexible and realistic, similar to policies in place for aircraft. The goal of spacecraft fire safety will be a compromise to achieve the lowest practical risk level consistent with the promotion of useful functions of habitation, science, and commercial operations in the spacecraft.

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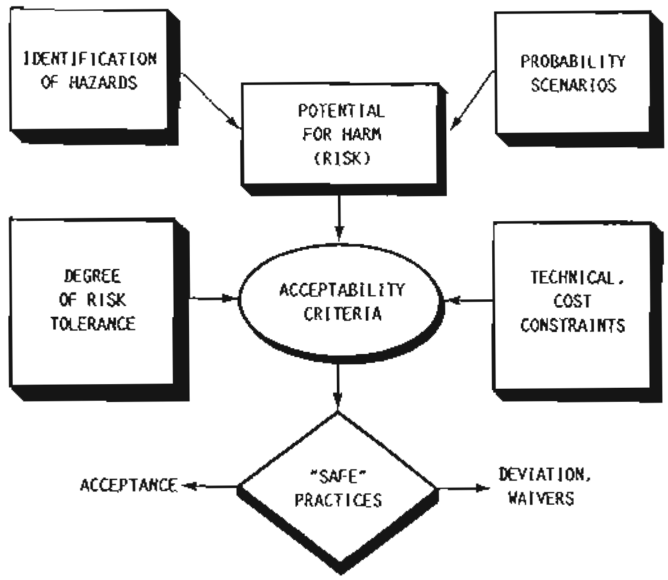

FIGURE 1. - REPRESENTATION OF SPACECRAFT SAFETY PROCEDURES.

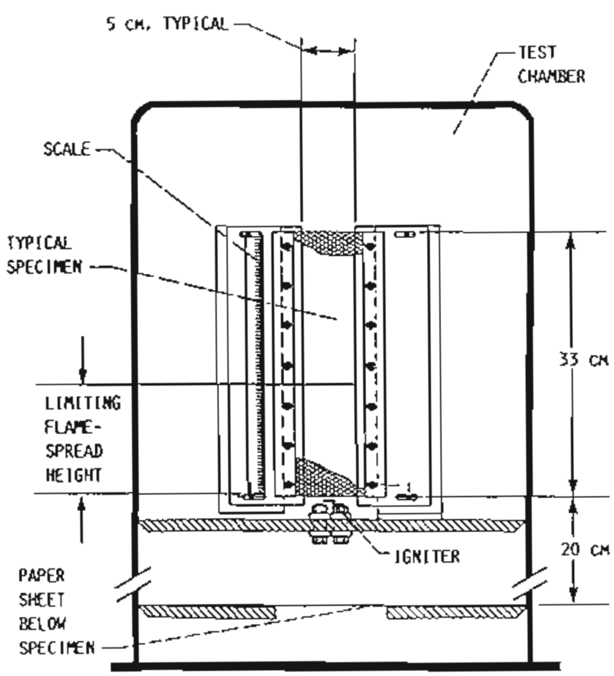

FIGURE 2. - STANDARD UPWARD BURNING TEST METHOD FOR SPACECRAFT MATERIALS.

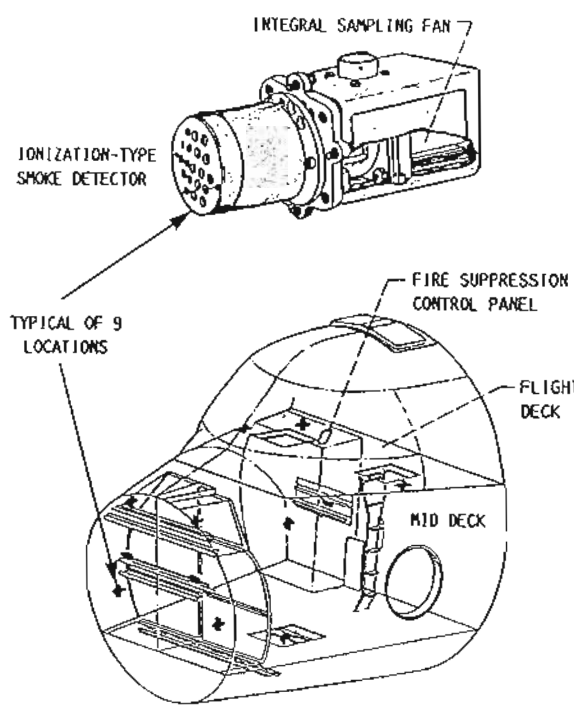

FIGURE 3. - FIRE DETECTION IN THE U.S. SHUTTLE ORBITER CABIN.

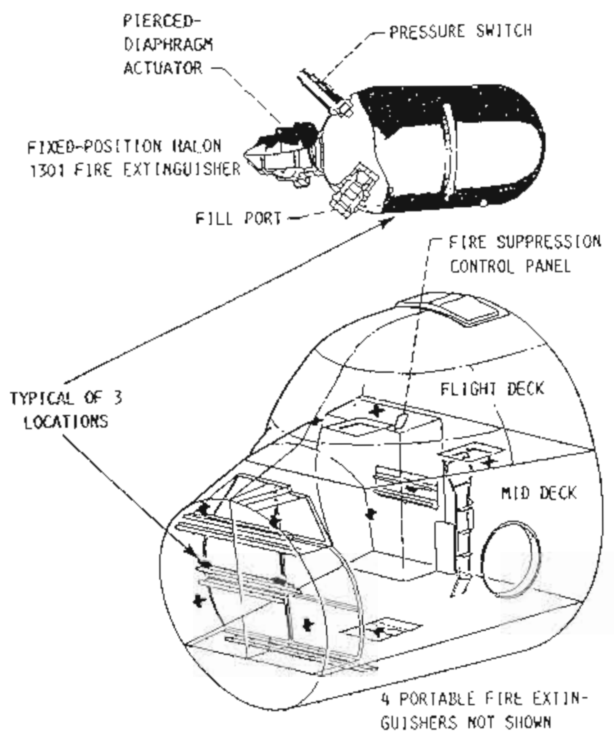

FIGURE 4. - HALON 1301 FIRE EXTINGUISHERS IN THE U.S SHUTTLE ORBITER CABIN.

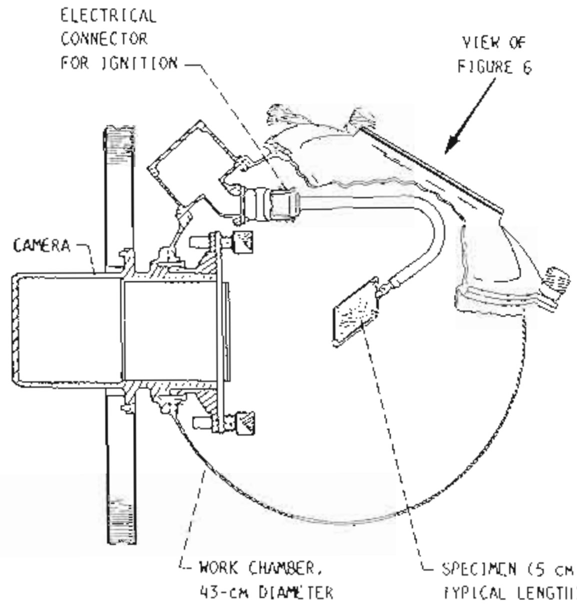

FIGURE 5. - LOW-GRAVITY FLAMMABILITY APPARATUS FLOWN IN THE 1974 SKYLAB MISSION.

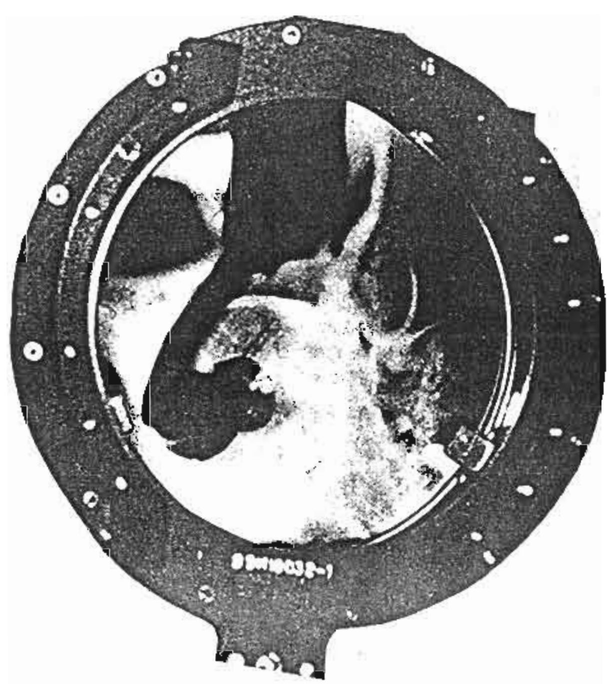

FIGURE 6. - SPHERICAL FLAME SURROUNDING POLYURETHANE FOAM SPECIMEN AT LOW GRAVITY, 65%-OXYGEN ATMOSPHERE, IN THE 1974 SKYLAB EXPERIMENT.

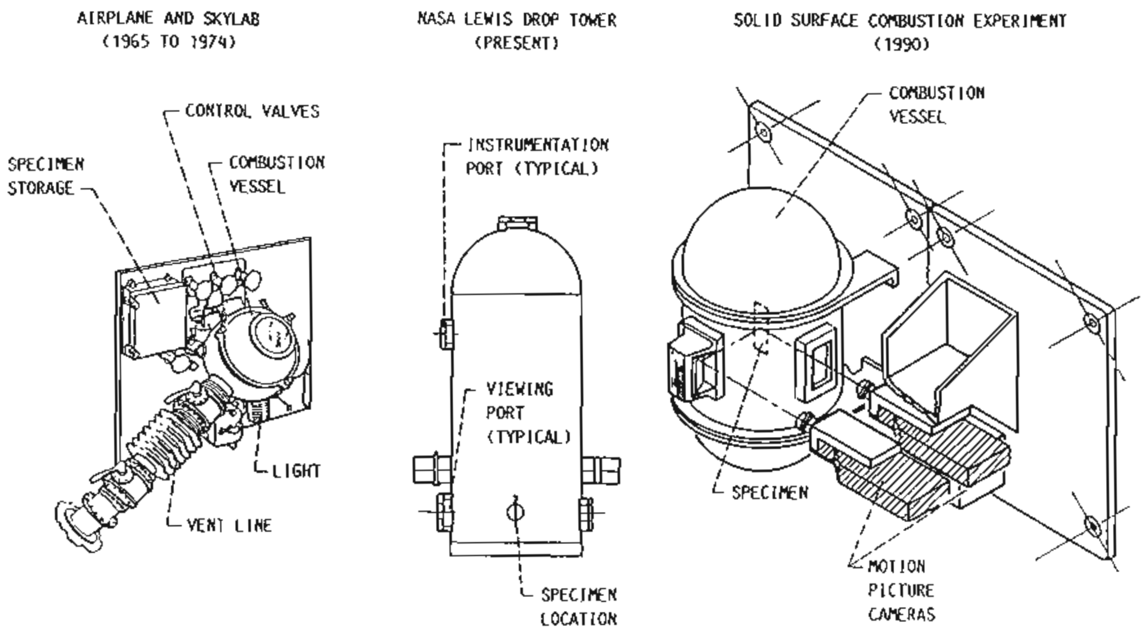

FIGURE 7. - REPRESENTATIVE LOW-GRAVITY, SOLID-SPECIMEN FLAMMABILITY TEST FACILITIES.

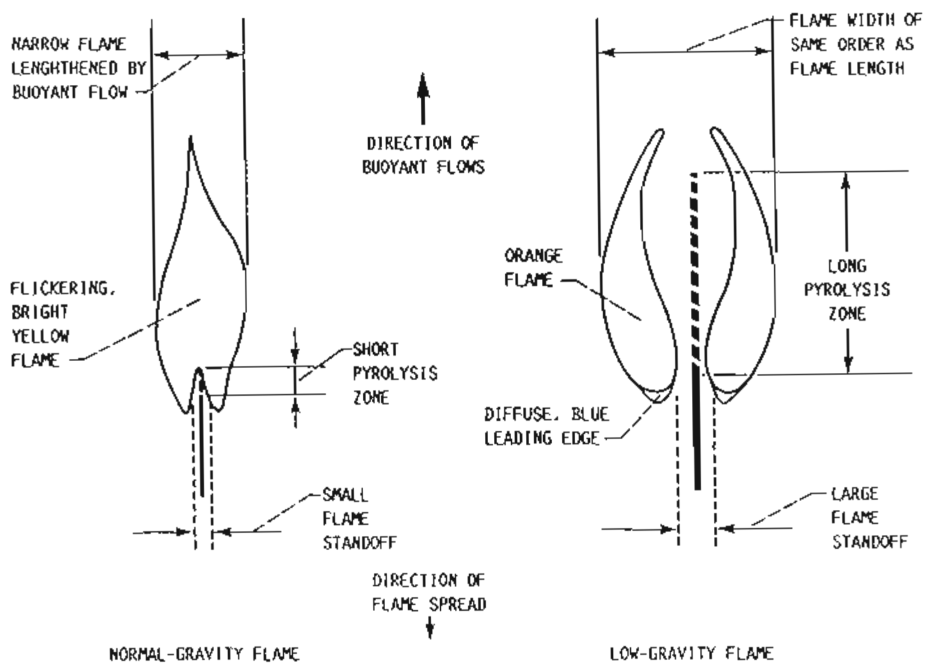

FIGURE 8. - COMPARISON OF TYPICAL NORMAL- AND LOW-GRAVITY FLAMES ON THIN SOLID SURFACES (PAPER, PLASTIC, E.G.).

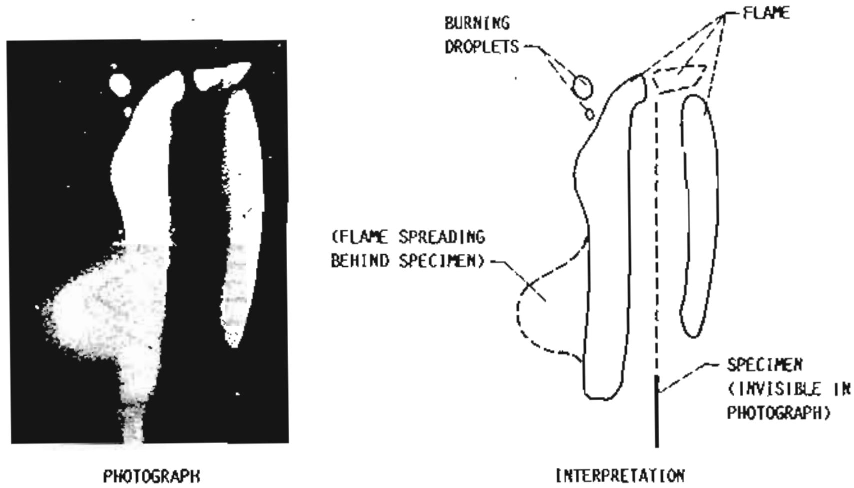

FIGURE 9. - EXPULSION OF BURNING DROPLETS FROM BURNING NYLON VELCRO SPECIMEN IN DROP-TOWER LOW-GRAVITY TEST.

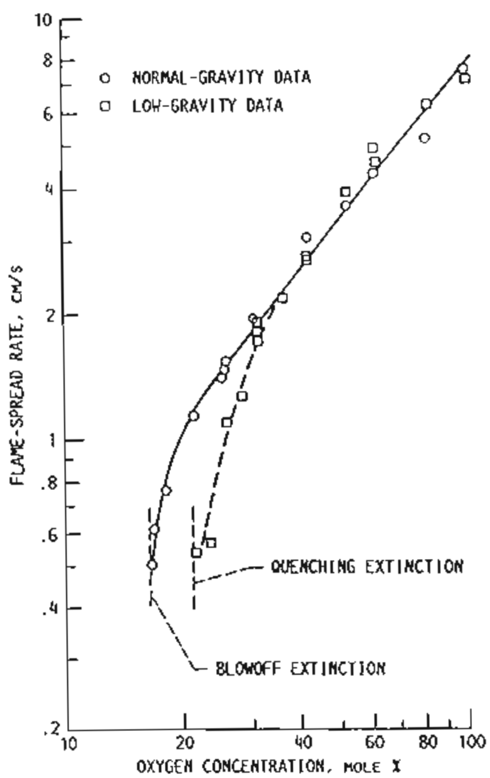

FIGURE 10. - COMPARISON OF FLAME-SPREAD RATES FOR NORMAL AND LOW-GRAVITY COMBUSTION OF THIN-PAPER SPECIMENS IN DROP-TOWER TESTS.

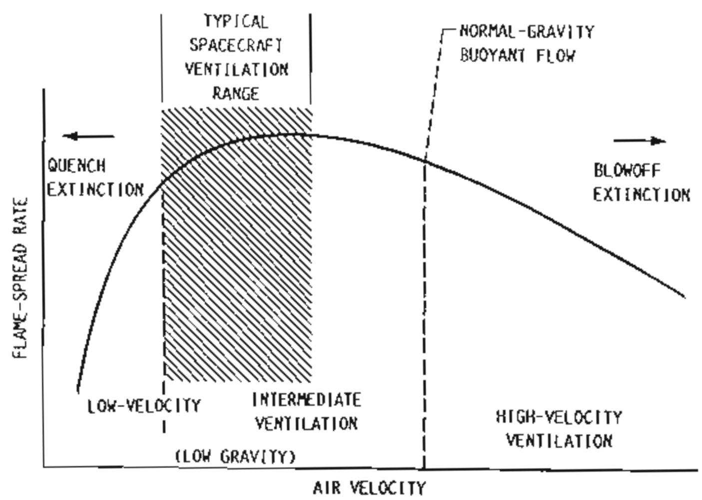

FIGURE 11. - EFFECT OF VENTILATION AIR FLOW ON FLAME-SPREAD RATE FOR THIN-PAPER SPECIMENS.

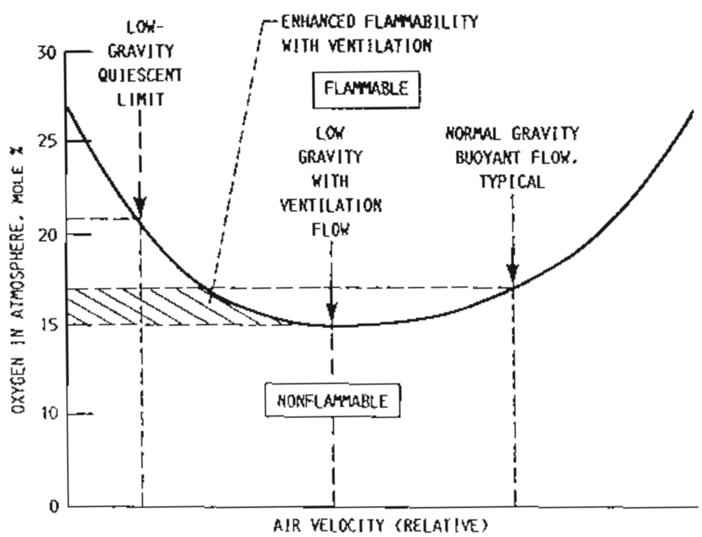

FIGURE 12. - FLAMMABILITY-LIMIT COMPARISON FROM DROP-TOWER LOW-GRAVITY DOWNWARD BURNING THIN-PAPER TESTS.

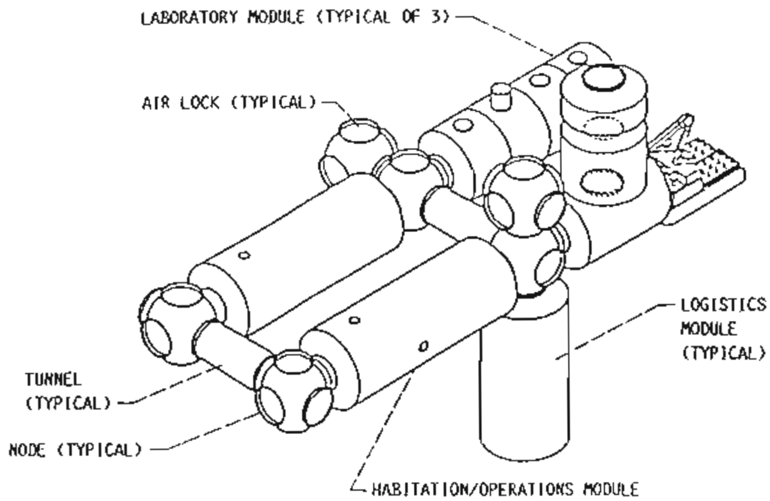

FIGURE 13. - PROPOSED "LADDER" CONFIGURATION OF U.S. SPACE STATION FREEDOM MODULES.

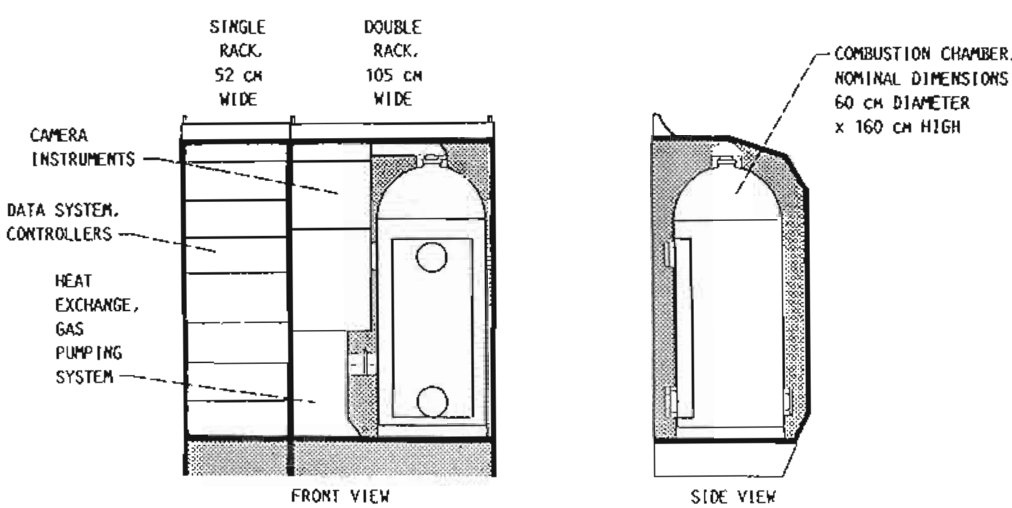

FIGURE 14. - PROPOSED MULTIEXPERIMENT COMBUSTION CHAMBER FOR FIRE-SAFETY EXPERIMENTS IN SPACE STATION FREEDOM EXPERIMENT RACKS.

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Summary

The increased awareness of fire hazards in both passenger transport and buildings has precipitated a reappraisal of models of fire spread embracing both empirical and more fundamentally-based computational approaches. The paper describes recent developments in the fire science-related aspects of such hazards, contrasting the broad strategies adopted with those applied in the more highly developed combustion technologies.

It seeks to demonstrate how current capabilities and future developments, particularly in the computational modelling of fire, and driven primarily by the study of fires in building enclosures, might be utilised to guide layout, design and the control of furnishing materials in aircraft cabins.

Examples of current capabilities of computational fluid dynamic models in describing such critical fire phenomena as smoke movement, fire growth and flame spread are presented.

1. Introduction

One way or another, the release of energy from the combustion of hydrocarbon fuels is used within the propulsive powerplants of nearly all modern transport vehicles. Much research and development effort continues to be expended on these controlled combustion processes in order to improve their efficiency and reduce their pollutant yield. By carrying large quantities of aviation fuel and lubricants, however, the potential for uncontrolled combustion in air transport is particularly great.

Whilst much success has been reported in minimising the fire hazard due to fuel spillage, accident statistics for transport aircraft suggest that it is the post-crash fire which poses the most serious threat to the safety of aircraft occupants. A key feature of attempts to reduce both this threat and that due to the in-flight fire is a more thorough understanding of the consequences of a particular choice of cabin design and internal furnishing materials. With such an understanding it is possible for both designer and legislator to ensure optimum fire safety for reasonable cost.

It was for this purpose - what might now be termed building control - that primitive attempts to design for fire began. The progress that is today evident in the subjects of fire science and engineering has been driven primarily by national concerns for fire safety in buildings.

Although the contrasts between the building and aircraft industries could not be greater in terms of their stance towards new technology, the laws of physics are the same for both and much of the research that has been undertaken with initial concern for buildings is applicable to aircraft.

Unfortunately the requirements of comfort and of fire safety, whether in relation to habitation or transport, tend to conflict. The very materials that are comfortable to sit on also have low thermal inertia. Their surfaces quickly heat up to our own body temperature and so feel warm. In the event of fire they can also heat and ignite rapidly, ultimately giving rise to the dramatic fire growth known as flashover. Fire is distinguished from most other combustion systems by the strong coupling between radiant heat from the combustion products of the initiating fire and the further potential fuel in the form of furnishings and linings. In the open this process may be relatively benign but within the confines of an enclosure, such as a room in a building or an aircraft cabin, the combustion products are constrained to move above the potential fuel, thus giving rise to the possibility of heating it to the point at which all the fuel ignites, often simultaneously. This is just one possible manifestation of the phenomenon known as flashover.

Whilst life may be tenable within an aircraft cabin before flashover, there is little doubt that it is impossible afterwards. Most attempts to control the hazard from fire are concerned therefore with delaying the onset of flashover within the enclosure and indeed, where possible, using compartmentation to limit the physical extent of fire growth.

It is the coupling between the fire source and the structure containing it which makes the fire such a complex problem to analyse. There are a number of differences between buildings and aircraft which must be considered when attempting any technology transfer. Aircraft cabins are characteristically long with a narrow cross-section; buildings, with the exception of tunnels and corridors, are not. Current ventilation systems on aircraft act in opposition to natural buoyancy forces generated by a fire. They introduce fresh air at high level and extract at low level. Building design by contrast attempts to use the buoyancy forces that a fire would generate to help keep combustion products above the heads of the occupants. Furthermore, aircraft cabins are generally better thermally insulated than most buildings thereby ensuring that, in the event of fire, little of the heat evolved is lost to the structure. This can have an important effect on reducing the time to flashover even if the insulation is non-combustible.

It is now broadly accepted that the analysis of such phenomena within the broader field of fire engineering will concern the application of various levels of mathematical fire model. The wide variety of possible hazard scenarios and the cost of mounting experimental tests at realistic scales have encouraged the greater application of computational simulation. This clearly echoes other developments in the aerospace industry where significant cost benefits are claimed for design using the new technology of computational fluid dynamics (CFD). We shall return to the topic of CFD in more detail later in the paper.

Progress with such modelling will affect not only design per se but also the development of new, or the modification of old, flammability testing methods, the traditional instrument of regulatory control. Within the last decade, and partly driven by the needs of mathematical modelling, a reappraisal of flammability testing has been undertaken resulting in some new methods that provide quantitative material property information rather than just their ranking order.

Determining the rate of heat release to be expected from materials and products is central to any assessment of fire hazard. Although it may be necessary to control the ignitability of materials or products used to furnish cabin interiors, it is not sufficient. Whilst important to the prevention of accidental ignition from a dropped match or cigarette, for example, it is equally important to control the rate of heat release from the material if it is exposed to a much larger ignition source than that anticipated by the ignitability test, say an external fuel fire. It is the consequent rate of addition of heat from new fuel that will determine the rate of growth of fire in the cabin. This controls the rate at which combustion products are driven down the length of the cabin; the resulting volume and temperature of those products in turn determine heat transfer to fuel ahead of the fire source and thus the onset of flashover. Indeed, a control on ignitability alone can lead to undesirable consequences. If fire retardants have been used to meet such a requirement then, should the material ignite, it is important that those additives do not increase the toxic potency of the resulting combustion product or, even more simply, impair visibility further, causing increased exposure of the occupants to the products as they attempt to escape.

We shall return to these issues, as they relate to aircraft cabin fires, in section 3, we first outline briefly the present status of computationally-based models of fire growth and smoke movement in enclosures, since this represents one of the more influential recent developments in fire science.

2. Fire Modelling

Strategies for the mathematical simulation of fire in enclosures fall broadly into one of two categories. These are commonly referred to as either zone or field models. Their essential difference is in the way that they treat the gas phase and, in addition, their respective demands upon empiricism.

The most commonly employed zone models use essentially a one dimensional treatment to describe the filling of an enclosure with hot combustion gases. They assume that it fills from the ceiling downwards in the comparatively uniform manner of an inverted "bathtub" filling with water. Field models, in contrast, make no such assumptions about how the enclosure fills but use the techniques of computational fluid dynamics to determine the detailed local progress of the combustion products within the fire domain, finely resolved in the three space dimensions.

(i) Zone Models

The computer zone model, pioneered in the building context most successfully by Emmons and Mitler[1] divides the domain of interest into a small number of readily identifiable zones. In addition to the one-dimensional hot gas layer which grows at the expense of the lower, colder air layer, a thermal plume emanating at the fire describes a second zone which transfers mass and energy between these layers. For a naturally ventilated enclosure an inverted weir equation describes the flow of hot gases out through windows or doorways. This can be replaced by a prescribed extraction rate for a forced ventilated problem. In addition to these zones which determine the mass flow, a flame cone is included which together with the hot layer and enclosure boundaries radiate to unburnt fuel elsewhere within the enclosure. This fuel will ignite and generate a second thermal plume if specified ignition criteria are met.

An example of this type of model which has been applied to aircraft cabin fires is the DACFIR program[2], cf Fig. 1.

This modelling approach is a development of earlier two zone models[3] that had preceded the application of the modern electronic computer to fire problems. Its chief advantage is its relative simplicity and low computational cost but the modular approach also allows individual component treatments to be refined as new studies improve understanding. This modularity can also be a disadvantage however. In particular, the flow pattern to be expected in a given scenario has to be assumed, a priori, so that modules can be chosen which most closely represent that situation. Most existing zone models have been developed primarily for enclosures or groups of enclosures that are "room" sized where the one-dimensional hot layer treatment is most likely to be satisfactory. They should not be expected to apply without significant modification to say an aircraft hangar or large airport terminal building nor to an inflight fire in an aircraft cabin where air, for example, is introduced at high level and removed at low level. It is of course possible to construct different zone models for particular classes of problem. In the case of a post-crash cabin fire, a time-dependent ceiling jet can be incorporated to describe the flow of combustion products along the length of the cabin ceiling, for example, and a number of such refinements, including inter-layer mixing and wall jets, have already been reported[4,5]. A substantial programme of fire research directed towards the aircraft cabin fire and using this philosophy has been underway in the US for a number of years. Individual modular treatments for heat transfer to flammable walls and ceilings, for example, have been described elsewhere[6,7].

(ii) Field Models

The alternative to this approach is a higher level, much more detailed, model which seeks to incorporate all the important physical and chemical processes in quantitative predictions. This is the goal of the field model. The term, so called because it solves the fluid dynamic field equations, is used to describe the application of computational fluid dynamics (CFD) to the problem of fire simulation. All such approaches exhibit common features. They start with the 'exact' instantaneous partial differential equation set describing local conservation principles. These are then solved subject to the following critical decisions:

(a) how to treat the problem of turbulent closure

(b) which algorithm is to be used to calculate the numerical solution of these equations at interior points of the flow domain

(c) how to properly approximate boundary conditions along the domain boundaries and

(d) how to treat specific combustion chemistry or multi-phase flows.

A summary of the current status of fire simulation using field modelling will now be presented.

The basic equation set for the simulation of fires in enclosures comprises time-averaged conservation equations for mass, momentum, energy and chemical species of the general form

$$\frac{\partial(\rho\phi)}{\partial t} + \frac{\partial(\rho u_i \phi)}{\partial x_i} - \frac{\partial}{\partial x_i}\left(\Gamma_\phi \frac{\partial \phi}{\partial x_i}\right) = S_\phi \qquad (1)$$

$$\left[\begin{matrix}\text{time rate}\\ \text{of change}\end{matrix}\right] \left[\text{convection}\right] \left[\text{diffusion}\right] \left[\text{source/sink}\right]$$

where ϕ is the generic variable which may represent the three Cartesian velocity components u_i, the enthalpy h or the mass fraction of a particular species m_j. (The mass continuity equation is represented by the case $\phi = 1$). S_ϕ is a source term appropriate to ϕ which incorporates, for example, the effects of chemical production and radiative heat loss. A fuller description specifically in relation to enclosure fires is given by Cox and Kumar[8].

All dependent variables in eq(1) are time-averaged quantities and, since density fluctuations have been neglected, may be viewed as implicitly density-weighted, for example,

$$u_i = \frac{\overline{\rho u_i}}{\bar{\rho}} .$$

The diffusion term incorporates the effects of both turbulent and molecular diffusion through the exchange coefficient Γ_ϕ. It has been assumed that the Reynolds stresses and scalar fluxes, which involve the correlations of fluctuating properties, can be modelled by use of the gradient transport hypothesis, in particular, for scalars

$$\overline{\bar{\rho} u_i{}' \phi'} = - \Gamma_\phi \frac{\partial \bar{\phi}}{\partial x_i}$$

To determine the local value of Γ_ϕ, two further transport equations are solved for k, the turbulence kinetic energy and ε its rate of dissipation. The effects of buoyancy on extra turbulence production (in rising plumes) and inhibition (in stratified layers) require special attention[9].

Solution of these equations alone, together with the appropriate boundary conditions to incorporate the effects of heat and momentum loss to the enveloping structure, is sufficient to capture the major features of the smoke movement problem for a known fire size. The influence of effects such as the external wind on a cabin breach, for example, may be readily examined through adjustments to the boundary conditions.

Early work on the application of these models to building problems assumed that the fire could be represented in a very rudimentary fashion as a volumetric source of heat. A simple conserved scalar was then used to represent smoke concentration[10]. Among a number of deficiencies with this approach was the fact that the source volume needed to be prescribed, a priori, thus precluding any dynamic interaction between the enclosure and the fire source. Flame leaning or impingement could only be included by prescription.

So far, in the application of such modelling techniques to aircraft cabin fires, this has also been the level of input of fire science [11,12] (Fig. 2). Rather more effort[13] has been focussed on the effects of the complexity of internal shape and obstructions within the cabin on the smoke flow. Whereas in most building problems a Cartesian coordinate system can satisfactorily be used, in aircraft cabins the use of body-fitted, curvilinear coordinates to reproduce the essential features of the geometry are highly desirable.

such coordinate systems may be generated by algebraic methods or, increasingly commonly, through the solution of differential equations[14] describing the coordinate transformation. This permits the system of coupled conservation equations to be solved in a space in which the coordinate surfaces conform to the boundaries of the fire domain (cf. Fig. 3) and in which computational nodes are concentrated in regions of large spatial property gradients.

Although satisfactory for describing smoke movement in simple situations, the volumetric heat source prescription for the fire is restrictive not only in its inability to respond to the flow field. It does not provide a framework to address the critical issues of fire growth or the production and spread of the incapacitating products of combustion, both gaseous and particulate.

Combustion and radiation models are required to allow assessments to be made of the hazard to human life due to inhalation of toxic gases and to radiant and convective heat exposure.

(iii) Combustion Chemistry

The treatment of the effects of turbulent transport has already been discussed briefly. Unfortunately the turbulent mixing process also has a significant influence on the mean rate of chemical reaction in fires. The hydrodynamic mixing of fuel with air is much slower in fires than their rate of reaction and it is this process which controls the rate of fuel 'disappearance', R_{fu}, or product yield.

A simple method for dealing with this difficulty in modelling is to allow the combustion to be controlled only by the rate of small scale turbulent mixing between the reactants and for that rate to be further controlled by the concentration of deficient reactant. In air-rich locations, reaction is controlled by lack of fuel and vice-versa in fuel-rich locations, thus

$$R_{fu} = -\frac{C\rho\varepsilon}{k}\left[m_{fu}, \frac{m_{ox}}{s}\right]_{min}$$

where m_{fu}, m_{ox} are the local mass fractions of fuel and air, s is the stoichiometric ratio and C is a numerical constant.

A transport equation for m_{fu}, incorporating the above source term, is solved in addition to one for the normalised mixture fraction,

$$f = \frac{\left(m_{fu} - \frac{m_{ox}}{s}\right) + \frac{m_{ox,\infty}}{s}}{m_{fu,o} + \frac{m_{ox,\infty}}{s}}$$

which is simply conserved and does not therefore involve a source term. (The subscripts (o,∞) denote conditions in the fuel supply and ambient air respectively). This method, which also overcomes the need to prescribe a volumetric source of heat, has been reasonably successful[8,15] in predicting the major features of a wide range of building fire problems including the stable species of CO_2 and H_2O. Figure 4 illustrates predictions of the JASMINE model, here applied to a forced ventilated railway tunnel containing a 14 megawatt fire. The tunnel is 400m long, 5m high and 4m wide. Predictions are shown of the progress of a life threatening gas temperature surface, 80°C, down the length of the tunnel. Centreline predictions of CO_2 concentration are also shown for a short length of tunnel around the fire.

Chemical kinetics however have played little part in such a scheme. To determine the levels of toxic intermediates such as CO and for the prediction of soot formation, a prerequisite to the accurate prediction of luminous radiation from flames, a more realistic treatment for finite rate kinetics is required.

If the balance equation for mean mixture fraction, f, is complemented by a further equation for its variance, then the turbulent scalar mixing field can be characterised by a local probability density function, controlled by these two moments. As simply conserved scalars, lacking chemical source terms, their prediction in the flowfield is comparatively straightforward.

The modelling task then concerns the relationship between instantaneous species concentrations and the mixture fraction, which characterises the turbulent mixing field. The simplest such relationship assumes full local chemical equilibrium. However this assumption is not generally valid within the flame and substantial errors in estimating the yield of such intermediates as CO can result.

An alternative approach currently under development for application to fires is the laminar flamelet model[16].

Burning in a turbulent flame is here assumed to occur locally in laminar-like flamelets. The relationship between species compositions and mixture fraction in such circumstances can be determined entirely computationally for simple fuels such as methane or propane, for which the chemistry is sufficiently well understood. More importantly however it can also be determined "once and for all" by experimental measurement in well controlled laminar flames for fuels encountered in practical problems[17]. These "state relationships" can be stored in a library for access by the hydrodynamic calculation for the determination of detailed gas species.

comprehensive predictions of the composition field in buoyant fires employing this strategy have to date been restricted to the fire source alone[18]. Figure 5 illustrates the typical scalar structure for a simulated fire in which methane is burnt on a 25 cm circular porous burner.

More recently, this approach has been extended to the prediction of soot volume fraction in the same fire using a semi-empirical model for soot formation[18]. The processes of soot nucleation, surface growth and agglomeration are here represented by rate constants also determined by local mixture fraction and temperature.

(iv) Thermal Radiation

Two quite distinct difficulties need to be addressed for the realistic modelling of radiant heat transfer. The first concerns 'geometrical' problems associated in particular with the exchange of radiant energy between remote emitters and receivers, be they solid surfaces such as cabin wall panels or particulate/gas phase mixtures such as flames. The second difficulty concerns the calculation of local emissive power. The relative contributions from broadband soot and banded gaseous emissions will vary substantially between flame and smoke products. In addition, as with transport processes and combustion chemistry, the effect of turbulent fluctuations in temperature and gas composition must be considered, particularly at the fire source itself.

Both flux[20] and discrete transfer methods[21] have been used in conjunction with predictions of time-mean temperature and composition fields for enclosure fire simulations. Figure 6 shows radiative heat flux at the floor of the tunnel described earlier. The extent of life threatening conditions can be determined from examination of the $2kW/m^2$ contour, generally accepted to be that which causes unacceptable pain, after exposure for one minute. More comprehensive treatments of combustion which include the interaction effects of turbulent fluctuations, have to date been restricted to the fire source alone and again only for comparatively simple hydrocarbon fuels.

Figure 7 illustrates detailed radiative predictions for the methane fuelled fire described earlier, identifying the significant contribution made by turbulent fluctuations in scalar properties in the flame. Such a treatment can be readily extended to the enclosure fire problem.

(v) Solid Phase

It is in the coupling of the gas and solid phases where the zonal and field treatments tend to converge. Field models can in principle extend their numerical solutions of the conservation equations into the solid boundaries. Whilst this is useful for determining the heat lost from the gas phase into the structure by conduction, it is unlikely to be of much practical value for the calculation of rates of heat release or flame spread over flammable solid fuels of anything other than the simplest of materials. Those used in practice for furnishings and upholstery tend to be laminates and composites, which under fire conditions may melt, char or delaminate, all poorly understood processes at the level of detail necessary.

A pragmatic approach is thus required. Quintiere[22] has developed a model for flame spread which is based upon the measurement of material properties under "fire conditions" in a standardised small scale fire test. These are simply a critical heat flux for piloted ignition together with a flame spread coefficient related to the thermal properties of the material.

With such measurements, gas phase models of either zone or field type can be used to provide the appropriate surface boundary conditions to translate performance in a standard fire test to actual in-fire behaviour. This synergy between mathematical modelling and standard testing is likely to grow such that in future more meaningful appraisals can be made of fire hazard than those based on existing methods.

3. Fire Science in Aircraft Cabins

From the standpoint of hazard modelling and simulation there are two distinctive critical cabin fire scenarios; the in-flight fire, in which the cabin is sealed but subject to installed forced ventilation, and the post-crash fire in which natural, buoyancy-driven ventilation occurs through doorways or breaches in the fuselage and through which an external fire may enter the cabin. The emphasis of the design strategies to be adopted in response to these circumstances naturally differ.

In the in-flight fire, where evacuation is clearly impossible, the primary element in design for fire safety must be the inhibition of fire growth, giving cabin staff or automatic systems ample opportunity to extinguish nascent fires. The subsequent spread of incapacitating products of combustion may however prove the greatest hazard to passengers if the fire is not promptly extinguished.

More complex considerations surround the post-crash fire where the principal goal is the provision of adequate evacuation and rescue opportunities. The use of flame retardant materials, for example, which delay the onset of flaming combustion, may increase the burden of toxic products and smoke, thereby impeding escape whilst notionally increasing the time to flashover and large-scale engulfment by fire. The post-crash fire is unlikely to be significantly influenced by the cabin ventilation system. Instead interest must focus on any breach in the cabin, particularly if adjacent to an external fuel spill fire which might permit the ingress of flame and combustion products, threatening the occupants, many of whom may be injured. This ingress of flame will be determined largely by the external wind conditions and the opening of cabin doors for purposes of escape or rescue. Radiant heating of flammable cabin materials from outside the breach or both convective and radiant heating from combustion products entering the cabin may cause ignition of wall panels and seating. In this instance the ignition source is probably very large and controls on the ignitability of materials, derived from small-scale tests, are unlikely to be sufficient. The objective of flammability controls here must evidently be to reduce the rates of heat release and of flame spread to delay the possible onset of flashover.

The position in respect of an in-flight fire is rather different although the broad requirement is the same. Ignitability testing can promote materials which minimise the incidence of accidental ignition. The cabin ventilation should however be able to handle the combustion products from such an incipient fire so that passengers are not significantly discomforted. Clearly the current practice in commercial aircraft of injecting fresh air at high level and removing it at floor level is not then conducive to such a requirement. Until comparatively recently the implications of such counter-flow ventilation on cabin fire growth has attracted surprisingly little attention. Sarkos and Hill[23] did however report significant differences between the distribution of smoke and combustion products in sealed cabins with controlled ventilation and the naturally ventilated case which arises if the aircraft fuselage is breached; the former leading to the more extensive distribution of the fire hazard within the cabin.

In a preliminary investigation, McCaffrey and Rinkinen[24] more recently report thermocouple temperature measurements in a simulated fire in a ½-scale closed section model of a ventilated wide-body aircraft cabin. Here simulating the in-flight cabin fire, the measurements demonstrate that within a few air changes, each of between 2 and 4.5 minutes, little of the energy released in the fire is exhausted through the normal floor ventilation. Hot gases accumulating close to the ceiling appeared to be little affected by the incoming cold air and only at longer times, as the whole enclosure fills with hot combustion gases, do significantly elevated temperatures appear in the extractor. The strong buoyancy forces characteristic of fires evidently overwhelm the effects of the ventilation system; the situation relative to smoldering combustion is less well-defined however.

Each of these outline scenarios reveals a complex interaction between the flowfield configuration, combustion chemistry, surface heat transfer and material properties. Whilst the elements may be specified individually by comparatively simple models, derived from small-scale experiment and testing for example, their interaction poses particular challenges. If we consider the post-crash situation in which an external wind-blown pool fire penetrates the cabin through an opening, the individual realisations of such a scenario depend amongst other factors, on fuel spill size, wind speed, direction and orientation relative to the aircraft and fuselage breach. To establish for instance worst case configurations for purposes of cabin layout evaluation and furnishing materials selection repeated full-scale fire tests are evidently impractical. On the other hand, the individual component studies referred to earlier do not address their superposition.

Computational approaches, zone or field models, clearly offer unique opportunities to simulate a wide range of scenarios once the model elements are established. The particular strength in the field models lies in the level of detailed interaction which can be reproduced. The coupling of regimes in zone modelling inevitably involves an element of a priori prescription in the broad types of fire possible whilst their interaction arises essentially via global boundary conditions.

The evaluation of novel fire protection concepts is potentially yet another important role for such computational modelling. Considerable interest has recently centred on the possible application of water sprays to aircraft fires, for example. Sprinklers are used routinely to protect industrial buildings against the rapid growth of fire. These are based on the simple principle that applying water to burning fuel and potential fuel ahead of a fire will limit fire growth. The efficiency of such a system requires careful consideration however since the interaction of a spray with the products of combustion is extremely complex. The spray itself can entrain air and combustion products thus bringing smoke down to low level. If droplets have insufficient downward momentum they can be lifted by the buoyant plume and indeed evaporate without having the opportunity to extinguish a fire.

The field modelling approach has been applied to such problems[25] cf. fig. 8. Here a representative line of droplets is injected into a compartment containing a simulated fire source. With the 0.5 mm droplets chosen, very few reach the floor with most being lifted and evaporating near the ceiling. With 1 mm droplets all reach the floor.

All these applications are very demanding in relation to validation. Confidence in the underlying representation of basic mechanisms is central to the wider application of the computational field approach. Whilst reasonable validation can be demonstrated for some aspects of model predictions (e.g. refs 8-13), there are too few comprehensive measurements of the key properties to adequately test the detail. In enclosure fires, only the gas temperature has been subject to any detailed comparison throughout the flow domain. Comparisons for flow velocity, gaseous and particulate compositions and for thermal radiation fluxes are sparse, reflecting in part the lack of application of modern experimental techniques to the enclosure fire problem. Few, if any, of the recently developed non-invasive optical techniques, already widely used in a number of types of combustion systems, have been applied to fires. The situation in respect of fires in aircraft, as opposed to buildings, is even less satisfactory and there is an urgent need for such experiments. Photographic and anecdotal evidence from real incidents or inadequately instrumented fire tests is of little value in this respect and continues to place fire safety in an invidious position relative to combustion technologies.

4. Concluding Remarks

Fire science and engineering have evolved largely as a result of concerns for building fire safety. For the treatment of the aircraft cabin fire problem, careful consideration needs to be given to the transportability of this technology. This reflects the unique interaction that occurs in enclosure fires between the enveloping structure and the growing fire - the rate of growth and onset of flashover being largely determined by enclosure design. Details such as ceiling height, degree of ventilation, in addition to disposition of flammable materials, can all critically affect this process.

Studies of the response of solid materials to thermal exposure can be readily applied to either problem type but the determination of that exposure from the behaviour of the gas phase is more problem-specific. The paper has outlined some recent developments in fire science, notably in enclosure fire modelling, which address these problems. In particular it concentrates on developments in the application of computational fluid dynamics to the fire problem. Such a technique, known to fire scientists as field modelling, provides an emerging technology which offers substantial advantages over traditional methods in the translation of developments in fire science to compartment types for which there is a less well-established knowledge base.

Examples of current capability have been illustrated in both the general context (Figs. 4 & 6) and in as far as they have been applied to aircraft cabin fires (Fig. 2). More work is necessary to bring the level of the fire science incorporated within aircraft cabin fire modelling up to that already demonstrated for building fire problems. In addition, the detailed treatments required for the effects of turbulence on combustion chemistry and thermal radiation need further development and testing. In some respects the theoretical developments are now outstripping the ability of traditional compartment fire experimentation to supply the underlying data needed. Because field modelling provides a very detailed prediction of property fields this creates a severe demand on experimentation. There is a growing need to meet this demand for the measurement of local flow velocities, product concentrations and radiative fluxes with modern diagnostic methods that have already contributed significantly to other areas of combustion-related research.

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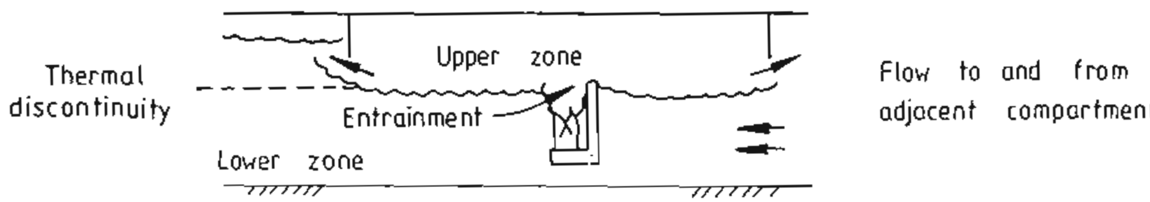

Figure 1. An illustrative two-zone cabin atmosphere model of the type used in the DACFIR code[2].

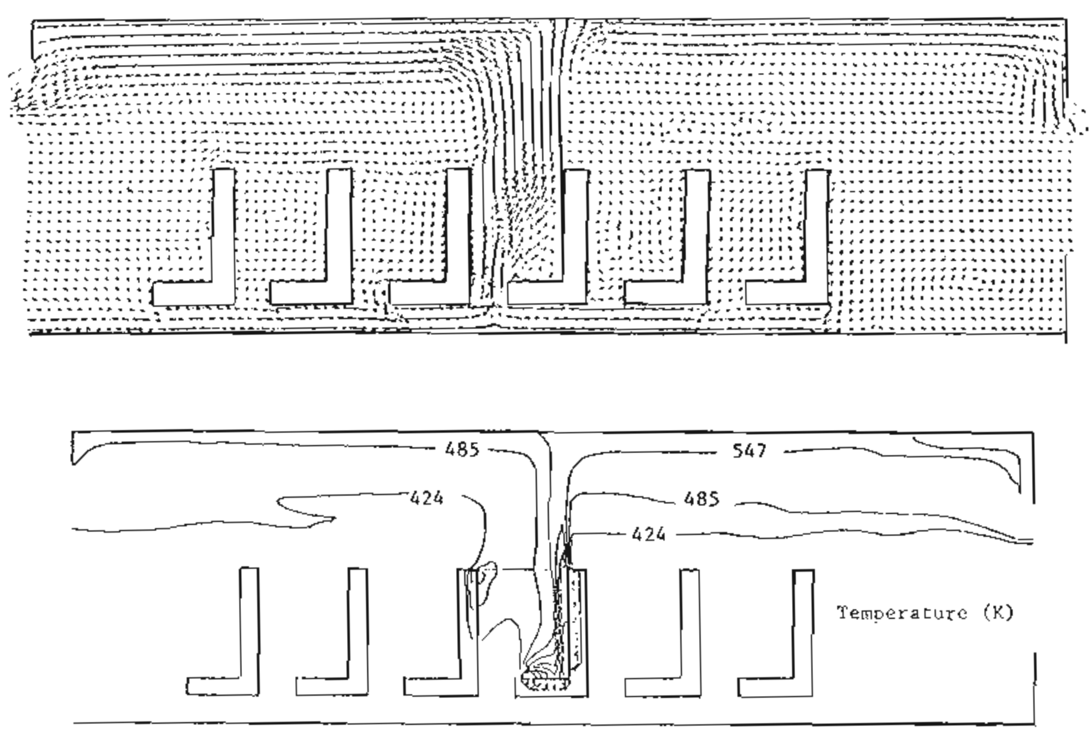

Figure 2. Field-model predictions of velocity and temperature in a simulated cabin fire[11].

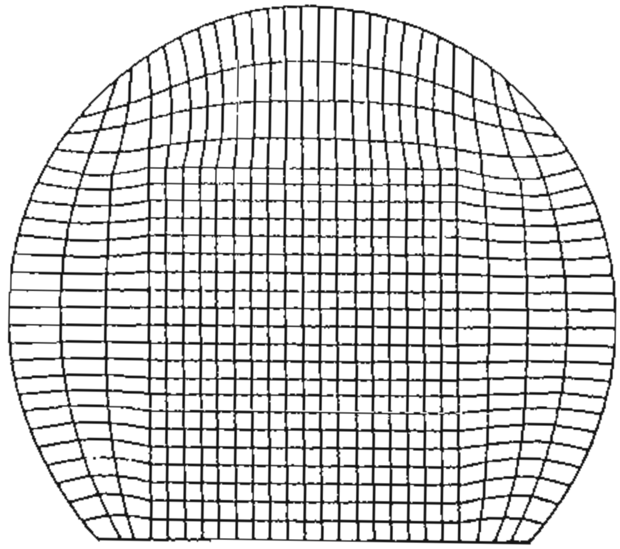

Figure 3. Body-fitted coordinate grid for an aircraft cabin interior[12].

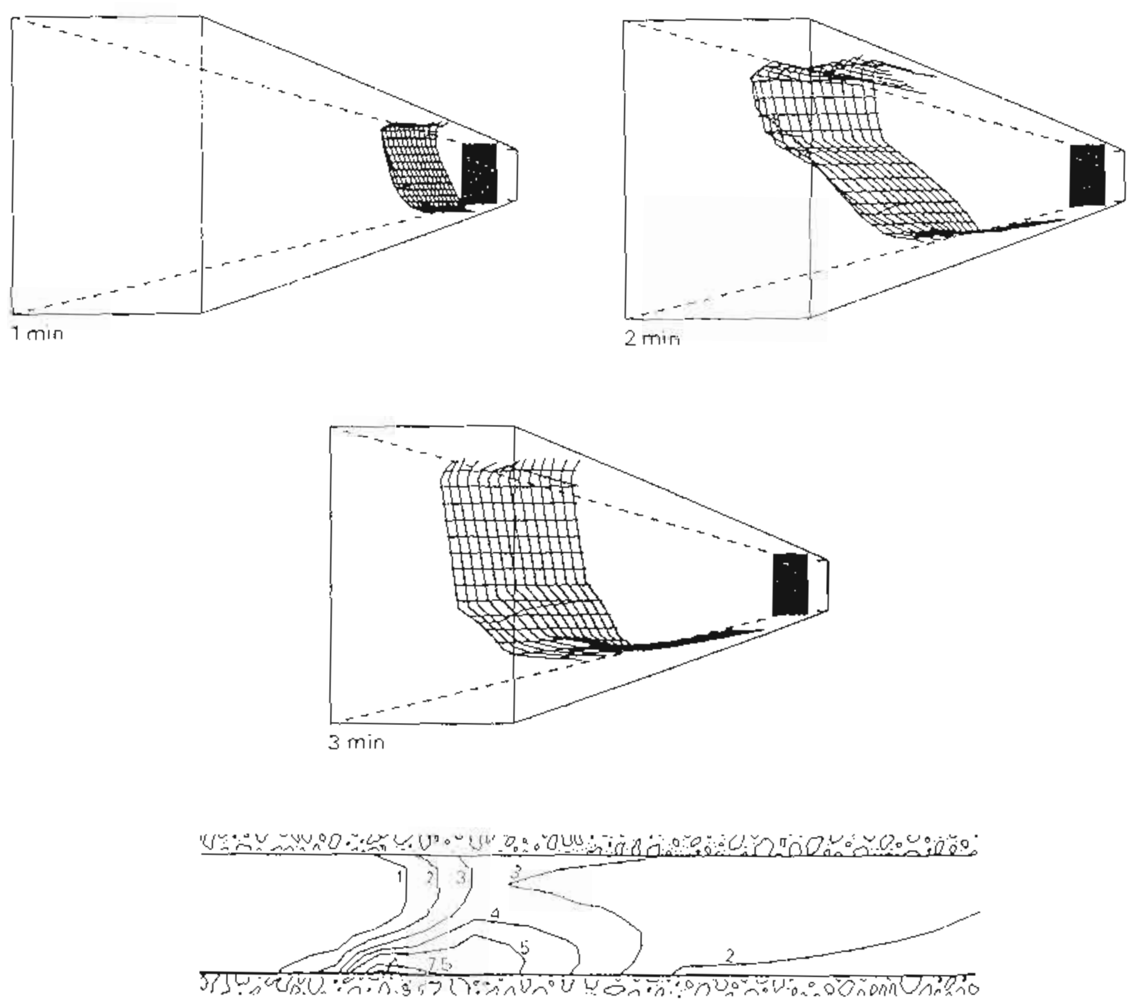

Figure 4. Field-model predictions[15] of
(a) "life-threatening" temperature surface in a tunnel fire
(b) Steady-state CO_2 concentrations (% volume) on the centre-line of the tunnel.

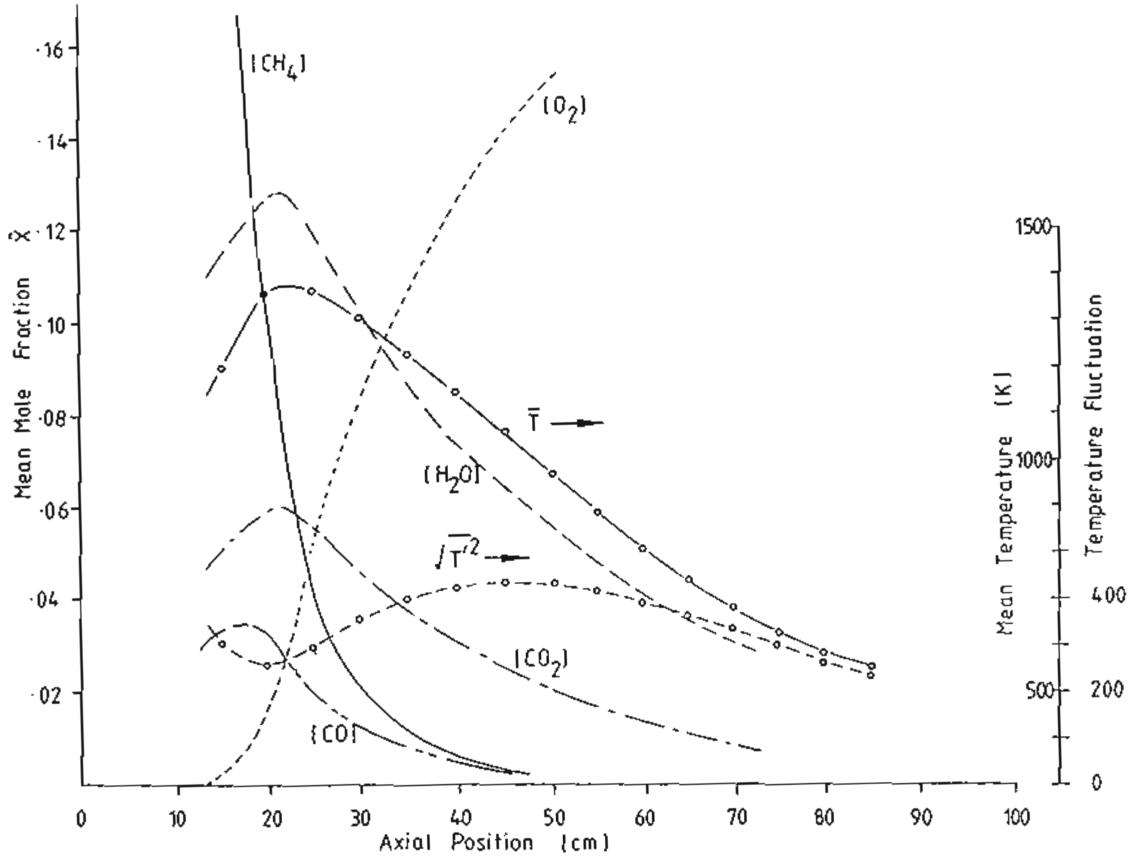

Figure 5. The axial development of mean composition in a simulated buoyant fire of 28 kW output, methane-fuelled.

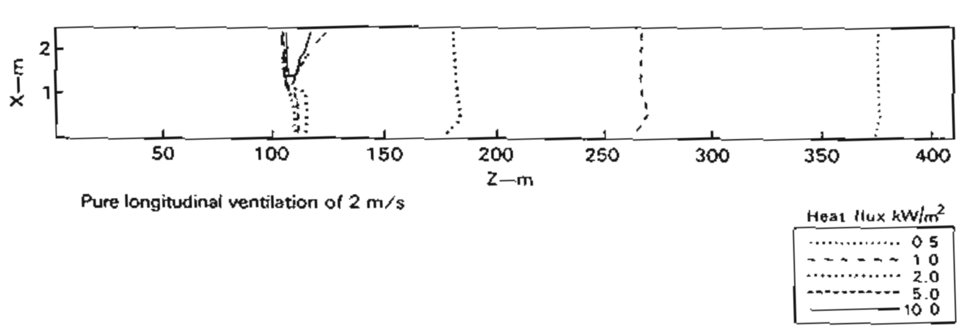

Figure 6. Predictions of radiant heat flux to the tunnel floor in the fire described earlier[15].

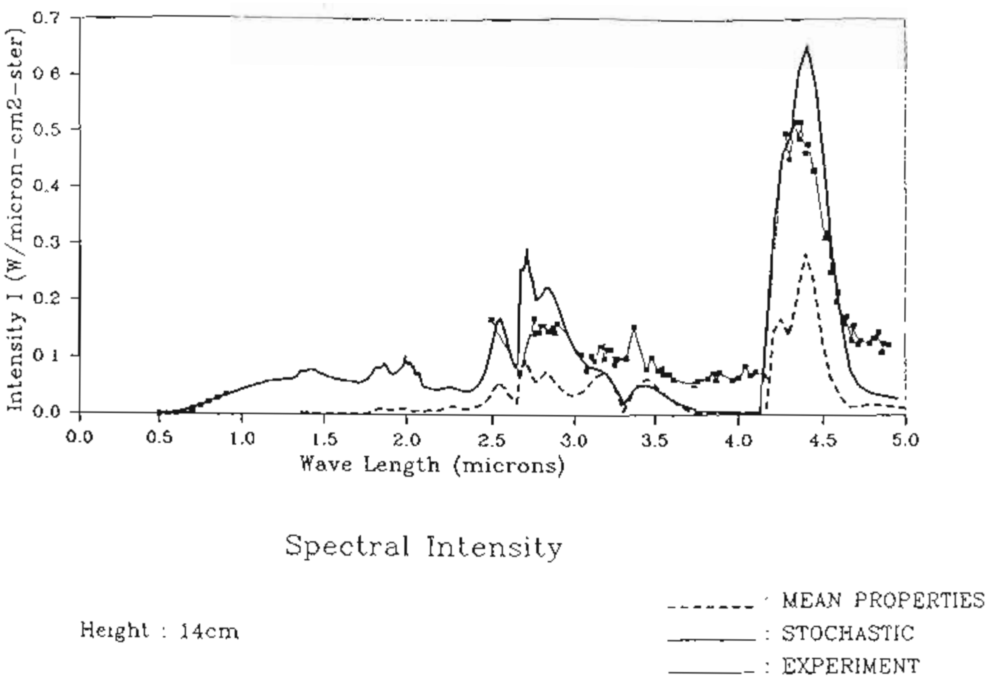

Figure 7. Predictions and measurement of spectrally-resolved radiant intensity in the simulated fire of Fig. 5[19].

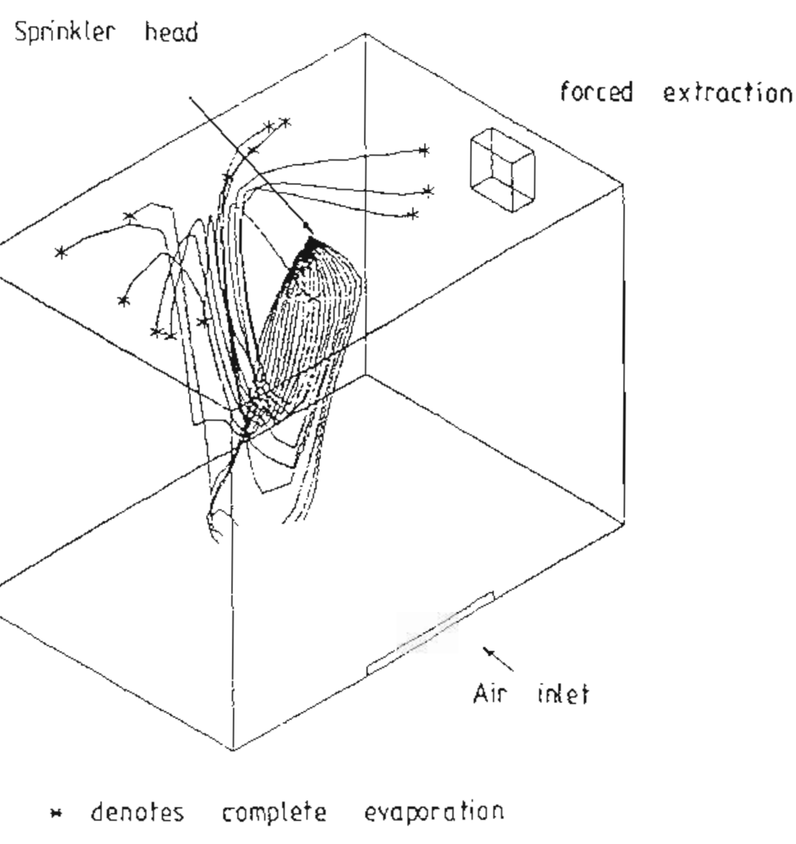

Figure 8. Predictions of droplet trajectories (0.5 mm diameter) from an idealised sprinkler in a room fire. The fire source is centrally located.

FORCED AND NATURAL VENTING OF AIRCRAFT CABIN FIRES - A NUMERICAL SIMULATION

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ABSTRACT

This paper presents a steady-state three-dimensional mathematical field model describing aircraft cabin fires. The fire is modelled by a simple heat source. The simulation is intended to represent non-spreading fires. The computer code uses a Body-Fitted Co-ordinate (BFC) formulation to model accurately the interior of the aircraft that is neither Cartesian nor polar-cylindrical. The dimensions of the fuselage are that of a BOEING-737. The effect of various openings in the fuselage on the temperature distribution within the empty aircraft cabin are investigated. With the cabin fitted with seats, ceiling panels and overhead stowage bins the effect of the aircraft's air-conditioning system on the temperature distribution within the burning fuselage is also examined. Early results suggest that a reverse flow situation (i.e. cold air injected through floor vents and hot air sucked out at ceiling vents) greatly reduces the temperature throughout the fuselage.

INTRODUCTION

The Manchester aircraft fire disaster of 1985 exposed the catastrophic consequences of a fire on board a commercial passenger aircraft. The nature of modern aircraft interiors, which consists of a densely populated passenger enclosure lined and furnished with organic (largely synthetic) materials (4200 kg on board a B747) and the vast quantities of flammable fuel carried (214,000 litres for the B747) make the possibility of fire a major concern. In the 10-year period from 1976 to 1985 some 6871 passengers and crew perished in aircraft accidents involving fire worldwide [1].

Life threatening aircraft cabin fires belong to one of two groups, the so-called post-crash fire and the in-flight fire. The post-crash fire involves survivable crashes, i.e. incidents in which occupants survive the initial trauma of impact. In post-crash fires the fire is initiated outside the cabin usually due to a fuel spill. The fire then attacks the aircraft cabin gaining entry via breaks due to impact damage. A Boeing study of more than 150 survivable crashes suggests that about 1300 people who may have survived the impacts perished as a result of fire [2]. In-flight fires mostly occur in accessible areas such as a galley or toilet. They can be due either to human intervention such as passenger indiscretion or sabotage or to technical causes such as electrical malfunctions. In the 20 years from 1964 to 1984 approximately 300 cases of in-flight fires have been reported, of these some 52 have proved fatal, accounting for about 1000 deaths [2-5].

To uncover details concerning the fire-dynamics involved and the hazards responsible for preventing escape by passengers and ultimately their death, it is necessary to perform simulations of possible fire scenarios. The simulation may be either numerical, i.e. computer-based mathematical models or experimental fire tests [6].

Mathematical modelling offers a cheaper and more general alternative to the experimental approach, provided that the models can be reliably validated. Both zone and field models have been implemented in describing aircraft cabin fires [5]. The zone modelling approach represents state-of-the-art technology currently in use; DACFIR (e.g. reference 7, for a comprehensive list see reference 5) being the most sophisticated of the zone modelling packages available for aircraft fires. The field modelling formulation, while still in its infancy, is emerging as the 'new technology' for modelling of aircraft cabin fires. It is already becoming a more widely accepted tool within the building fire community [8-13]. The field modelling approach potentially has great utility in assessing aircraft design for safety and in the training of flight and fire crews. Previous attempts at modelling aircraft cabin fires using the field modelling approach have been confined to two-dimensional studies (e.g. reference 14, for a comprehensive list see reference 5). Satoh et al [15] have performed a three-dimensional simulation of an aircraft cabin fire, however, this study lacked an accurate description of the aircraft cabin geometry. More recently Galea et al [16-20] have modelled aircraft fires using BFCs. This approach allows realistically shaped aircraft cabins to be simulated.

THE MODEL

In the following sections a mathematical field model describing the in-flight fire scenario is presented and discussed. The model, still under development, attempts to simulate turbulent buoyant fluid flow and heat transfer within a realistically shaped aircraft cabin. The dimensions of the cabin are that of a Boeing-737; its length is 17·1m with a width of 3·3m at the floor and a maximum height of 2·1m

The simulations presented here are steady-state, however, the model is capable of producing time-dependent simulations [16-19].

Two sets of results are presented and discussed. The first group examines the effect of various fuselage openings on the temperature distribution within an empty burning cabin. The fire, located on the floor, just off the cabin centre is simulated by a prescribed heat source of 50·7 KW. The openings consist of combinations of external doors and ceiling apertures. The doors have dimensions of 1·4m × 1·0m and are located on the port and starboard sides towards the forward and aft of the aircraft. The ceiling opening has dimensions of 0·8m × 1·0m and is centrally located towards the aft of the aircraft (see figure 1).

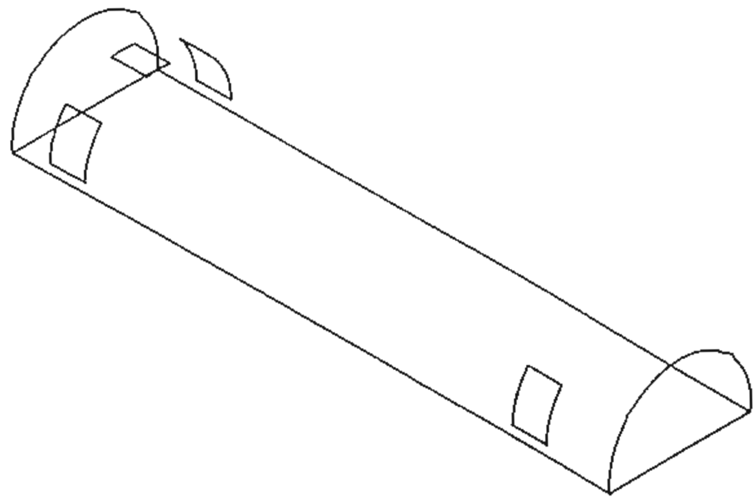
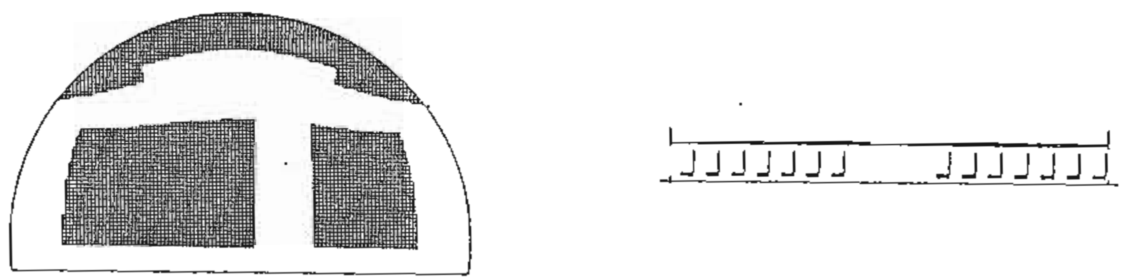


Figure 1: The above figure shows the locations and size of the openings in the simulated Boeing 737 fuselage.

In the second group the fire geometry is similar to that in the first case, however, cabin fittings and the cabin environmental control system are included. The fittings consist of two rows of seats and a ceiling unit including the passenger stowage bins. The seating configuration consists of a row of three seats abreast and a row of two seats abreast separated by an aisle. Seating in the vicinity of the heat source is not included (see figures 2(a) and 2(b)). Open doorways of dimensions 1·5m × 0·9m are situated in the forward and aft bulkheads. While the dimensions of the cabin are modelled on the B-737 it has been necessary to approximate the furniture specifications. The environmental control system consists of uniform venting at the ceiling and floor. The ceiling vents are situated at the top of the ceiling while



(a) (b)

Figure 2: The above figures represent: (a) cylindrical section of aircraft cabin showing position of seats, ceiling panel and overhead stowage bins, (b) axial section of cabin showing position of seats and ceiling panel and the open forward and aft doorway

the floor vents are located in the left and right corners where the side panels meet the floor. Both the ceiling and floor vents extend along the entire length of the cabin. From these vents either hot air may be sucked out of, or cool air injected into the cabin. The venting rate is such that a complete air change is produced in three minutes. In all simulations the ambient temperature was 19°C.

THE MATHEMATICAL PROBLEM

The starting point of the analysis is the set of three-dimensional, partial differential equations that govern the phenomena of interest here. This set consists, in general, of the following equations: the continuity equation; the three momentum equations that govern the conservation of momentum per unit mass (e.g. velocity) in each of the three space directions (the Navier-Stokes equations); the equations for conservation of energy and species concentrations; and, the equations for a turbulence model (in this case the k-ϵ model). The formulation of the differential equations describing the model will not be presented here as they may be found elsewhere [8-12,19].

The above-mentioned equations are transformed into general curvilinear coordinates, to allow for convenient and accurate treatment of irregularly shaped flow domains. The approach used here employs covariant physical velocity components in the form it appears in the general-purpose software package PHOENICS [19,21].

The Grid and its Generation

The BFC grid used can be considered as a distorted version of the usual orthogonal grid, in which grid lines and control cells are stretched, bent and twisted in an arbitrary manner, subject to the cells retaining their topologically cartesian character. This means that grid cells always have six sides and eight corners in the three-dimensional case.

The scalar variables solved by the BFC PHOENICS option are exactly the same as for the regular PHOENICS [12]. For details concerning grid generation and formulation of the conservation equations in BFC mode see Galea et al [19] and Hedberg et al [22].

RESULTS AND DISCUSSION

All numerical calculations were performed on the Thames Polytechnic NORSK 570 computers. Experience has shown that these calculations involve large quantities of computer time. A solution domain comprising of 4200 cells (10×10×42) requires approximately 13 hours of cpu while a mesh of 20,328 (22×22×42) cells requires in excess of 64 hours of cpu. The number of sweeps required to achieve convergence varies from 5500 to about 8500.

Detailed experimental data by which numerical models of aircraft cabin fires may be validated is not generally available. However, some effort has been made to validate the present model. Numerical results were compared with a set of experimental data from full scale fire tests conducted at the Johnson Space Centre [23]. In these tests a controlled pool fire (50·7KW) was ignited in an empty Boeing-737 fuselage which had open doors in the foreward and aft bulkheads. Results from this validation exercise are not presented here as details have been reported elsewhere [16-20].

It was concluded from the validation/grid refinement exercise that grids in excess of 20,328 (22×22×42) cells are required if quantitative results are desired, however, as little as 4,200 (10×10×42) cells will produce qualitative results. The good agreement between model and experimental results suggests that the model is capable of simulating non-spreading fires within aircraft fuselages. However, considerably more effort must be invested in the validation of the code.

The remainder of this paper is concerned with predicting the effect of cabin openings and the interaction of the cabin airconditioning system and seating configuration on conditions within the cabin

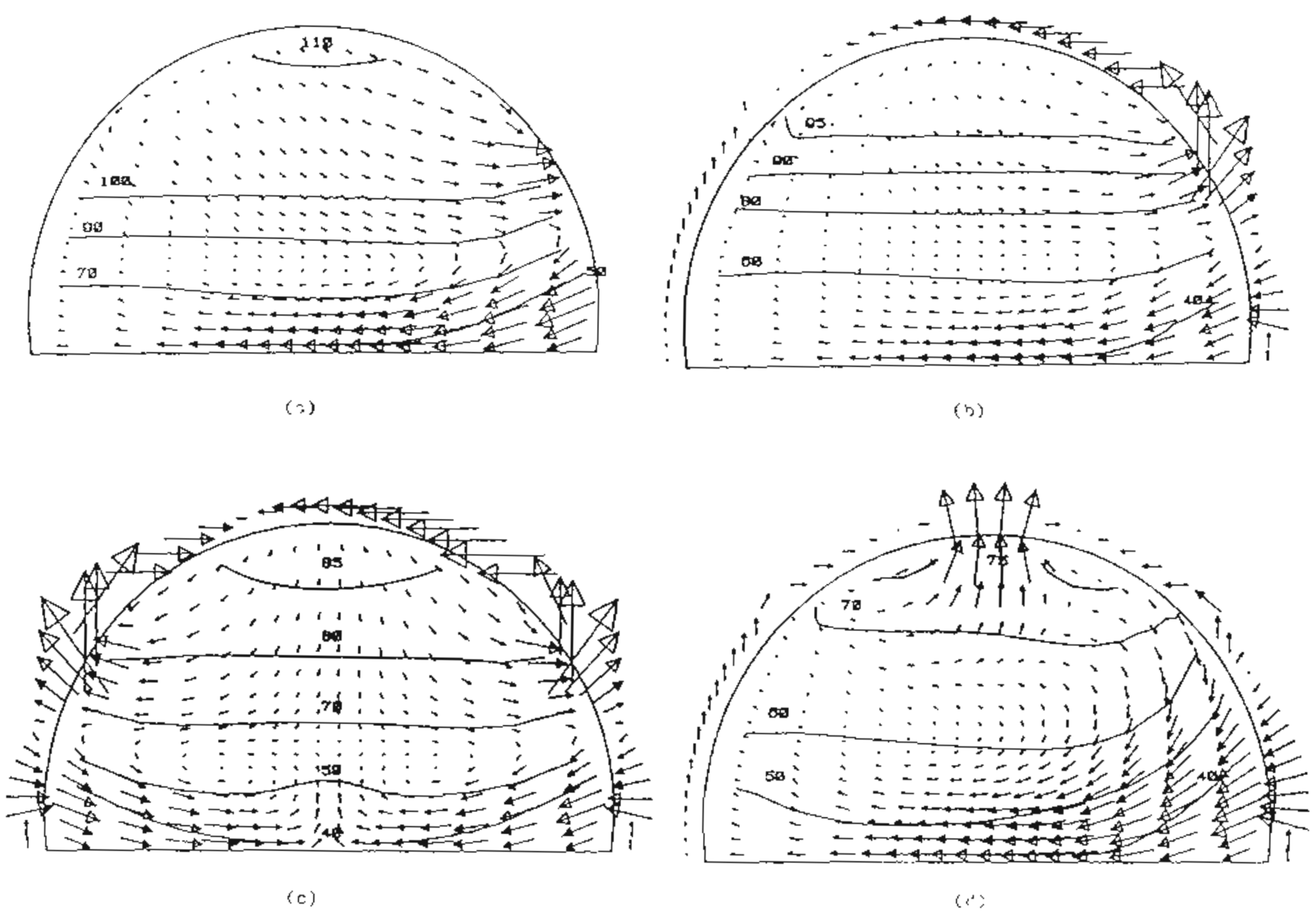
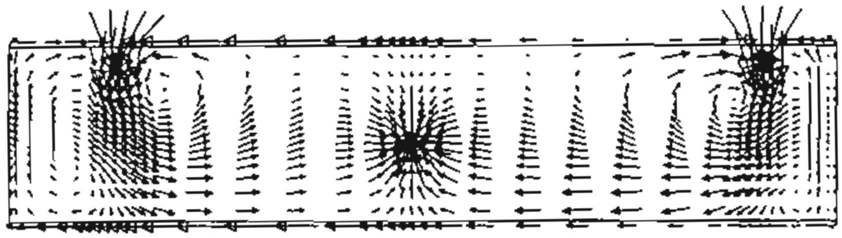


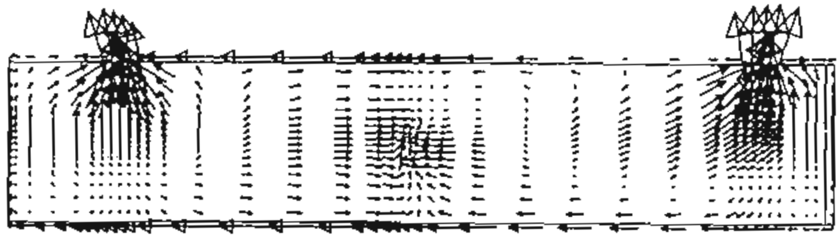
Figure 3: The above figures represent velocity vectors and temperature contours (°C) in a cylindrical section located 1·5m from the aft bulkhead. The plane depicted passes midway through the aft openings. They correspond to (a) Case A, (b) Case B, (c) Case C and (d) Case D

The effects of cabin openings on the temperature distribution throughout the cabin are demonstrated in the first set of results. Four cases are examined. Case A concerns the situation in which only the aft starboard door is open. In Case B, both the foreward and aft starboard doors are open, while the situation in which both port and starboard aft doors are open comprise Case C. Finally, the situation in which both the starboard aft door and the ceiling above the door are open constitutes Case D (see Figure 1). The centres of the aft and forward doors are located 1·5m and 14·9m respectively from the aft bulkhead. The centre of the ceiling opening is situated 1·5m from the aft bulkhead. In these simulations 10,496 (16×16×41) internal cells were used. As in earlier studies, in order to find physically realistic behaviour in the vicinity of doors opened to the exterior it is necessary to extend the solution domain to regions outside the fire compartment. An additional row of cells along the port, starboard and ceiling were used for this purpose making the total number of cells 12,546 (18×17×41).

Figures (3a) to (3d) show velocity vectors and temperature contours in a cylindrical section 1·5m from the aft bulkhead. This plane passes through the centre of the aft openings. Situations excluding the ceiling opening display the familiar two layered structure in the doorway. Relatively cool air enters the cabin through the bottom regions of the doorway while hot air billows out from the top sections. This is seen more clearly in figures (4a) and (4b) which show planes parallel to the floor at heights of 0·5m and 1·1m respectively above the floor. The situation depicted corresponds to Case B. The neutral plane is located approximately midway in the open doorway. With a ceiling opening located just above the door (Case D figure 3(d)), air is entrained into the cabin through almost the entire area of the open doorway while the hot ceiling gases are vented out through the ceiling opening.

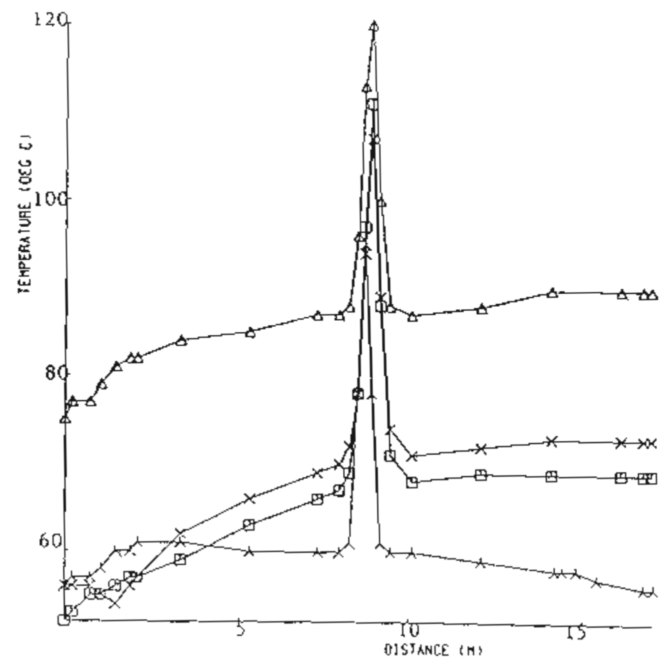


(a)

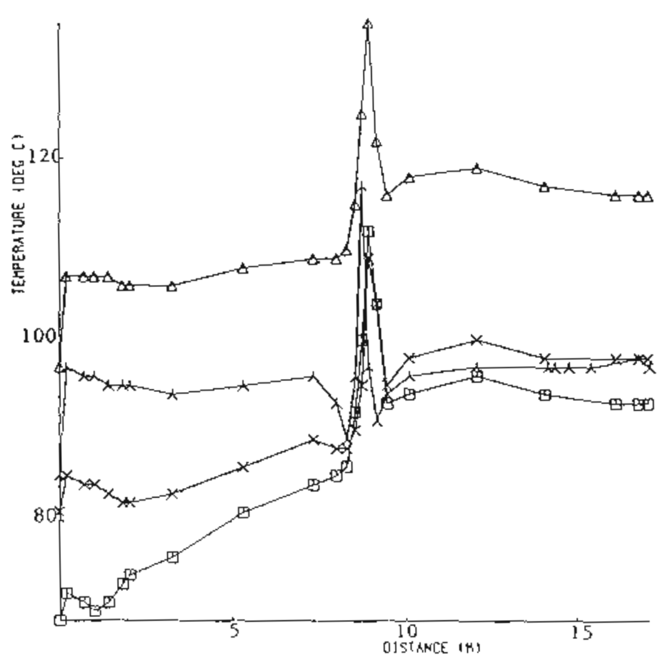


(b)

Figure 4: The above figures represent velocity vectors in a section parallel to and (a) 0·5m and (b) 1·1m above the floor. The situation depicted corresponds to CASE B.



(a)



(b)

LEGEND :
CASE A △
CASE B ×
CASE C ⊡
CASE D ⅄

Figure 5: Model generated temperatures (°C) along the centreline of the cabin for the various venting scenarios at (a) 0·53m and (b) 1·50m above the floor.

Figures (5a) and (5b) show centre line temperatures along the length of the fuselage at 0·5m (figure (5a)) and 1·5m (figure (5b)) above the floor for the four cases described above. These figures clearly indicate that the temperature distribution is strongly affected by the nature of fuselage openings. The highest temperatures are found in Case A (single side opening). This is consistantly true, throughout the length of the fuselage and in the vicinity of both the floor and ceiling. In this case temperatures near the floor are typically 80°C while temperatures in the ceiling region are about 115°C. High up in the cabin, temperatures are minimal for Case D (ie. ceiling and side opening), this is particularly true in the aft section of the cabin, which contains the openings. In the aft section temperatures range from about 75°C to 85°C while in the foreward section temperatures are about 95°C. Figure 3d shows that relatively cool air is being entrained into the cabin throughout the open starboard doorway while hot ceiling gases are being vented out through the ceiling opening. In the lower regions the situation is somewhat different, temperatures are minimal for Case B (two starboard doors) except in the immediate vicinity of the aft door. For Case B temperatures near the floor are typically about 60°C.

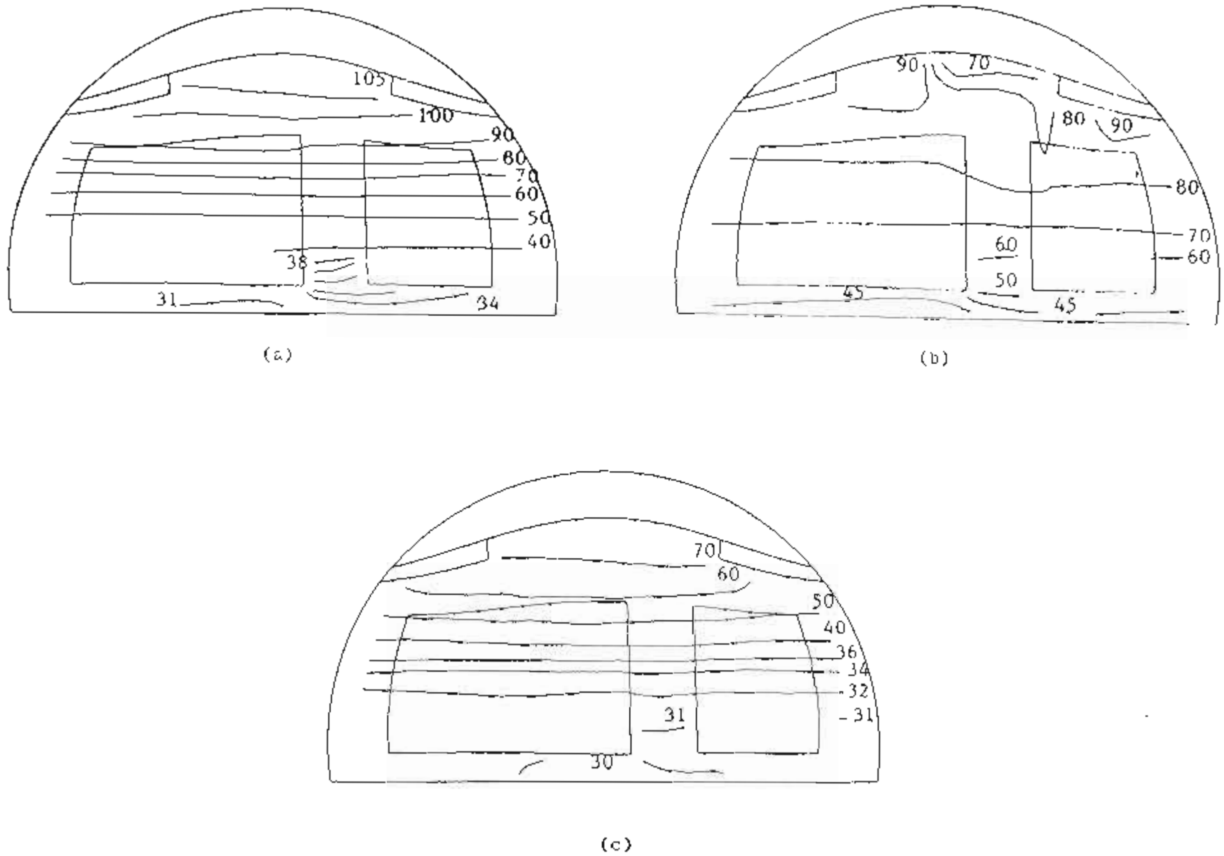


Figure 6: The above figures represent temperature contours (°C) in a cylindrical section located midway between the open aft door and the fire, for the cases (a) no venting, (b) forward venting and (c) reverse venting.

The two different configurations in which two openings are confined to the aft sections (Case C and Case D) produce similar temperature distributions. In the lower regions of the cabin, except in the immediate vicinity of the open aft doors, Case C (two facing doors) results in slightly higher temperatures. A similar situation exists higher up in the cabin. The lower temperatures found in Case D suggest that the ceiling opening in conjunction with the side door is more efficient at venting the hot gases than two facing doorways.

It should be remembered that the fire in these simulations is represented by a simple heat source. The fire is strictly non-spreading and the power output of the fire is constant. The observed differences offered by various cabin openings assumes that the fire is not changed by the compartment configuration. In reality, any beneficial effects may be overshadowed by creating a more intense fire, thereby increasing the generation of fire hazards such as heat, smoke, gas etc. In planned extensions to the existing program, a kinetically controlled combustion model will replace the heat source. With such a model the supply of oxident and fuel will determine the power output of the fire.

The final group of results concerns numerical models which predict the effect of the cabin environmental control system on the heat flow in the B-737 fuselage fitted with furniture. No experimental results are available for comparison. The solution grid used to produce these results consists of 11,008 (16×16×43) internal cells and 1024 (16×16×4) external cells outside each open door The fire strength was 50·7KW.

Three venting scenarios were investigated. The first case, case A, involved no forced ventilation. In the second case, case B, fresh air is injected from the ceiling vents while hot air is sucked out from the floor vents. Case B is intended to simulate the operation of the environmental control systems found in most commercial aircraft.

Figures 6 and 7 show temperature contours and velocity vectors, respectively, in a cylindrical section located approximately midway between the fire source and the open aft doorway for the three venting scenarios. In venting cases A and C (Figures 6a and 6c) the cabin atmosphere is stratified into horizontal layers parallel to the floor. Relatively cool air exists near the floor while hotter air may be found in the vicinity of the ceiling. This is in agreement with experimental observations [24]. In venting case B (figure 6b) the atmosphere is still stratified into more or less horizontal layers near the floor, however, in the region above the seat tops this simple stratification is destroyed. The jet of cold air into the hot atmosphere sets up a large circulation region (figure 7b) throughout the length of the cabin which extends from the ceiling to just below the seat tops. In case A and C the tendency is for the air to rise from the floor to the ceiling region (figures 7a and 7c). The expulsion of gases from the floor vents (case B) attempts to reverse the natural tendency of hot air to rise. In venting case A (no venting) temperatures near the seat bases are approximately 40°C (figure 7a). In the case of forward venting (case B) these temperatures are increased to approximately 60°C (figure 7b) while in the reverse venting situation (case C) the temperatures are reduced to approximately 31°C (figure 7c). Temperatures near the ceiling are reduced from 105°C in venting case A (figure 7a) to 70°C in venting case C (figure 7c).

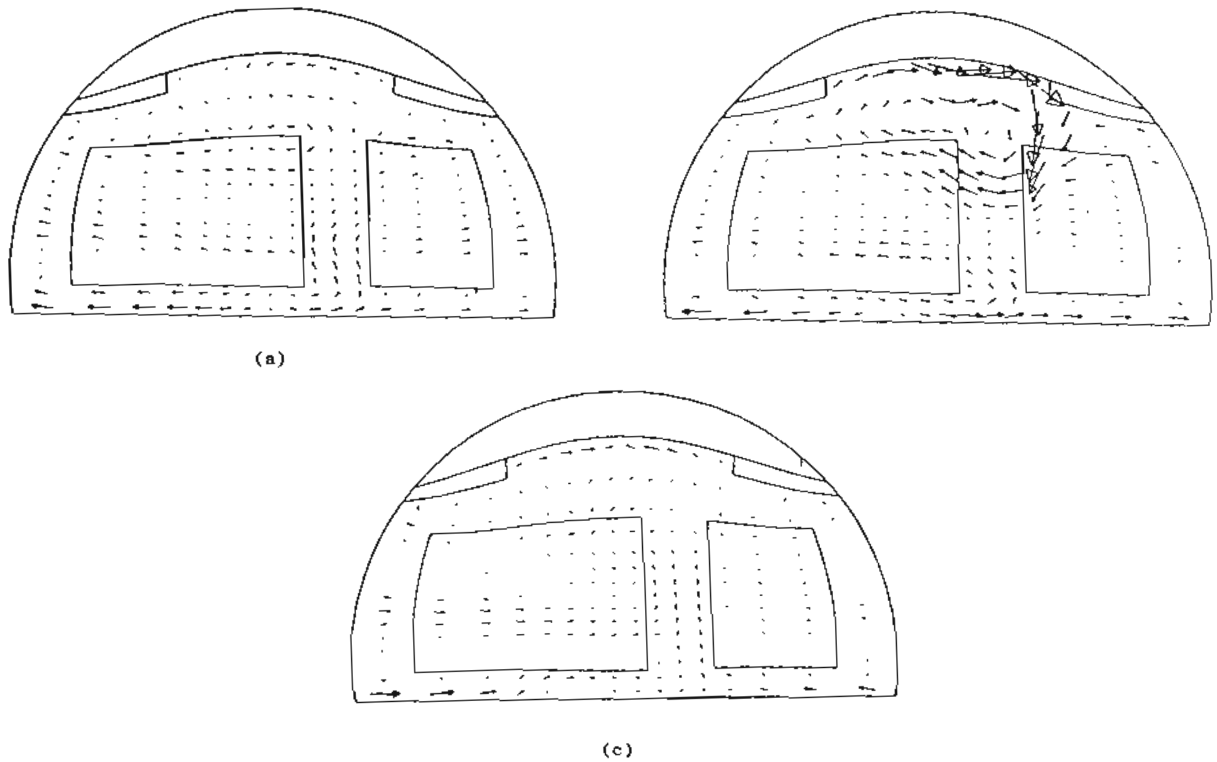


Figure 7: The above figures represent velocity vectors in a cylindrical section located midway between the open aft door and the fire, for the cases (a) no venting, (b) forward venting and (c) reverse venting. The vector scale is identical in each case.

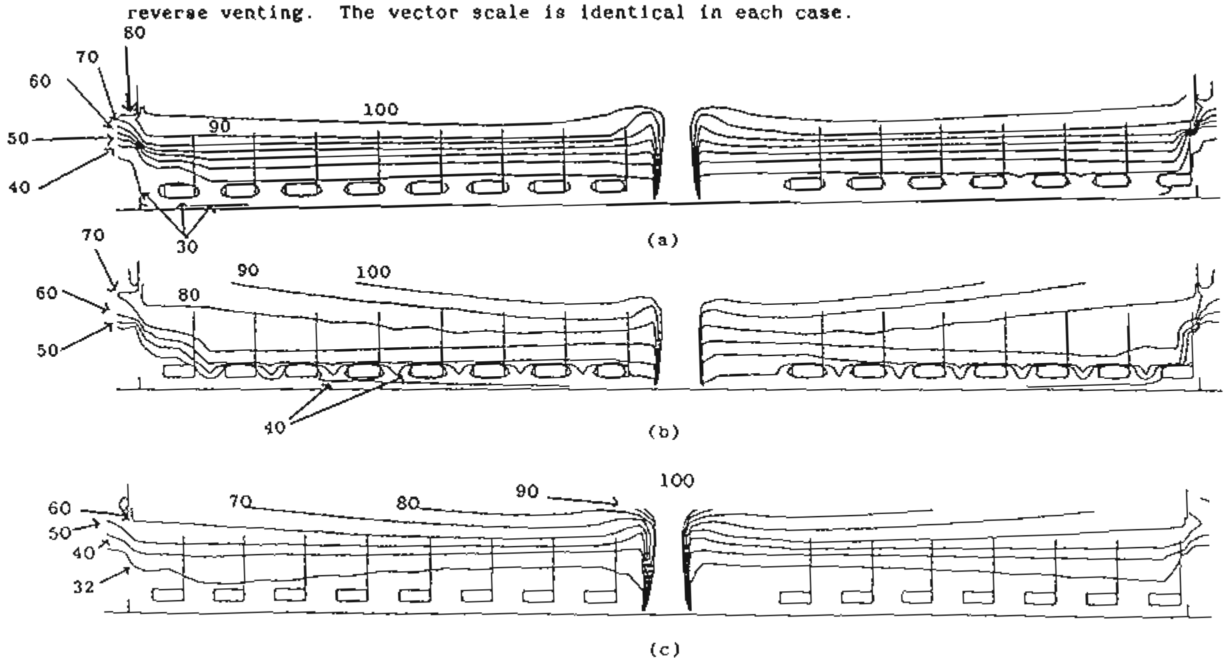


Figure 6: The above figures represent temperature contours (°C) along the length of the fuselage passing through the fire for the cases (a) no venting, (b) forward venting and (c) reverse venting.

Figures 8(a),(b) and (c) show temperature contours along the length of the fuselage passing through the fire source and seat rows. In venting case A, temperatures of 100°C occur just above the seat tops and temperatures of 40°C occur just above the seat bases (figure 8a). In the forward venting configuration (case B) temperatures in the vicinity of the seat tops have reduced slightly to 90°C, however temperatures just above the seat bases have increased to 60°C (figure 8b). In the reverse venting situation (case C) temperatures near the seat tops and seat bases are significantly lower. In the vicinity of the seat tops the temperature has fallen to 60°C while just above the seat base the temperature is near ambient (figure 8c).

It is recognised that in view of the fact that the model has not been completely validated by experiment, and due to the course nature of the grids used here, these results should be viewed with some degree of reservation. However, the usefulness of reverse venting in reducing temperatures and smoke concentrations near the floor has been observed in full scale experimental room fires [25].

CONCLUSIONS

Through the use of BFCs the feasibility of simulating non-spreading fires in realistically shaped and equipped aircraft fuselages has been demonstrated.

The location and nature of fuselage openings was observed to exercise a major influence on the temperature distribution within the passenger compartment. Knowledge of such behaviour is crutial for the safe evacuation of burning aircraft.

The action of the aircraft's ventilation system was also observed to have a major effect on the temperature distribution within the burning fuselage. With the system extracting hot air from the floor vents and injecting cold air from the ceiling vents, as is found in most commercial passenger aircraft, temperatures in the vicinity of the seat bases increase by about 20°C over the temperatures found in the non-venting case. In the reverse flow situation temperatures fall to just above the ambient temperature.

High up in the cabin, in the vicinity of the ceiling, temperatures are also greatly reduced in the reverse venting situation.

The use of this venting strategy could lead to the control of the rate of spread of fire within the cabin. Such control is particularly pertinent to the in-flight fire scenario.

Current research has two aims. Firstly, we are attempting to extend the analysis to include combustion and radiation models. We are also using the field modelling approach to simulate the considerably more complicated water spray-fire situation. In this way it will be possible to model not only the effect of fire but also the suppression of fire spread and its eventual extinguishment [26]. Secondly, we are involved in increasing the efficiency of the numerical procedures which lie at the heart of field models. This involves adapting existing sequential fire codes to make use of relatively inexpensive parallel hardware in the form of transputer technology. In this way we hope to reduce the high overheads incurred in using field modelling.

ACKNOWLEDGEMENTS

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VULCAIN

AN EXPERT SYSTEM DEDICATED TO FIRE RISK ANALYSIS WITHIN COMPLEX INDUSTRIAL ENVIRONMENTS

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ABSTRACT

VULCAIN is an expert system which allows rapid fire risk analysis within complex industrial environments. It works step by step as a function of the risk criticality. It uses :

- As a first step, a risk analysis using standards
- Then more complete diagnosis based on various aspects which are not covered by standards (viz : fire propagation on targets, influence of both natural and forced ventilation).
- Finally complete spatial and temporal numerical simulations of fire propagation where temperature vs time diagrams are obtained to characterize fire propagation and/or extinction.

VULCAIN is a very convivial software tool to carry out complex sensitivity analysis concerning all critical parameters (combustible material, openings, wall thermal and chemical characteristics) and systematic studies concerning a given criterion (for instance : possibility of fire control by human means).

All the knowledge base within VULCAIN has been validated with respect to small and full scale experiments. Good results have been obtained for such industrial sites as : nuclear power plants, storage areas, submarines. Its use can be envisaged for vulnerability studies of airplanes.

RESUME

VULCAIN permet, suivant le site étudié, de déterminer rapidement le risque incendie, avec plusieurs niveaux de précision en fonction de la "criticité" du cas. Il utilise :

- en première approximation une évaluation fournie par les normes
- puis des diagnostics complets sur differents aspects (propagation sur des cibles, influence des ouvertures ou ventilation, ..)
- et enfin une simulation numérique spatio-temporelle qui permet d'affiner les diagnostics précédents et de fournir des diagrammes d'évaluation du feu dans le site considéré en fonction du temps.

La souplesse et la convivialité de VULCAIN permettent d'effectuer facilement des études de sensibilité sur tous les paramètres d'entrée (position du combustible, des ouvertures, caractéristiques des parois, ...) ou des tests systématiques sur un critère précis (ex : possibilité d'intervention humaine)

Toutes les connaissances de VULCAIN ont été validées par des comparaisons à des cas tests. Des essais en vraie grandeur ont montré que VULCAIN donne des résultats précis et cohérents pour des sites industriels aussi variés que des centrales nucléaires, des sites de stockage, des sous-marins. Son application à des études de vulnérabilité d'aéronefs est aussi possible.

1 - INTRODUCTION

The fire expert's approach to risk analysis is progressive : starting with hypotheses on fire initiation, the evaluation uses the standard formulas (ISO, TNO, ...) and gives first the duration of the fire and the peak temperature in the building on fire. Various conclusions can then be derived from these results, concerning the behaviour of the materials, the usefulness or the feasibility of human intervention, etc ...

For ten years now, the experts of the Thermodynamic Direction of BERTIN have improved this procedure in three ways :

- by introducing a more accurate physical analysis of the phenomenae involved, in order to refine the computation of the variables used by the norms (fire duration, peak temperature). A continuous relationship between temperature and time is then established

- by evaluating these improved computation methods against full scale or reduced scale experiments

- by integrating technical data in the diagnosis steps, which allows a better evaluation of the efficiency of human intervention or automatic fire fighting

The various aspects of this approach have been gathered into an expert system : VULCAIN

With VULCAIN, users have a convivial tool allowing to study in a short time a wide range of fire scenarii, with in each case an identical procedure for risk evaluation. Also, the system has been designed for an easy adaptability : experts and computer scientists can make it evolve as new technological or scientific knowledge is acquired.

The software has a general structure, and can easily be personalized for specific needs, in particular for fire risk evaluation or aided design for maximum security in closed area such as in factories, ships or aircrafts.

2 - DESCRIPTION OF VULCAIN

2.1 - Architecture

VULCAIN deals with three kinds of information (fig. 1) :

1) The position of the inflammable materials in the premises on fire, and the ventilation conditions

2) The expert deduction knowledge covering four levels :

- the norms and related calculations
- the simplified physics of fire, in order to improve the evaluations given by the norms
- a model for fire-spreading simulation, implemented in the module VESTA which produces a continuous relationship between temperature and time and yields an accurate estimate of fire evolution
- the technological or technical criteria which authorize the evaluation of fire-fighting methods

The knowledge is modeled :

- in a fact base for the description of the configuration to be studied (geometry of the premises, fuels, ventilation ...)
- in a data base for the thermo-physic characteristics of materials and fuels
- in a knowledge base structured in two levels for the know-how of aerothermic and fire technology specialists, and for the basic physical knowledge (thermodynamic laws, thermal models)

The data and fact bases can be directly accessed through appropriate interface, by the operator who can adapt them to the case to be studied.

The software is written in three languages :

- PROLOG II, for the general management of the system, and particularly for facts manipulation, hypothesis verification, model choice and some simple calculations

- FORTRAN for the computation (model simulation)

- PASCAL for user interfaces

2.2 - How the system functions

The user is guided by the software to follow the procedure of an expert

Step 1 : the user gives the expert system the geometrical data of the premises (walls, openings), the positions of and data on the combustible materials, the ventilation, ...

Step 2 : strict application of the norms allows for an evaluation of the risk level, based on the use of a classical procedure

Step 3 : the user sets a starting fire scenario. Order of magnitude calculations based on physics provide an improved evaluation by giving values (temperature, time) closer to the real valued than in step 2

Step 4 : if the uncertainty level on the results is given by the expert system as too high, the user can ask the module VESTA a time variation of several characteristic variables such as : burnt gas, walls, ceiling and floor temperatures, gas flow, etc ... These values allow a better evaluation of the risk and a more precise estimation of the intervention possibilities once the fire has broken out.

The approach used consists in reproducing the risk logic defined by the experts : the diagnosis works on the basis of backward chaining (see figure 2).

For the global evaluation of the situation, the system considers successively different kinds of risks (for example : spread burning, propagation to distant fuel targets, ...) and verifies if all the conditions are present for the starting of the phenomenon.

This examination of the risk tree leads to a characterisation and a classification of each case studied.

3 - VALIDATION OF VULCAIN AND APPLICATIONS

3.1 - Validation

The validation of the expert system has been conducted in two steps :

- At the coding level : it was important to check that the interpretation and the formulation made by the expert system developers did not introduce a bias in the procedure and reasoning specified by the expert. This verification has been made by a sensivity analysis on the influence of input parameters on the output values. This analysis has been validated by the experts who provided the knowledge.

- On the expertise level : the problem was to verify and qualify the expertise itself. This step, more difficult, has been performed by matching VULCAIN outputs against simulations, real experiments and other expert opinion.

The presence, in the same company, of the experts and the development team has made the validation phase, and the initial step of knowledge formulation much easier.

One of the real experiments used for the validation is the fire of a polyrethane sofa. This experiment has been performed by the Technical Institute of Lundt in Sweden. This combustion of a sofa, in a room of about 9 square meters, with an open door, simulates a possible house fire (figure 3).

As it is shown in figure 4, the maximum temperature level predicted by the norms ISO et TNO is quite lower than the one given by VULCAIN (550°). However, the fire durations calculated by the norms (100 s) and VULCAIN (120 s) are very similar. In fact, the very specific nature of the fuel - polyrethane block - forbids a precise prediction of this value without a more precise description of its combustion. This is what is provided by the VESTA module, which gives a satisfactory prediction of the time dependant fire evolution.

The knowledge of the evolution allows, at the same time, a better evaluation of the risk level, and a precise study of fire prevention policies in similar premises (influence of the openings, remote inflammation, ...).

3.2 - Applications

Two cases illustrate the capabilities of application of the system :

3.2.1 - Oil fire in a large ventilated room

This accident is typical of energy producing installation or industrial plants, where oil is used as lubrification or hydraulic transmission fluid.

The experiment studied by the French Commissariat for Atomic Energy considers the evolution of an oil fire (10 kg on 1 m2), in a ventilated room (dimensions : 9 X 6 X 7,6 m). On the results shown in figure 5, it can be noticed that VULCAIN leads to a preliminary diagnosis very coherent with the results of the experiments : average burnt gas temperature of 200°C for a duration of 400 s. In this case, the norms lead to an over-evaluation of the maximum temperature (norm ISO) or an under-evaluation, which could be dangerous for the installation. Once again, the standard fire duration (35 s) given cannot lead to a rational policy of prevention.

The burnt gas temperature given by VESTA is very close to the gas temperature measured just under the ceiling and the burnt gas temperature at the extraction outlet level (after mixing with fresh air). The interest of the VESTA results concerns again the intervention policies in the room, including the influence of the ventilation conditions.

3.2.2 - Oil fire in a submarine

Due to the importance of ventilation, VULCAIN evaluates a peak temperature level (200° c) slightly higher than the temperature reached during the experiments, and a fire duration of about 14 minutes, while the norms ISO and TNO give 70 seconds (figure 6).

The results given by VESTA indicate a good agreement at the burnt gas temperature levels.

In a submarine, another important parameter is the evolution of the oxygen-rate in the room, after the fire breaks out. Figure 7 compares the computed and measured evolution of the oxygen-rate : the knowledge of this parameter is fundamental to suggest prevention and intervention policies in a closed area.

4 - USE OF VULCAIN

VULCAIN is presently used for internal needs at BERTIN, for instance for systematic analysis of fire risks in 900 MWe nuclear power plants. The system brings a solution to the requirements of rapidity of studies and unified approach.

4.1 - Use in nuclear industry

The French Commissariat of Atomic Energy has a specific version of VULCAIN which includes additional knowledge related to nuclear environment (ventilation filters, fighting means, ...).

The expert system is mainly used for fire risk analysis in nuclear power plants and subsequent studies to define improved conditions in critical cases.

The operators do not have a computer background, but they have a good level of knowledge in fires. This feature leads to emphasize two points : the user friendliness and ergonomy of the software and the explanation of the various diagnosis. In particular the operator inte.face includes an on-line help function.

Concerning diagnosis, two levels of explanations can be obtained :

- a short justification of the diagnosis to allow results interpretation
- a summary of the reasonning and the intermediate steps that led to the diagnosis

4.2 - Other uses

- Manufacturing industries which are particularly fire prone such as food industry, oil industry, and for which fires are linked to important economic consequences.

- Insurances

  VULCAIN can be transformed into a handy tool allowing insurance companies to perform quick evaluations, based on scientific arguments, of fire risks of industrial installations.

- Aircraft industry

Even though VULCAIN has not yet been used in applications related to the aircraft industry, it can easily be envisaged to take advantage of its assets such as rapid and accurate diagnosis, scientific and technological bases, easy manipulation, to examine fire risks and fire fighting procedures

- in manufacturing and aircraft assembly halls
- inside the aircrafts, in passenger or cargo areas

Indeed, the architecture of VULCAIN and the techniques used allow an easy personalization of the tool by taking into account specific characteristics and by performing analysis such as :

- fire risk evaluation
- qualification of an environment against given risks
- aid for the design of the organization of premises to reduce fire risks
- aid for the definition of fire fighting procedures.

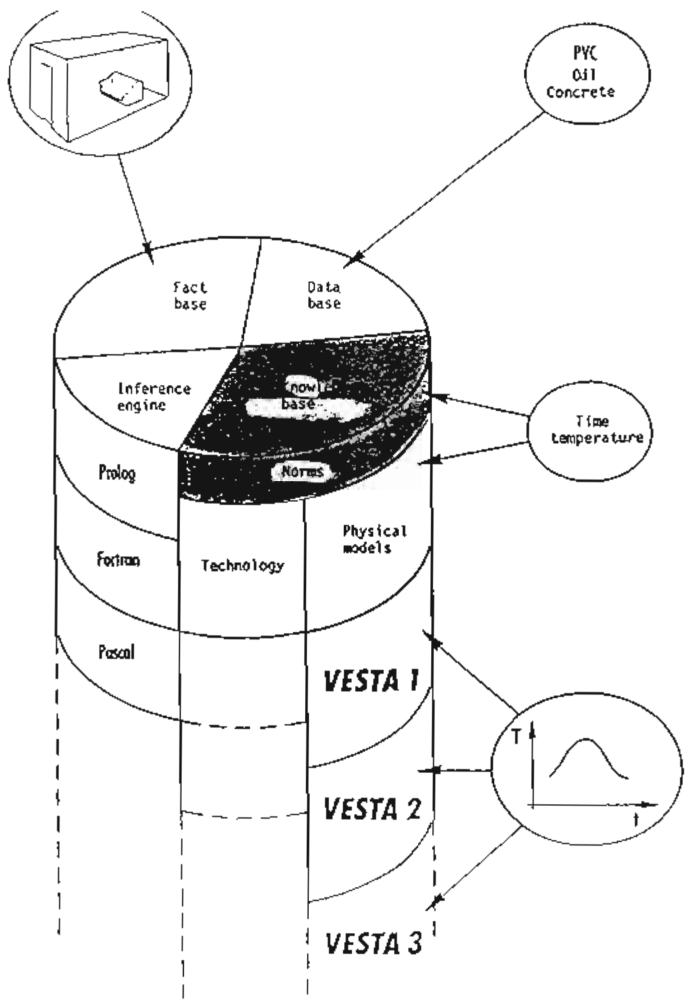


FIGURE 1 - ARCHITECTURE OF VULCAIN

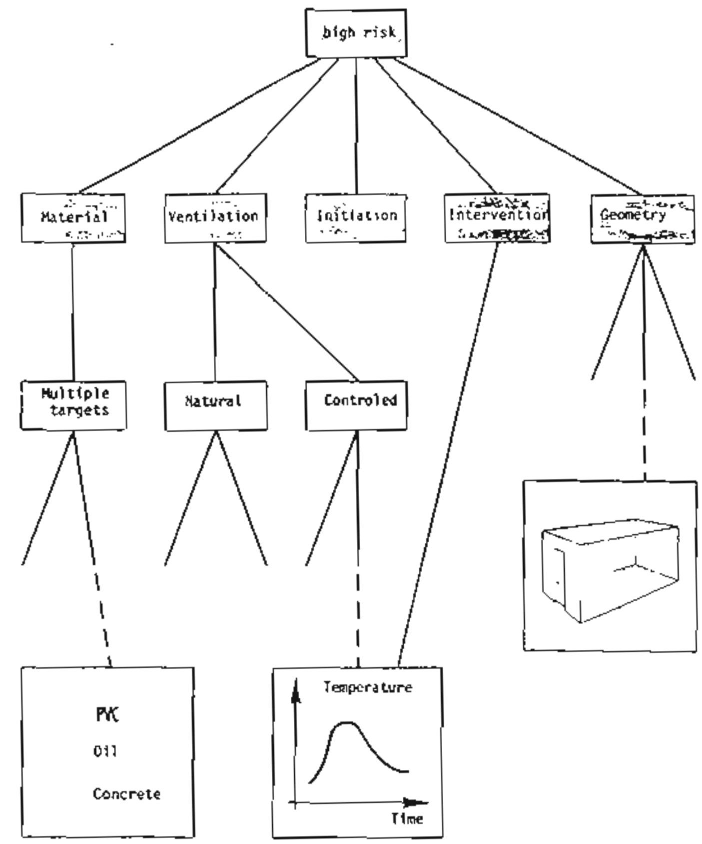


FIGURE 2 - LOGIC OF RISK EVALUATION

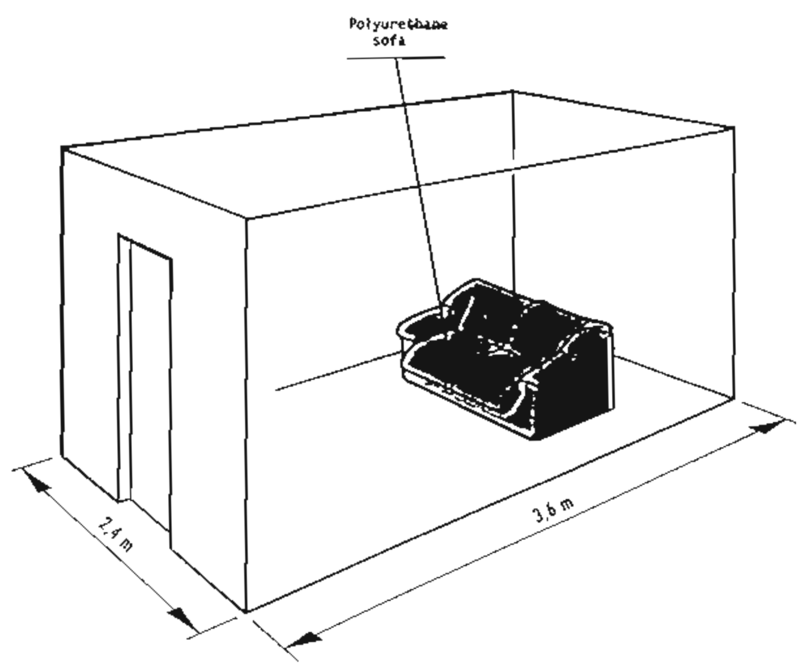


FIGURE 3 - EXPERIMENTS OF POLYURETHANE FIRES

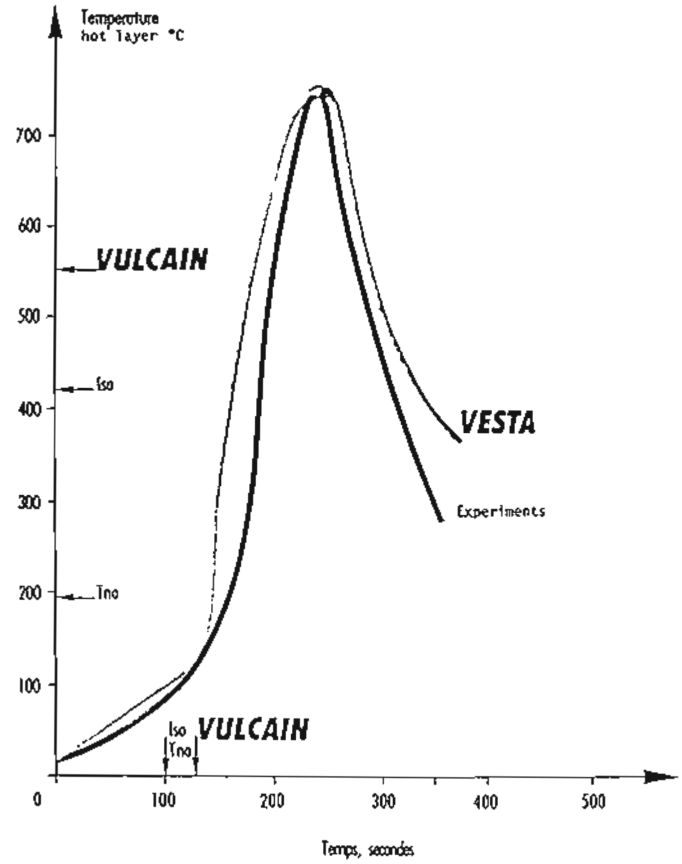
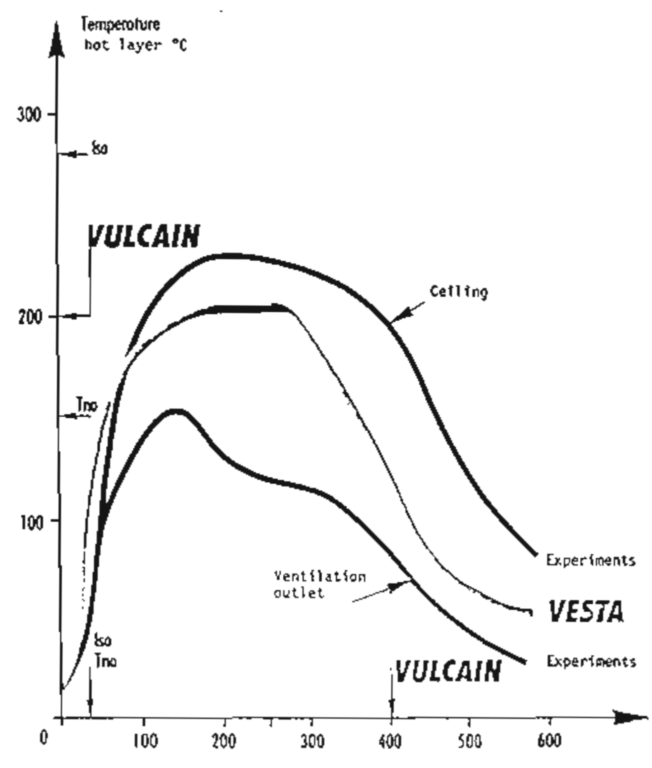


FIGURE 4 - POLYURETHANE FIRE, NATURAL VENTILATION
(ITL-SWEDEN)



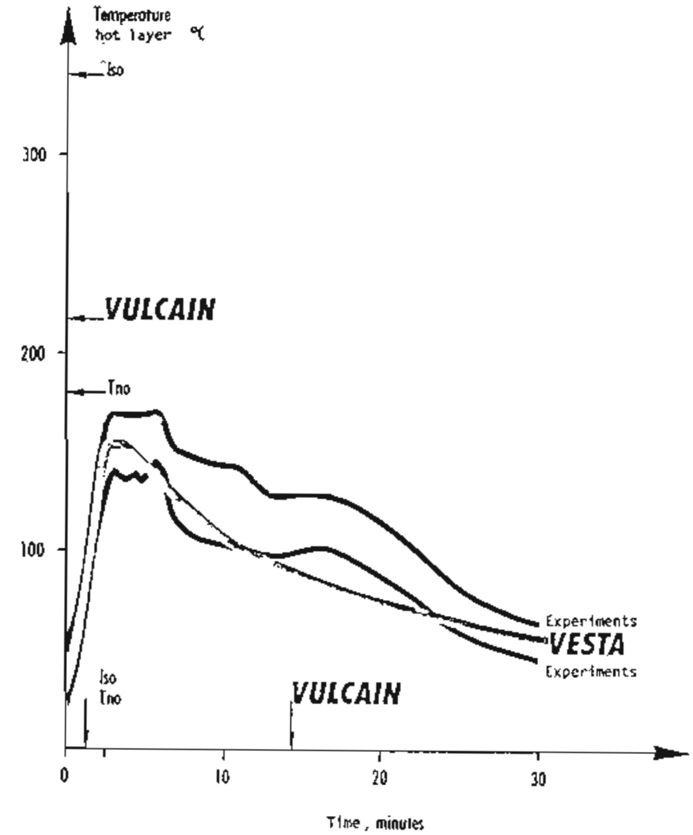


FIGURE 6 - OIL FIRE, CONTROLED VENTILATION (DCN)

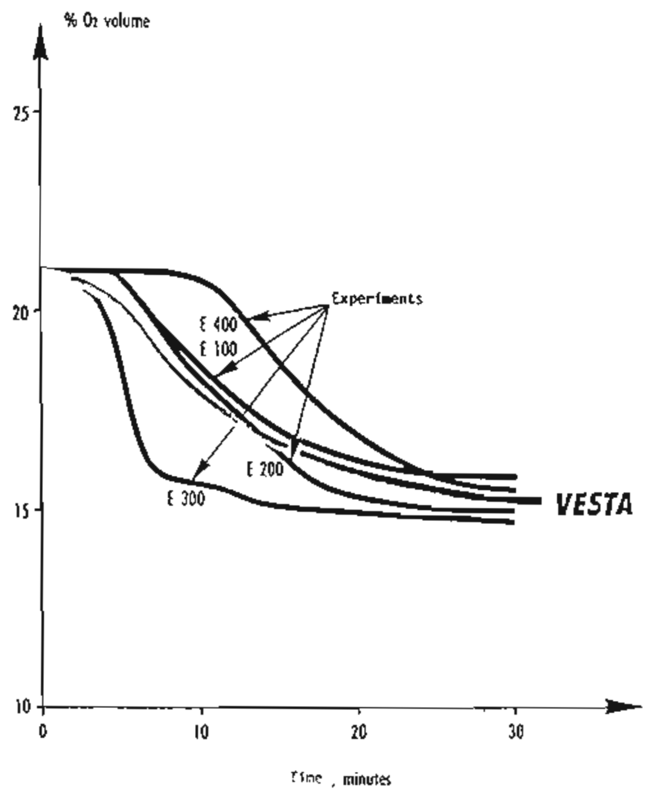


FIGURE 7 - OIL FIRE, CONTROLED VENTILATION (DCN)

HOT SURFACE IGNITION STUDIES OF AVIATION FLUIDS

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SUMMARY

Hot surface ignition temperature testing was performed in the Aircraft Engine Nacelle Fire Test Simulator (AENFTS) located at Wright-Patterson Air Force Base, Ohio. The objective of this test program was to measure Minimum Hot Surface Ignition Temperatures (MHSIT) of five common aircraft fluids (MIL-H-5606 and MIL-H-83282 hydraulic fluids, JP-4 and JP-8 fuels and MIL-L-7808 lubricating oil) using an air-heated bleed-air duct in a high realism test article.

A simulated portion of the F-16 engine compartment and F100 engine was inserted into the AENFTS and the five aircraft fluids were injected as spray or drips (streams) onto various locations on the hot bleed-air duct. Ventilation air pressure, temperature, velocity and the flammable fluid flow rate were varied to study their effect on the MHSIT of these fluids.

The results show that MHSIT is dependent on both fluid application mode, spray or drip, and application location. MHSIT increased for all test conditions as ventilation air pressure decreased. Increasing ventilation air temperature tended to decrease the MHSIT. Although MHSIT increased with ventilation air velocity increases, this is not a dependable safety criteria since stagnation regions are known to exist in engine compartments. In general, due to the high level of simulation achieved in this program and the wide scope of the test conditions, the results will be of significant value in the fire safety design of future aircraft systems.

INTRODUCTION

This paper describes tests performed to define the Minimum Hot Surface Ignition Temperature (MHSIT) for five fluids commonly found in an aircraft engine compartment, MIL-H-5606 and MIL-H-83282 hydraulic fluids, MIL-L-7808 lubricating oil and JP-4 and JP-8 fuels, when they were sprayed or dripped (streamed) onto a hot engine bleed air duct (1.5" O.D. Inconel tubing 0.035" thick). For simplicity, these fluids will henceforth be referred to as 5606, 83282, 7808, JP-4 and JP-8. These tests were performed to provide a better understanding of the mechanism and risk of hot surface ignition in an aircraft engine compartment and to improve the existing data base available to the aircraft designer.

The hot surface ignition tests were conducted with two test articles:

1. SIMPLE DUCT TEST - A short section of bleed duct mounted in an uncluttered test section, heated alternately by electrical resistance heaters and by hot high pressure air

2. HIGH REALISM TEST - A F100-PW-200 engine right-side bleed duct mounted in a test section cluttered by actual engine components and simulated F-16 aircraft structure.

The test facility employed, the Aircraft Engine Nacelle Fire Simulator (AENFTS), located at WPAFB, Ohio, is equipped so that the velocity, pressure and temperature of its simulating engine compartment ventilation air could be varied to represent a variety of aircraft flight conditions.

This paper will concentrate on presenting some of the test results, with little discussion of the test methodology, hardware and analysis of the results. A complete discussion of the program is contained in AFWAL-TR-88-2101, "Hot Surface Ignition Tests of Aircraft Fluids", published early in 1989 (Reference 1).

BACKGROUND

During the fire safety design of an aircraft engine compartment, it is necessary to define a surface temperature which is considered safe for the fluids and environmental conditions of interest. If this temperature is exceeded, then other fire protection measures may be required. The Auto-Ignition Temperature (AIT) as determined by method ASTM D 2155 is generally considered the lowest temperature at which fluid vapors will spontaneously ignite in air at atmospheric pressure with no external source of ignition. Some companies/designers reduce the AIT by 50°F to define a safe operating temperature. Some use the AIT value directly while others select a temperature up to 200°F greater than the AIT based on hot surface ignition testing under more realistic conditions than ASTM D 2155. A summary of the results of previous hot surface ignition studies (References 2 to 6) is given on Figure 1. The plotted temperatures should be reduced as noted for each study in order to estimate the temperature at which ignition would not occur. This is due to test methodology and measurement errors. A 5°F reduction in the ASTM D 2155 AIT value is acceptable due to the known precision of this test method.

Due to the wide range in safety criteria presently used, the current program was initiated to investigate realistic test conditions not previously possible in order to better select a safe design temperature without over-designing which could be an operational penalty or under-designing which could cause loss of an aircraft.

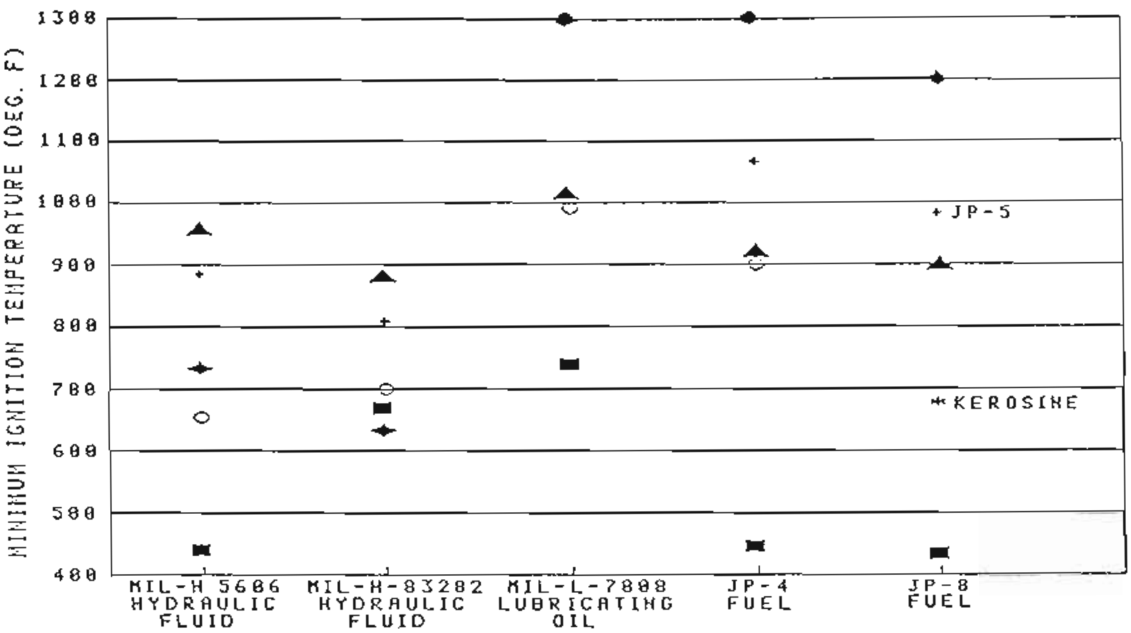

FIGURE 1. SUMMARY OF PREVIOUS HOT SURFACE IGNITION STUDIES
(Minimum reported ignition temperature at ambient pressure and temperature and flow between 0 and 3 ft./sec.)

ASTM-D-2155
* ROLLS-ROYCE (BEARDSLEY) (NO IGNITION TEMP. UP TO 100 DEG F LOWER)
\+ AFAPL-TR-79-2095 (MYROHUK) (NO IGNITION TEMP. UP TO 100 DEG F LOWER)
AFAPL-TR-79-2055 (PARTS) (NO IGNITION TEMP. UP TO 100 DEG F LOWER)
AFAPL-TR-71-86 (STRASSER) (NO IGNITION TEMP. UP TO 80 DEG F LOWER)
O AFAPL-TR-85-2060 (FOOSE) (NO IGNITION TEMP. UP TO 25 DEG F LOWER)

OBJECTIVE

The objective of the first part of the program, "THE SIMPLE DUCT TESTS", was to investigate the phenomenon of hot surface ignition of flammable fluids within an aircraft engine compartment with a test article that was simple enough to allow control of most of the test variables. This part of the program was planned to allow:

1. comparison to past data, especially the General Dynamics data (Appendix A of Reference 6).
2. determining the differences between an electrically heated duct and an air heated duct.
3. determining the differences between aircraft fluids
4. investigating the effect of clutter.
5. investigating the effect of duct orientation (horizontal or vertical).

The objective of the second part of the program, "THE HIGH REALISM TEST", was to determine the minimum hot surface ignition temperatures for each aircraft fluid of interest over a range of severe but realistic aircraft operating conditions. These tests were intended to provide design information, that had previously been unavailable concerning safe surface temperature limits within aircraft engine compartments, based on the actual aircraft fluids and the temperature, pressure and velocity of the compartment ventilation air flow.

The test fluids had the following properties: JP-4, 490°F AIT; JP-8, 475°F AIT and 118°F F.P.; 7808J, 725°F AIT and 460°F F.P.; 7808H, 715°F AIT and 450°F F.P.; 83282, 700°F AIT and 430°F F.P.; and 5606, 440°F AIT and 192°F F.P. (AIT per ASTM D 2155 and flash point per ASTM-D93 for JP-8 and 5606 and ASTM-D92 for 7808 and 83282.)

TEST FACILITY

The AENFTS is a ground test facility designed to simulate the fire hazards which exist in the annular compartment around an aircraft engine. The AENFTS is located at Wright-Patterson Air Force Base, Ohio. This facility (Fig. 2) includes air delivery and conditioning equipment designed to simulate engine compartment ventilation air flow, a test section within which fire testing can safely be conducted, and an exhaust system which can cool the combustion products and scrub them sufficiently to allow their release into the atmosphere. In addition, it includes a gas fired heating system to provide simulated engine bleed-air to the test section. Up to 1500°F and 220 PSIA could be provided at flow rates up to 1 pound per second at the exit of this heater.

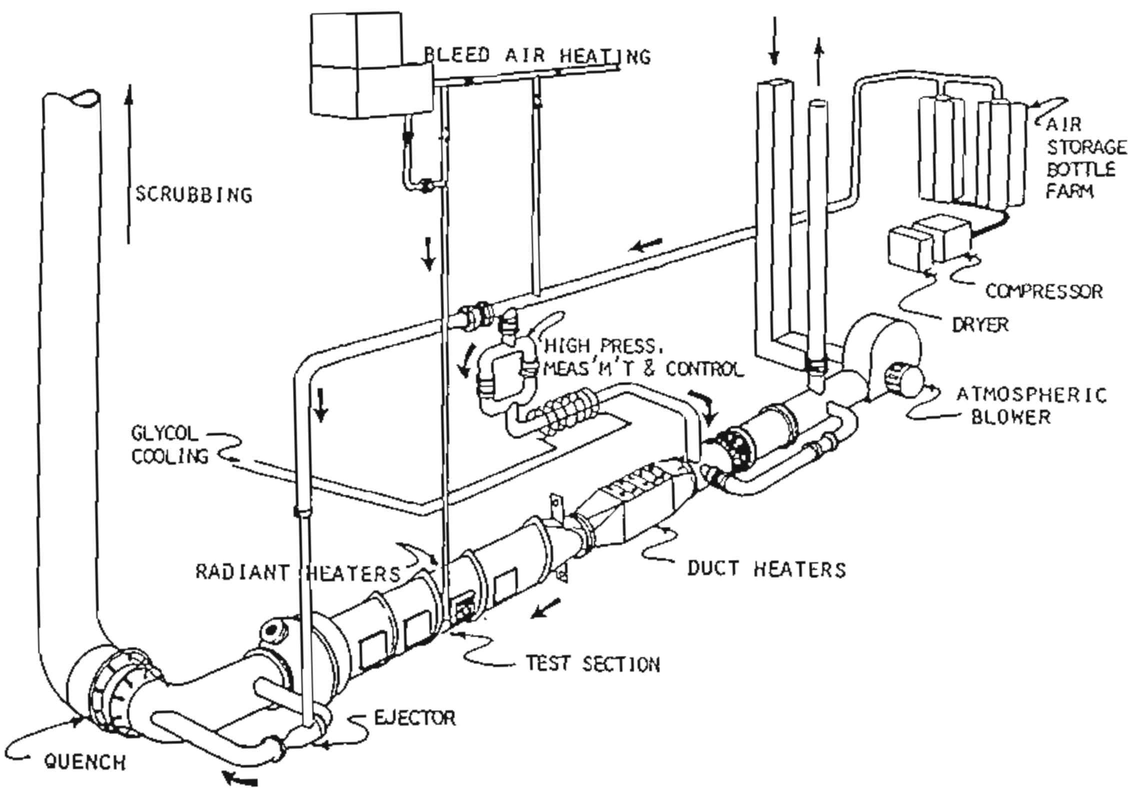

FIGURE 2. AENFTS FACILITY

The test section of the AENFTS is a two radian (114 degree) segment of the annulus between a 15-inch radius duct, which simulates an engine case, and a 24-inch radius duct, which simulates the engine compartment outer wall. The test section is approximately 14 feet long and is equipped with access ports and viewing windows that are provided for access to test equipment and instrumentation and for observation of the test activities taking place within the compartment. To simulate a more realistic environment, having the complexity of tubes, ribs, clamps, wires and other flow disturbances of a real aircraft engine compartment, a portion of the F-16 aircraft nacelle was simulated. Components from the forward right side of a F100 engine, as it exists in the portion of the F-16 engine compartment selected for simulation, were installed on a 5-foot long simulated engine side stainless steel base plate constructed to fit the engine side of the AENFTS test section (Fig.3). The final assembly represented one-third of the engine compartment annulus. The remaining AENFTS test section length, approximately 60 inches, simulated the less cluttered annulus around the afterburner.

The balance of the AENFTS facility included 8800 pounds of air stored at 2000 psi to allow high pressure testing, simulating ram air at high speed and low altitude and to drive an ejector for low pressure testing, simulating high altitude flight. Five hundred kilowatts of electrical power was available to heat the nacelle ventilation air and, although not used in this program, a 21-ton refrigeration system at -50°F was available to cool the ventilation air.

Up to 11 pounds per second of ventilation air was available from a blower at atmospheric conditions. Additional details of the AENFTS may be found in Reference 7.

Both "THE SIMPLE DUCT TESTS" and "THE HIGH REALISM TESTS" used the AENFTS facility and both had similar heated bleed air ducts. Only "THE HIGH REALISM TESTS" contained the clutter associated with the F-16.

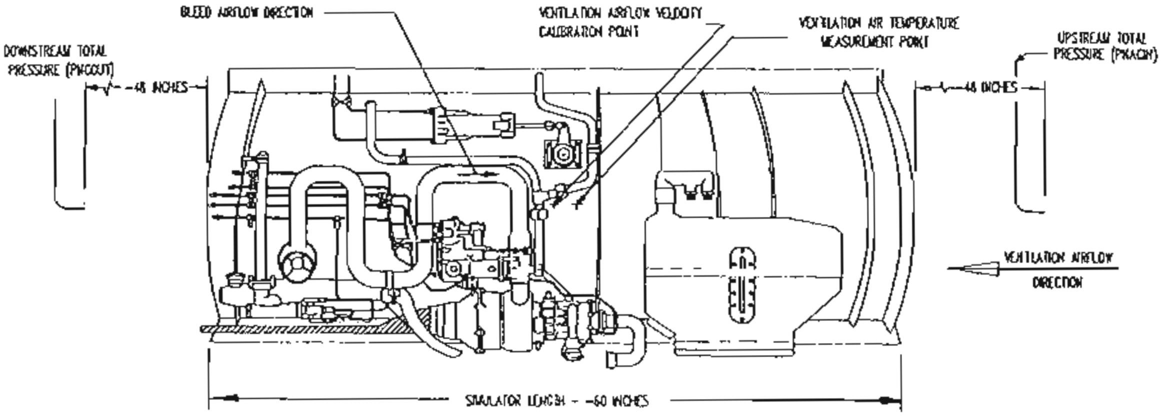

FIGURE 3. HIGH REALISM TEST ARTICLE

TEST PROCEDURE

In this test program, the bleed air duct temperature was started from a high value where fluid ignition was insured. The duct temperature was then reduced by 50°F and the fluid was reinjected with all other variables such as ventilation velocity, fluid flow rate, etc., held constant. The optimum amount of test fluid to be injected had previously been determined. This process was repeated until ignition did not occur. Two additional injections were then performed at that duct temperature. When a bleed duct temperature was reached where no ignitions occurred in three attempts, testing at those ventilation air conditions and test fluid conditions was ceased. The minimum hot surface ignition temperature (MHSIT) was defined to be the lowest bleed duct temperature that produced ignition and was approximately 50°F above the temperature where three tests without ignition had occurred. For example, at location DL2 on Figure 4 the MHSIT was approximately 940°F for a 5606 drip of 2 milliliters per second. MHSIT data for the five test fluids was obtained in this way throughout the test program. There was the potential for a 25°F error in the temperature measurement, therefore, a conservative value for the "no ignition temperature" would be about 75°F below the MHSIT.

During the initial phase of the high realism test program, six locations on the bleed air duct were investigated individually to determine the MHSIT for a fluid drip. (NOTE: Drip and stream are used interchangeably in this paper.) These locations are noted as DL1 through DL6 on Figure 4. Also two fluid spray locations were investigated. Location SFD was downstream of the bleed air duct and SFU was upstream of the duct. On Figure 4, the 1 FPS denotes a ventilation air velocity of one foot per second, the 2ML/S drip is 2 milliliters per second fluid drip for locations DL1 through DL6 and the 8 ML/S spray is 8 milliliters per second fluid spray at locations SFD or SFU. After an understanding of which locations resulted in the lowest value of MHSIT was reached, only these locations were investigated in later phases of the program as other parameters were varied.

TEST RESULTS

1. SIMPLE DUCT TEST RESULTS

a. For most of the test conditions, the duct with a cushion loop clamp generated lower MHSITs than the bare duct (without clamp).

b. Method of duct heating is important. Lower MHSITs were generally measured with the air-heated duct than with the electrically resistance heated duct. This was probably mostly due to the higher heating rate available with the air-heated duct.

c. Lower MHSITs were noted when the duct was mounted horizontally and normal to the air flow compared to when the duct was vertical and normal to the air flow.

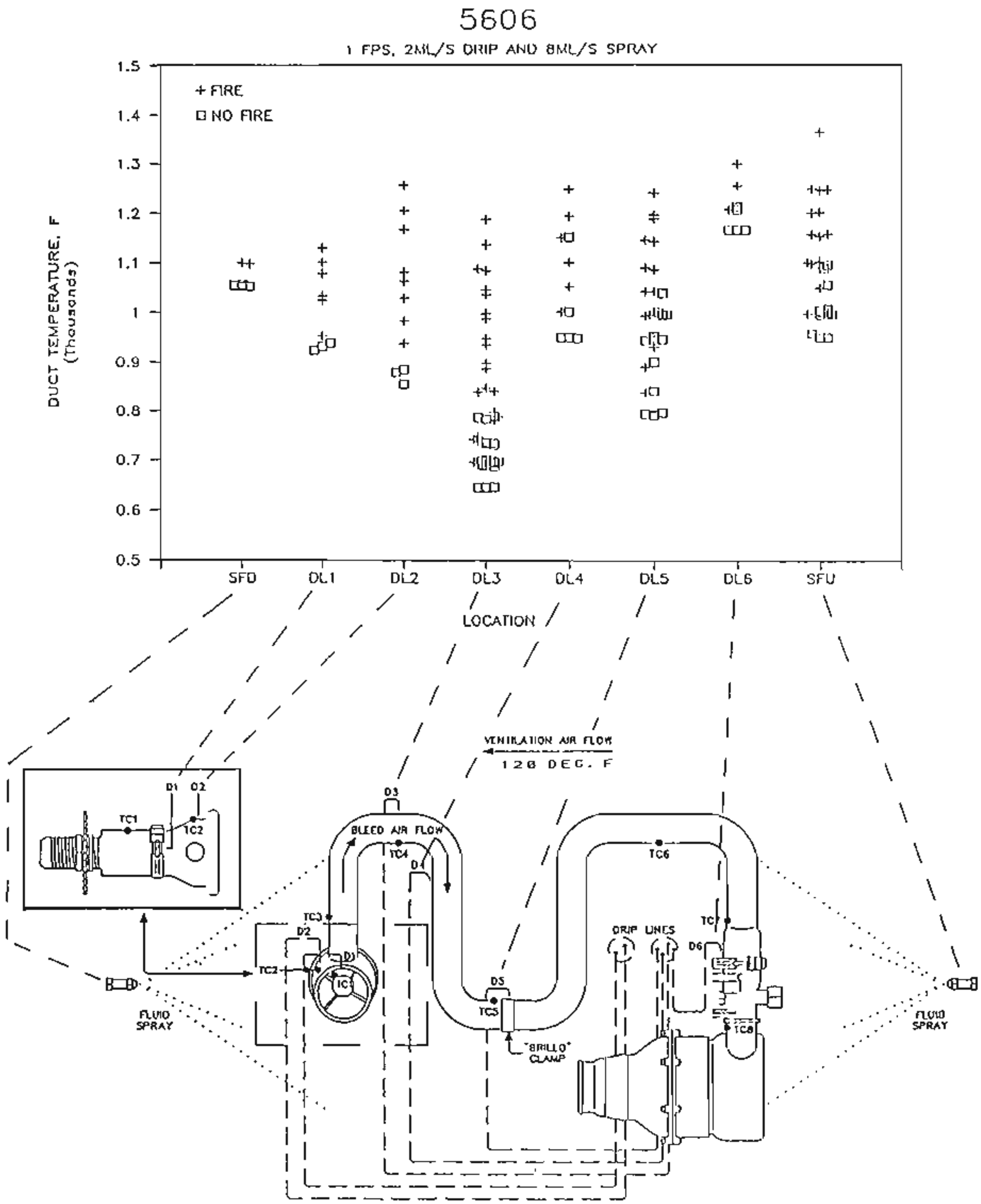

FIGURE 4. HIGH REALISM TEST INJECTION LOCATIONS

The "SIMPLE DUCT TEST" results are presented on Table 1. The General Dynamics data ((Reference 6) shown on Table 1 was increased by 50°F to allow comparison with the present data. The General Dynamic reported temperatures were the highest value for no ignition whereas the present program reported the lowest temperature value that resulted in ignition.

TABLE 1. SUMMARY OF RESULTS FOR THE SIMPLE DUCT TESTS

FLUIDS SPRAYED FROM UPSTREAM -- AENFTS HORIZONTAL EXCEPT AS NOTED (AIR AT 14.4 PSIA & 120 DEG. F)						
* NO TEST	VENTILATION AIRFLOW VELOCITY (FT/SEC) 0	1	2	4	6	8
5606 - SIMPLE DUCT						
AIR HEATED SIMPLE DUCT	*	1300	1200	1300	>1350	>1350
AIR HEATED SIMPLE DUCT (AENFTS VERTICAL)	*	>1350	>1350	>1350	*	*
RESISTANCE HEATED SIMPLE DUCT	*	1150	1170	1360	1510	1550
G. D. (RES. HTD. BARE DUCT)	1160	1060	1260	1360	1470	1400
5606 - DUCT WITH CUSHION CLAMP						
AIR HEATED DUCT WITH CLAMP	*	1100	1100	1150	1200	1300
RESISTANCE HEATED DUCT W/CLAMP	*	1150	1170	1190	1320	1380
G. D. (RES. HTD. DUCT W/ CLAMP)	1190	1100	1070	1370	1470	*
JP-4 SIMPLE DUCT						
AIR HEATED SIMPLE DUCT	*	>1350	>1350	>1350	>1350	>1350
RESISTANCE HEATED SIMPLE DUCT	*	1370	1370	1500	1520	1540
G. D. (RES. HTD. BARE DUCT)	1390	*	1370	1380	1380	1390
JP-4 DUCT WITH CUSHION CLAMP						
AIR HEATED DUCT WITH CLAMP	*	1250	1250	1350	*	1340
RESISTANCE HEATED DUCT W/CLAMP	*	1360	1430	1510	1520	1540
G. D. (RES. HTD. DUCT W/ CLAMP)	1370	*	1360	1430	*	*

2. HIGH REALISM TEST RESULTS

a. Table 2 presents the effect of ventilation air velocity on MHSIT for the test fluids under several fluid injection conditions. The drip locations shown had previously been determined to represent worst case locations. Caution is necessary if these test results are to be applied to an aircraft design problem. While the effect of increasing the velocity was, as anticipated, to generally increase the MHSIT's, these velocities were measured in a single location within the test article. In an aircraft engine compartment, there are also regions of higher velocity and regions of stagnation. Unless the designer is confident of uniform air flow, the minimum MHSIT's found in these tests should be applied with the understanding that low local velocities may well exist in the vicinity of an aircraft bleed duct or other hot surfaces.

b. Table 3 shows that as ventilation air pressure increases, the MHSIT decreases for all conditions evaluated except for JP-8 at 14.9 psia and 20 psia and this exception was within experimental error.

c. Table 4 gives the effect of increasing ventilation air temperature on MHSIT.

For the above tables, the MHSIT's measurements uncertainty is approximately +25°F and -75°F. The >1350 denotes no ignition up to the 1350°F maximum temperature due to facility limitations with the air heated bleed duct.

<u>DISCUSSION OF TEST RESULTS</u>

1. The injection location was found to strongly affect the MHSITs in the "HIGH REALISM TESTS". A variety of factors, including the local ventilation air velocity and temperature and the heat transfer coefficients of the particular fluid contact site on the duct, affected what MHSIT was determined for the fluid. It was found that a stream (drip) onto a horizontal bare section (DL3 of Fig. 4) of the duct ignited 5606, 83282 and 7808 at the lowest temperatures. It was found that a stream onto a horizontal section of the duct where a clamp was located (DL5 of Fig. 4) ignited JP-4 and JP-8 at the lowest temperatures. (Note: The AENFTS test section was mounted in the vertical position.) It was also found that spray from downstream also ignited 83282 at a relatively low temperature. For the range of spray and stream flow rate that were investigated, little effect of injection flow rate or duration was observed.

2. The MHSITs of all five test fluids, both spray and stream, increased dramatically as ventilation air pressure was lowered. Hence, MHSITs are significantly increased for aircraft at altitude.

3. The MHSITs of all five fluids generally decreased as the ventilation air temperature was increased. The MHSIT of 7808, however, was affected only slightly. With an air temperature of 600°F, the MHSIT of 83282 (spray and stream) was below the fluid's AIT (700°F per ASTM D 2155).

TABLE 2. SUMMARY OF THE EFFECTS OF AIR VELOCITY ON MHSIT

		VENTILATION AIRFLOW VELOCITY (FT/SEC) (14.4 PSIA & 120 DEG. F)						
		0	1	2	4	6	8	11
DRIP INJECTION LOCATION	FLUID							
DL3	5606	*	700	740	840	990	1040	1140
DL3	83282	800	790	840	800	840	850	1100
DL3	7808	*	990	990	1090	1090	1130	1230
DL5	JP-4	1250	1200	1200	1250	1260	1210	1320
DL5	JP-8	1160	1150	1150	1200	1250	1260	1220
SPRAY FROM UPSTREAM	5606	1050	1000	1210	1100	1200	1250	*
SPRAY FROM DOWNSTREAM	5606	*	1100	750	*	*	*	1300
	83282	750	800	800	750	800	1010	1220
	7808	*	1100	1060	*	*	*	1270
	JP-4	*	1150	1160	*	*	*	1330
	JP-8	*	1150	1100	*	*	*	1290

* NO TEST

TABLE 3. SUMMARY OF EFFECT OF AIR PRESSURE ON MHSIT

		ALTITUDE SIMULATION (2 FT/SEC & 120 DEG. F)			RAM SIMULATION (11FT/SEC & 120 DEG. F)	
PRESSURE (PSIA)		5	10	14.4	14.4	20
DRIP INJECTION LOCATION	FLUID					
DL3	5606	1320	1100	740	1140	1000
DL3	83282	1350	1150	840	1100	840
DL3	7808	>1350	1340	990	1230	1140
DL5	JP-4	>1350	1210	1200	1320	1240
DL5	JP-8	>1350	>1350	1150	1220	1240
SPRAY FROM DOWNSTREAM	5606	>1350	>1350	750	1300	1200
	83282	>1350	>1350	800	1220	820
	7808	>1350	>1350	1060	1270	1190
	JP-4	>1350	>1350	1160	1330	1240
	JP-8	>1350	>1350	1100	1290	1250
SPRAY FROM UPSTREAM	5606	*	*	1210	*	*

* NO TEST

TABLE 4. SUMMARY OF THE EFFECT OF AIR TEMPERATURE ON MHSIT

		VENTILATION AIRFLOW TEMPERATURE (DEG. F) (14.4 PSIA & 2 FT/SEC)		
		120	300	600
DRIP INJECTION LOCATION	FLUID			
DL3	5606	740	640	600
DL3	83282	840	750	600
DL3	7808	990	1040	850
DL5	JP-4	1100	1210	1100
DL5	JP-8	1130	940	1040
SPRAY FROM DOWNSTREAM	5606	750	700	600
	83282	800	650	*
	7808	1060	1060	950
	JP-4	1160	1050	750
	JP-8	1100	950	600

* 83282 WOULD IGNITE WITH AIR TEMPERATURE AT 600 DEG. F EVEN WITHOUT DUCT HEATING

SUMMARY OF HIGH REALISM TEST RESULTS

4. For all fluids, the MHSIT for both spray and stream was higher at a velocity of 8 ft/sec than at a velocity of 1 ft/sec. The MHSITs of JP-4 and JP-8 (spray and stream) were affected only slightly by velocity, however.

5. The effect of ventilation air temperature on the MHSIT of JP-4 and JP-8 was different for spray and stream fluid introduction. High ventilation air temperatures dramatically decreased the MHSIT of JP-4 and JP-8 spray while affecting the MHSITs for stream introduction only slightly. This was probably because the spray droplets were preheated in heated air before they made contact with the hot duct while the fluid stream had less time for preheating before it struck the hot surface.

6. In general, the hydraulic fluids, 5606 and 83282, tended to ignite at lower MSHITs than the JP-4 and JP-8 fuels. Lubricant 7808 was somewhere in between for the majority of the test conditions.

7. Both fluid injection modes, spray and stream, are important in determining the lowest MHSIT depending on test conditions and type of fluid.

8. The "HIGH REALISM TESTS" with their associated clutter gave lower values of MHSITs than the "SIMPLE DUCT TESTS". This difference may have even been greater if the AENFTS test section had been horizontal for the "HIGH REALISM TESTS".

9. The actual MHSITs may be up to 75°F lower then the values generated in this study due to measurement uncertainties. The MHSITs, based on the "SIMPLE DUCT TEST" results, could have been even lower if the AENFTS test section was mounted horizontally.

10. In reference to Figure 1, the results of this program would plot as follows: 5606--700°F, 83282--750°F, 7808--990°F, JP-4--1150°F, JP-8--1100°F. The no ignition temperature could be up to 75°F lower due to test methodology and measurement errors. Figure 1 together with the present results demonstrate the dependency of MHSIT on test hardware and test procedures.

11. Many of the MHSIT values generated in this program may have been lower if the heated test section was mounted horizontally, if the test section was larger in heated area, and if the initial temperature of the test fluid have been higher. (Note: In this test program the fluid injection temperature was near ambient. In current engine compartments the fluids of interest may be as high as 325°F for the fuels, 275°F for the hydraulic fluids and 350°F for the lubricants.)

12. To determine the maximum safe design temperature, the highest operational compartment temperature and pressure should first be established. At these conditions, the lowest MHSIT, independent of ventilation air flow but at least zero ft/sec, should be noted for each fluid of interest and both injection modes (spray and stream). All relevant hot surface ignition information should be considered. The lowest value of MHSIT resulting from the above procedure should then be reduced by at least 150°F to arrive at the maximum safe design temperature. Elevated fluid temperatures and large hot surfaces (engine case) were not considered in the above suggested reduction of at least 150°F.)

CONCLUSIONS

The results of the present study add significantly to the data base available on hot surface ignition temperature particularly for aircraft engine compartment design. The most important features of the new data are:

1. their collection on a simulated portion of an F-16 nacelle using real components and system configuration.
2. a systematic variation of ventilation air pressure, temperature and velocity covering a range of realistic conditions simulating aircraft operation under various ram air and altitude conditions.
3. use of the five flammable fluids of most interest in aircraft applications injected as sprays or streams and determination of their relative flammability under identical test conditions.
4. ignitions of 83282 at temperatures below its AIT per ASTM D 2155.

RECOMMENDATIONS

The results of this program together with other pertinent hot surface ignition studies, including additional testing as necessary, should be reviewed with the objective of developing an universally accepted criteria for establishing safe operating temperatures for a wide range of aircraft applications.

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THE STABILITY OF FUEL FIRES

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SUMMARY

The mechanisms of ignition, stabilisation and propagation of aviation turbine fuel fires are examined and discussed in the context of aircraft accidents. This appraisal suggests that the crucial role of a suitably sized aerodynamic stability zone in the stabilisation of fuel spray fires has not been adequately recognised in the past. It also suggests that the importance of hot surfaces as sources of fuel preparation and ignition has, similarly, been neglected. From considerations of the buoyancy and radiative characteristics of even moderately sized pool fires it is concluded that great care is required in the interpretation of results from smaller experimental fires.

1. INTRODUCTION

Fire is the major cause of fatalities in otherwise survivable aircraft accidents. Because of this an understanding of the causes and spread of fire is of considerable importance. Most research into the nature of combustion has been conducted using laboratory scale experiments and it is necessary to examine to what extent such data are valid when applied to aircraft fires.

The areas of primary concern in predicting fire behaviour are fuel preparation, ignition, flame propagation and stabilisation. These are, of course, strongly inter-related and the boundaries between them can be quite blurred.

The fuel preparation process involves the evaporation or atomisation of the fuel in order to generate either an air-vapour mixture having a fuel/air ratio within the flammable range or sufficiently small droplets that they can be ignited by the ignition source.

There are only two essential requirements for ignition. The first is that the energy which is applied to the system must be sufficient to generate a temperature at which exothermic chemical reactions begin. The second is that the heat generated by these reactions after the initial ignition energy has dissipated must exceed the heat losses from the system.

The velocity at which a flame can propagate into a turbulent stream of kerosine vapour or droplets in air at standard temperature and pressure is only about 1 metre/sec. If the flow velocity over an ignition source is less than this then the flame will propagate upstream into the approaching mixture until either the fuel/air source is reached or until the velocity or fuel preparation or some other factor becomes unfavourable. If the flow velocity exceeds the burning velocity then the flame will be swept downstream and ultimately extinguished.

For the flame to become stabilised ie. fixed in space relative to some structure such as the ground or a moving aircraft, there must be a continuous supply of prepared fuel and an ignition source at the origin of the flame. The ignition source could be a continuation of the original ignition process - such as a prolonged electrical discharge, but it is more likely to be feedback from the flame itself by the physical recirculation of hot combustion products in the wake behind a bluff body.

Each of these stages of the combustion process, as they apply to aircraft fires, will be discussed in this paper. As will be shown, behaviour in practical circumstances may be quite different to that observed under laboratory conditions and may often cause a serious underestimate of the threat.

2. FUEL PREPARATION

Fuel can be prepared for ignition in only two principal ways. It may be vaporised, either by contact with a hot surface or hot gas or by an input of thermal radiation. Alternatively it may be atomised, either by a high velocity airstream or by being projected at high velocity into a slower moving airstream.

The droplet sizes produced by substantial fuel leaks from moving aircraft can be estimated using relationships devised to predict the atomisation of liquid fuel in high velocity airstreams. In practice it is much more likely that the bulk of the fuel would be spilled from a relatively fast moving aircraft into stationary air. In this case the atomisation takes place when the relative velocities of fuel and air are high and atomisation ceases when the fuel has been brought to rest by drag. In contrast both in the predictive equations and in most simulations, the injection of fuel into a fast moving airstream creates additional atomisation as a result of turbulence within the air jets and the mixing of the air jet itself with the stationary environment. In the aircraft situation much higher local fuel concentrations will occur and larger droplet sizes will be produced than those produced in simulation or predicted from airspray atomiser theory.

Assuming that the aircraft is moving at 80 m/s, atomisation theory predicts that a Sauter mean droplet diameter (SMD) of about 60 microns would be produced. When the aircraft speed drops to 20 m/s this would increase to about 180 microns. Since the terminal velocities of these sprays are 0.1 m/s and 1.0 m/s respectively it is clear that sedimentation losses will produce large differences in flammable 'lifetimes'. As will be discussed in the next section, although combustion of the larger droplets would not often present a problem, ignition by any means becomes increasingly difficult. As the aircraft velocity decreases, two particularly threatening modes of fuel preparation become important. One is the possibility of disruption of the high pressure fuel system on an engine, together with severe mechanical damage to the engine itself. Although the quantity of fuel which may be liberated may be relatively small it is likely to be well atomised, either because of its own high pressure source or because of association with high energy air from a disrupted engine. The proximity of this fuel to a variety of ignition sources presents a severe threat. The second possibility is that large quantities of vaporised fuel can be produced from hot surfaces such as engines and aircraft brakes.

3. IGNITION SOURCES

Sparks

Rao and Lefebvre (Ref 1) have investigated the spark ignition characteristics of flowing kerosine spray/air mixtures. Their data are shown in Fig.1. Because their primary interest was in combustion systems their data do not extend either to sufficiently high air velocities or droplet sizes for present purposes. Nevertheless for the coarsest spray which they used (85 microns SMD) and for the highest velocity (49.5 m/s), values which approximately represent a fast moving aircraft, the range of fuel/air ratios over which ignition is possible is clearly very narrow. Similarly the ignition range even for the lowest velocity (19 m/s) and the 85 microns SMD fuel spray is again very narrow, Fig.2. It is considered, therefore, that the risk of ignition from sparks, is low under either of these circumstances.

Ignition of vapour clouds or well atomised fuel by means of sparks in the vicinity of stationary aircraft poses a substantial threat both because the spark energy required may only be a few milli-Joules and because a large but localised mass of airborne fuel may be available.

Hot air

The spontaneous ignition of fuel in hot air streams has been explored in detail by several workers because of its importance to air breathing engine technology. References 2,3,4,5 are typical of this work.

Figure 3 which is taken from the work of Spadaccini and TeVelde, (Ref 4), shows collected data from a number of sources. One of the principal features of this mode of ignition is the characteristic ignition delay time which varies widely as a function of air temperature (and pressure). Sources of high velocity, hot air, such as the engine exhaust or air escaping from a disrupted engine pressure casing, have a considerable potential for atomising and vaporising fuel and raising the mixture to a temperature where it will spontaneously ignite. For example the injection of stoichiometric quantities of fuel into stationary air at 880K would produce a fuel/air mixture at about 810K in which the ignition delay time would be 100 milli-secs. However for a sonic velocity jet, which would be typical of engine exhausts or damaged engine pressure casings, the ignition would occur about 60 metres downstream of the point of fuel injection. Even at this point ignition is by no means certain because the jet would be heavily diluted and cooled by entrainment of ambient air. As with spark ignited combustion the greatest threat is brought about if the air jet/fuel mixture is slowed down so that when the ignition delay time has been reached the ignition still occurs close to the aircraft.

Hot surfaces

The minimum spontaneous ignition temperatures of most fuels are determined by injecting small quantities of fuel into a hot crucible. Importantly, there is a time lag of several tens of seconds between injection and ignition at this minimum temperature. This ignition lag is only rarely described and coverage of this subject is not extensive. Data from Ref.6 for gasoline is shown in Fig.4. Since it is clear that any fuel introduced into the crucible will quickly evaporate it would seem likely that this test should produce very much the same ignition delay characteristic as the experiment where fuel is injected into hot air. The crucible test does however allow the estimate of very long ignition lags which would not be possible in a flowing gas stream. With this in mind the data from Fig.3 has also been plotted on Fig.4. Although the range of air temperatures in the two experiments do not quite overlap it seems reasonable to assume, as a working hypothesis, that the ignition characteristics of hot surfaces and hot gases are identical for practical purposes.

It seems difficult to understate the threat posed by hot surfaces as ignition sources. Engines and aircraft brakes, for example, provide considerable masses of hot material which are likely to come into contact with fuel during an accident. Turbine disks can be expected both to vaporise and ignite fuel up to half an hour after the engine has stopped running. It is significant to note that only 10 kg of nickel alloy (or graphite) at 600°C will vaporise and ignite about 5 kg of fuel. The consequences of a fireball containing this much fuel will be discussed in Section 6.

The principal threat from hot surface ignition comes about when the aircraft is slow moving or stationary so that flame stabilisation is unnecessary, and when large masses of flammable vapour can accumulate. Several, well documented examples of fires started by hot surfaces are available. The fire that occurred in the Controlled Impact Demonstration, which was organised in 1984 under the auspices of the United States Department of Transport and NASA, in which antimisting fuel was evaluated, was started by a hot surface/hot gas ignition on a massively disrupted engine. A fire in an engine test cell which was analysed by the author was similarly started by a hot, broken drive shaft. The fire in the British Airtours accident at Manchester in 1985 was started by fuel from a holed fuel tank coming into contact with a badly disrupted engine.

Flames

Flames themselves tend to be very effective sources of ignition for several reasons. In the first place even small flames present orders of magnitude more energy than the minimum required for ignition under ideal circumstances. For example even a modest 250mm high flame on a 25mm wide wick produces about 750 watts. In the second place the flame is a ready source of active chemical species, such as radicals, which are essential to the chain branching reactions of the combustion process. Clearly however, criteria such as low velocity and low turbulence level have to be met both for the pilot flame itself to survive and for the ignition to succeed.

Radiation

The potential for moderate and large fires, particularly pool fires, to start secondary fires, at a distance, by radiative heat transfer alone deserves serious attention. For example an eye witness at Lockerbie reported seeing splashes of fuel falling from the sky onto house roofs some distance from the main fire and catching fire there. Hardee et al, (Ref 7), summarise much of what is known about radiation from LPG fires and about the growth and lifetime of fireballs. These data confirm the seriousness of radiative heat transfer as an ignition mechanism. For example, Fig.6, shows estimates of the radiative output from a range of diameters of pool fire. The scale of the fire profoundly affects its flame temperature, emissivity and for geometric reasons its optical properties. For a target surface far from the fire, the fire appears to be a small optical source and the radiation received at the surface varies as the inverse square of the distance from the fire. As the distance from the target surface to the fire decreases the view is increasingly of an extended area many times larger than the target. In the limit the radiant energy received is the same as that leaving the flame.

Exploratory experiments and calculations illustrate the ease with which roofing slates and cement mortar can be heated by radiant heat transfer to temperatures suitable for the ignition of fuel or other organic debris. By way of example, a radiation flux of 120 kW/m^2 would raise the surface temperature of both slate and cement to more than 700°C in just less than a minute (see Fig.5). According to Hardee a radiation load of about 110 kJ/m^2 (over only a few seconds) will start grass/paper/fabric fires and produces third degree burns.

The heating of pools of kerosine on concrete surfaces by thermal radiation appears to be approximately 90% efficient. This is because while the concrete intercepts most of radiation not absorbed by the fuel the concrete is a poor conductor of heat and the incident energy almost entirely ends up in the fuel. As an example, a 7mm deep pool of kerosine would be heated to its boiling point in about 15 seconds by a radiative flux of 130 kW/m^2. The generation of hot fuel and fuel vapour and local surface temperatures sufficient to produce ignition is therefore a substantial threat which is strongly influenced by the scale of the fire.

Ingestion in engines

An engine can normally be expected to be tolerant to ingested fuel in modest quantities, comparable to the engine fuelling rate, provided that the fuel flow into the engine increases slowly. Most engine fuel control systems would respond to the increased fuelling rate by turning down the engine fuel to compensate. In the cases of heavy overfuelling by ingestion or step changes in fuelling an engine surge will normally be provoked. During a heavy surge large fireballs may appear both in the engine exhaust and out of the engine intake. These fireballs may act as ignition sources to produce a much larger fire around the engine. The probability of ignition under these circumstances is very high, and is a particular threat with rear mounted engines where there is a greater likelihood of spilled fuel being ingested.

4. PROPAGATION

It has been noted that the velocity at which combustion can propagate into a flow of fuel and air at normal temperature and pressure is only about 1 m/s. However it does not follow that combustion will cease if the velocity exceeds this value. Particularly in a turbulent jet flow the ignition source may, intermittently, ignite part of the mixture and flame can propagate across the flow to produce a series of fireballs. These fireballs will be convected away, downstream from the ignition source as they grow. If the turbulence level in the jet is very high or the scale of the experiment is small and the size to which the fireballs can grow is limited the fireballs will become diluted and dissipated and finally become extinguished. This mechanism was used by References 8 and 9 as a test of the effectiveness of anti-misting fuels. In these experiments a small wing or other obstacle was mounted in the efflux of a small high velocity air jet. Fuel could be injected into this airflow through a simulated leak in the wing and a propane torch flame was located close to the wing as an ignition source. Success or failure of the test fuel was judged by the readiness of the fuel to ignite and stabilise on the obstacle or by the rate of growth of fireballs convecting downstream.

It is important to recognise the differences between what was observed in these experiments and what would happen in the case of an aircraft crash. In the first place, in the experiment, the jet velocity continually decreases through momentum exchange with the surrounding atmosphere and the contents of the jet are progressively mixed and dispersed into the environment. If the velocity or turbulence in the jet is high enough even a stabilised flame cannot survive and the flame kernels produced at the ignition source progressively reduce in size and are finally extinguished. In contrast, in a crash situation the aircraft is moving through a more or less quiescent environment. In this case airborne concentrations of fuel droplets or fireballs rapidly come to rest in an environment which is only turbulent by virtue of the aircraft wake. Hence mixing and dilution are relatively slow and the extinction of a fireball is very improbable. The time which a fuel droplet cloud can stay in contact with a stationary ignition source is therefore high and the radiative heat transfer from a fireball to a particular area will also be high. In addition because of the larger scale the extent of the heat losses from the fireballs is much reduced. The probability of continuing combustion is, therefore, significantly higher.

The burning velocity even of stoichiometric mixtures is strongly sensitive to temperature. Estimates of sensitivity have been made which vary from about $T^{1.5}$ to T^2. This feature of burning velocity is of considerable importance in situations where there is appreciable preheating of the reactants either by recirculation, or from the flame originating on a hot surface, or through radiative heating.

Significantly, radiation from full sized fires can also produce more fuel evaporation than is needed to sustain the fire and thus contributes substantially to its stabilisation and propagation. In the case of the pool fire, radiation is, of course, the main contributor both to the stability and to the spread. In this case the fire propagates across the pool because flame speed is higher than the buoyant convective velocity of the fire column down near the surface of the pool. As an example, while a 160mm wide pool fire, (Ref 8), spread at between 20 and 35mm/s, it could be anticipated that a fully developed fire 3 or more metres diameter would spread at up to 3 m/s.

The thermal radiation emitted by pool fires is very often poorly modelled in small scale experiments and its contribution to the stability of recirculation stabilised flames is usually ignored.

5. STABILISATION

As noted in the introduction, even if ignition is achieved the resulting fireball would be left behind in the wake of the aircraft at all but the lowest speeds unless the flame became stabilised in the slow moving wake behind an aerodynamic obstruction.

The aerodynamic attachment of the fire to the aircraft structure represents one of the most efficient ways in which any ignition event can proceed to produce a stabilised fire. It is therefore a very serious threat. Firstly it allows a well developed fire to follow a moving aircraft. Secondly it allows well aerated, turbulent fires, which generate intense convective and radiative heat transfer, to attach to the aircraft structure.

An aerodynamic flame stabiliser consists of no more than an obstruction of some sort placed in an airflow so that the airflow is diverted around it leaving a slow moving, recirculating wake behind the obstacle. If the residence time of fuel and air in the recirculation is more than a few tens of milliseconds, combustion reactions can proceed to completion, filling the wake with flame temperature combustion products which then act as a massive flame ignition source for fuel and air passing by the stabiliser.

It can be shown that only about 4% of the airflow which is deflected around an obstacle finds its way into the recirculation zone. Because the recirculation zone is well stirred, freshly entering material is thoroughly mixed with the existing contents at all times and the dilution of original contents of fresh material follows an exponential relationship. Figure 6 shows a typical concentration decay characteristic measured behind a stabiliser which shows the expected exponential form. The cyclic fluctuations superimposed on the characteristic are a result of eddies being shed from the stabiliser at the characteristic Strouhal frequency; these eddies are the principal method by which fluid is introduced into and removed from the recirculation. It is clear from this characteristic that the long residence time within the recirculation offers both the combustion reaction time which is needed and provides a buffer with which the system can even survive short term interruptions to the fuel supply. Since about 4% of the fuel/air mixture which was deflected around the obstacle finds its way into the recirculation it follows that an equal mass of gas at flame temperature must leave the recirculation. Behind even a modest stabiliser this outflow at flame temperature represents a massive ignition energy source. Just as importantly the entire fire may be stabilised behind a large stabiliser such as a fuselage.

The obstacle does not even have to be a solid one; for example a sheet of air deflected off a surface or a jet from a thrust reverser which penetrates into the air-stream could act as an efficient stabiliser, (Ref 10). In practice solid surfaces such as flaps, spoilers, engine mountings, undercarriage, thrust reverser buckets and in the extreme the entire aircraft fuselage are all capable of acting as highly effective stabilisers.

Because flame stabilisers are essential to the operation of gas turbine combustors, reheat systems and furnaces etc the characteristics of their performance are well known. As with ignition the basic requirement is that the rate of heat release in the recirculation zone must at least equal the rate of heat loss. The objective of most correlations is to relate the ability of a particular stabiliser geometry to maintain combustion, to various conditions such as fuel/air ratio, stabiliser size, pressure, temperature and, of course, flow velocity. Generally the data are correlated in terms of a stability parameter 'S' and the overall fuel/air ratio. Figure 7 shows a typical stability loop.

Here the stability parameter $S = V \times 1000/D^{.85} \times P^{.95} \times T^{1.2}$ where P = atmospheric pressure, T = temperature of the air/fuel flow approaching the flame holder, D = flameholder hydraulic width and V = the flow velocity approaching the flame-holder.

It can be seen, for example, that the stability parameter for a modest 1 metre wide flameholder in a 50 m/s airstream indicates that it will have stable flame holding capacity over nearly the entire flammable range of fuel/air ratio. The illustration also shows the reduction in stability which occurs with a 25mm flameholder and the effect of a small increase in reactant temperature.

An additional factor which should be noted in small scale experiments (and fires) is that larger droplets, which have too much inertia to follow the strongly curved streamlines behind a small stabiliser are unable to enter the recirculation. The fuel/air ratio in the recirculation zone will therefore be significantly less than that in the fuel/air mixture approaching the stabiliser and the stability will therefore be limited at the weak boundary because of a shortage of fuel. It is believed that this underestimate of stability, as a result of small scale work, may be substantial.

It should be noted that the stability parameter takes no account of the need to evaporate fuel. If the stabiliser dimensions are greater than about 1 metre, the time which even a very large droplet spends within the burning zone will ensure its evaporation and combustion. In contrast, in a small scale stabilised combustion experiment (which is typical of the experiments used to define stability limits) there may well be insufficient time for evaporation to be achieved. This leads to lower heat release and a low estimate of the possible stability range. Figure 8 shows theoretical estimates of the evaporation and combustion histories of droplets falling freely in a flame temperature environment. Only convective heat transfer to the droplets has been considered and it has been assumed that there is no buoyant rising airflow in the fire. The figure shows that even a 500 micron droplet will be burned within one second during which time it will fall only 0.6 metres. Hence in spite of these conservative assumptions, the model demonstrates that a larger scale fire will be capable of vaporising and burning even very poorly prepared fuel and will therefore be self sustaining. Figure 8 also shows, in contrast, that if the same droplets were to fall through a 0.2 metre deep fire, (in about 120 ms), only about 10% of the droplet mass would be evaporated and the fire would not be self sustaining.

6. PRACTICAL EXAMPLES

a. A fire in an atmospheric pressure engine test facility

This incident began when an engine HP fuel pump drive shaft fractured. For a short time the shaft continued to rotate due to friction between the broken ends and these quickly became heated to a temperature in excess of 450°C. When the ends of the shaft became disengaged one of them struck a high pressure fuel pipe causing a small hole. The high pressure kerosine jet which escaped produced a cloud of fuel droplets which were ignited by the hot shafting. An analysis of the damage to engine fittings, based on the data of Reference 7 but using increased flame emissivities appropriate to kerosine flames, suggested that the initial fireball which resulted was about 3.75 metres radius and contained about 1.7 kg of fuel. This estimate could be confirmed because the fireball lifted off and pooled under the ceiling of the test hall where damage to more fittings allowed both temperature and hot gas volume to be estimated as an independent check. At about this time automatic fire fighting equipment operated to extinguish the fire and preserve the evidence of the first few seconds of the fire's development. The predicted lifetime of the fireball in contact with the engine was only about 2.7 seconds. It was found that light alloy fittings had been heated to their melting points (650°C) during this time as expected from theory. Although it was not a feature of the incident it can be calculated that 2mm deep pools of fuel on concrete surfaces would have been heated to boiling point and would almost certainly have caught fire.

This example serves to demonstrate that the data of Reference 7 can be used, with slight modifications, to predict verified observations in a kerosine fire incident. It also illustrates the scale of the fire resulting from the combustion of less than 2 kg of fuel. Had the test hall design allowed pooled fuel to accumulate the initial fireball would almost certainly have been followed by a pool fire.

<u>Second Example</u>

b. The Controlled Impact Demonstration fire

In 1984 a Controlled Impact Demonstration of a Boeing 720 aircraft took place at Edwards Airforce Base, California. The heavily instrumented, remotely controlled aircraft loaded with anti-misting fuel was landed 'wheels-up' in a controlled fashion to simulate a 'survivable' accident. During the slide out after touchdown the aircraft ran through an array of robust cutters designed to open up the cargo bay and the wing fuel tanks. In the event the aircraft touched down with the port wing low and slid through the obstacles to a final halt slewed at about 45 degrees to the direction of travel. Even before encountering the cutters the engines on the port wing had been ripped off and it is likely that there would have been considerable fuel release in the wake behind the aircraft cabin. Dust raised in the slide out demonstrated that the entire fuselage and vertical stabiliser were acting as a very large stabilisation zone. The fire was started when a cutter intersected the inner starboard engine in the vicinity of the combustion section and tore the engine in half. The ignition of on-board engine fuel was due to a mixture of hot surface, hot gas and probably flame sources. The very high initial rate of growth of the fireball which followed was largely due to the explosive rupture of the engine. Measurements of the fireball diameter suggest that about 4.5 kg of fuel was involved in this initial stage. As was discussed earlier the scale of this fireball was quite sufficient to vaporise and burn even poorly prepared, anti-misting fuel pouring from the breached wing tanks. Within 1 second expansion due to combustion had increased the size of this fire, on the starboard (upwind) side of the fuselage, to about 14 metres 'diameter' and the fire had been swept over the cabin roof into the recirculation zone in the fuselage wake. Within one more second a massive fire had become established in the recirculation zones behind both the fuselage and the vertical stabiliser. Eventually the slide-out ended with the starboard wing thrown ahead of the fuselage placing the entire structure within a huge pool fire. This fire was extinguished promptly and it was found that damage to the fuselage structure was 'surprisingly slight'. One suggested explanation at the time was that the fuselage had been covered with fuel spray and had, in effect, been fuel cooled. This is thought to be unlikely on two grounds. The first is that there would not have been a continuing supply of fuel spray after the aircraft came to rest; the second is that this could not have cooled the structure for more than a few seconds in the face of the expected radiation load. A more likely explanation is thought to be found in a phenomenon known as radiation blocking. Most of the combustion in a pool fire occurs within two to three metres of the periphery of the fire where there is an adequate supply of oxygen. If the fire is very large this leaves a central core region where very little combustion takes place. The interface between this region and the flame is however a zone of intense soot formation; and it is the soot which acts as an absorption barrier to radiation from the outer burning zone. In this particular fire great attention had been paid to spilling very large quantities of fuel and, as has been described the aircraft structure was totally enveloped in a huge fire within a very few seconds.

This example, again, serves to demonstrate the importance of scale. The few kilograms of prepared fuel in the initial fireball which was ignited on the hot engine is modest by aircraft standards. It is however a massive ignition source by laboratory standards. It is the scale of the fireball which enabled it to vaporise and ignite the poorly prepared anti-misting fuel from the wing tanks, and to be convected over the fuselage to ignite the fuel in the aircraft wake.

7. CONCLUSIONS

This paper has surveyed possible mechanisms of fuel preparation, ignition and subsequent flame stabilisation and propagation that could occur in an aircraft accident. The features that are likely to contribute the greatest risk to a major fire are identified as follows:-

1. The potential for hot surfaces, such as engine components and aircraft brakes to vaporise and ignite large quantities of fuel is very high. If even modest quantities of fuel are ignited the capacity of the resulting primary fire to cause a subsequent, major fire is very great.

ii. Aerodynamic stabilisation of a fire in the wake behind parts of the aircraft structure or in jets of high velocity air presents the greatest threat to a moving aircraft. The capacity of these zones to stabilise combustion is very heavily dependent on their scale - the larger the structure, the more stable the fire becomes.

iii. Radiation from a primary fire, such as a pool fire, has the capacity to enhance flame stability and burning velocity. It also has the ability to vaporise and ignite fuel at a distance. The scale of the primary fire has a profound influence on the radiation flux emitted - the larger the fire the higher the radiative output.

Over the years, extensive research has been carried out into the mechanics and chemistry of combustion; much of it at laboratory scale. It has been demonstrated that the effects of scale are profoundly important to the extent and severity of aircraft fuel fires. There are therefore good reasons to treat the validity of many existing data, which are the result of small scale tests, with great caution. There are also good reasons to challenge the designs of new experiments and the results from them with the question "Have the effects of scale been considered?"

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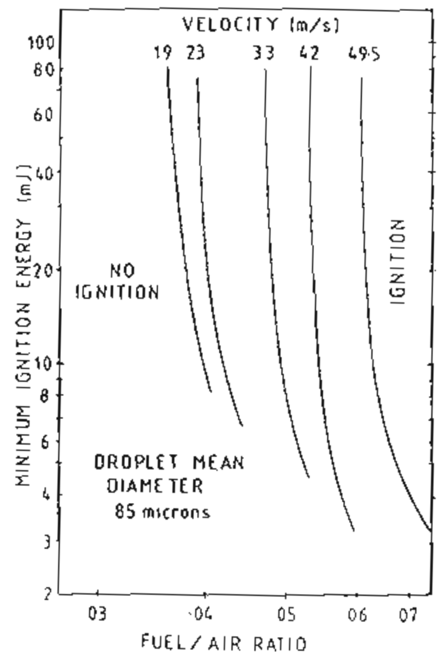

Fig.1 Effect of velocity on spark ignition energy

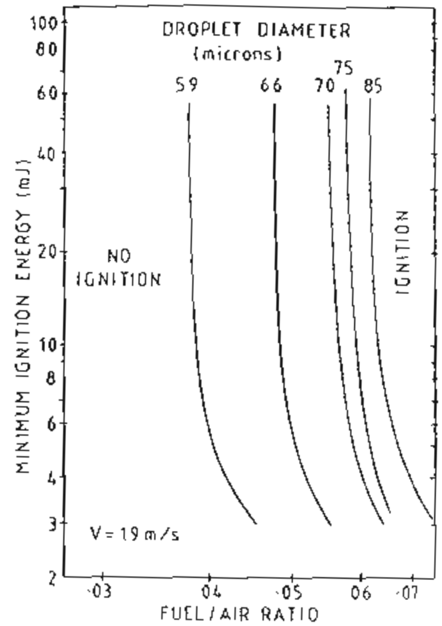

Fig.2 Effect of droplet diameter on spark ignition energy

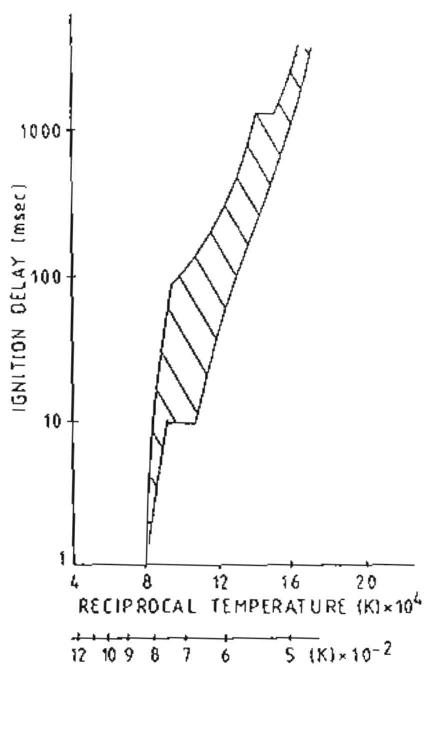

Fig.3 Spontaneous ignition delay in hot air

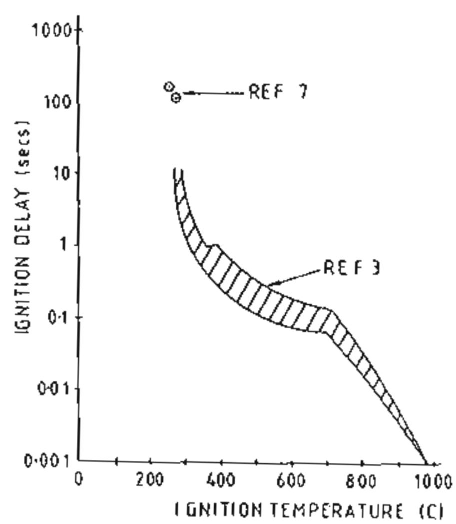

Fig.4 Spontaneous ignition delay on hot surfaces

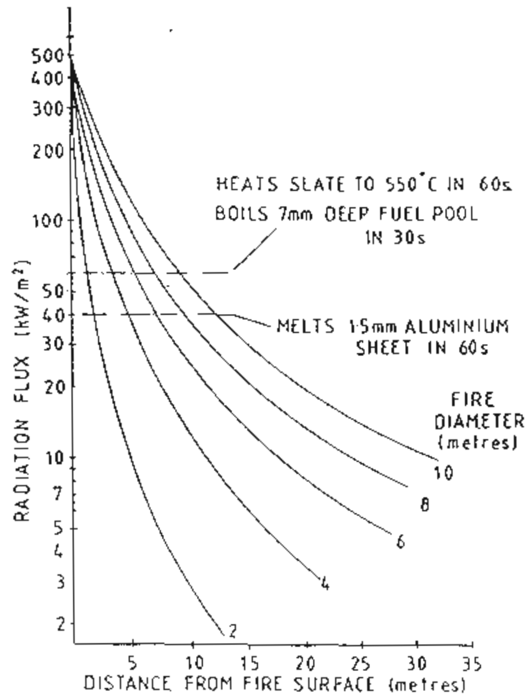

Fig.5 Scale effects on thermal radiation from fires

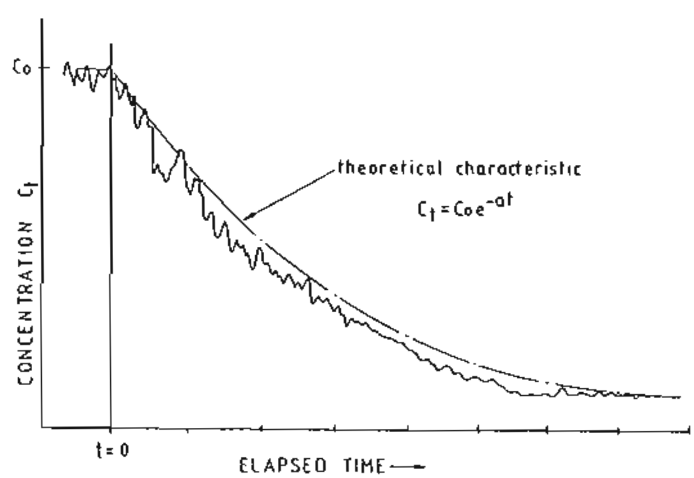

Fig.6 Concentration decay behind a flameholder

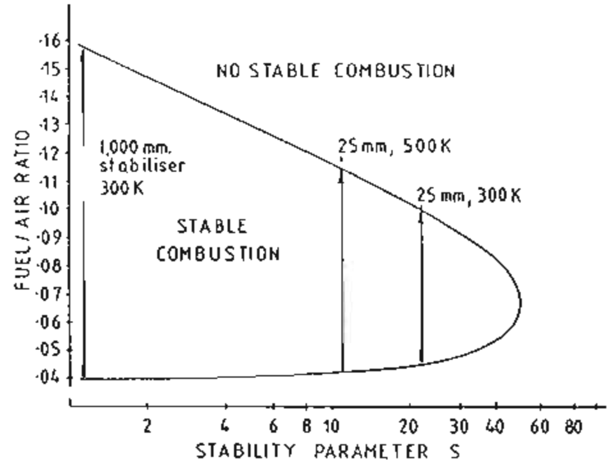

Fig.7 Typical flameholder stability loop

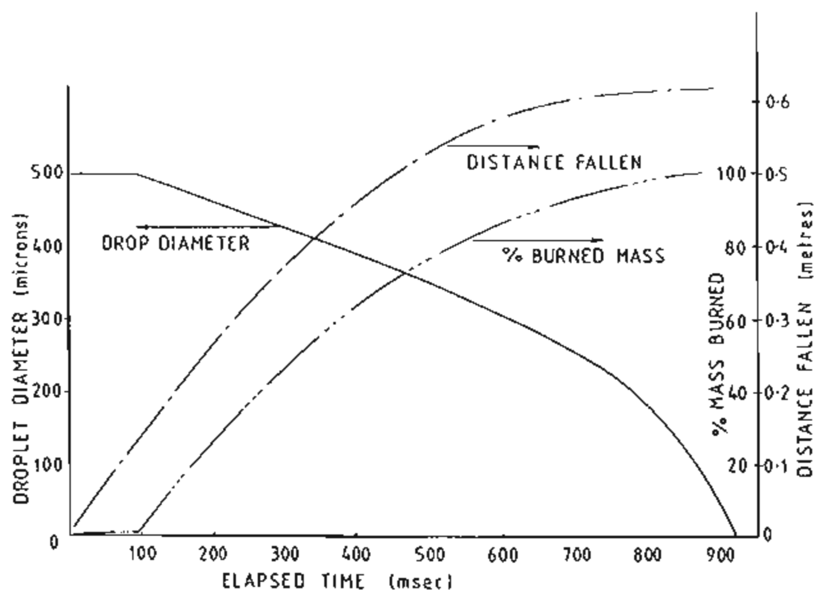

Fig.8 Droplet evaporation characteristics

US NAVY AIRCRAFT FIRE PROTECTION TECHNOLOGY

by

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SUMMARY

US Navy aircraft are routinely exposed to various combat and non-combat threats that could cause either a fire or fuel system explosion. This paper provides an overview of the design concepts to prevent, detect and extinguish these fires and explosions. Examples are given of actual designs and equipment installed on current Navy aircraft. An assessment is included on how well these systems perform under test and operational conditions.

SYMBOLS AND NOTATION

APU	Auxiliary Power Unit
CO_2	Carbon Dioxide
FSD	Full Scale Production
Halon 1211	Bromodifluorochloromethane ($CClF_2Br$)
Halon 1301	Bromotrifluoromethane (CF_3Br)
NATOPS	Naval Air Training and Operating Procedures Standardization Program
OBIGGS	On Board Inert Gas Generating System

1. INTRODUCTION

Aircraft fire protection is composed of three basic design principles; (1) prevention, (2) detection and (3) extinguishing. These principles are applied to the basic aircraft design in the General Specification for Design and Construction of Aircraft Weapon Systems, SD-24. The aircraft design contractor's engineers expand upon these requirements to meet the overall system performance and survivability goals. SD-8706 requires an analysis of the design and documented demonstration of the performance of the components. System performance demonstration is required on the completed aircraft by either MIL-D-8708 for fixed wing airplanes or MIL-D-23222 for helicopters.

The intent of this paper is to describe the requirements imposed on the designers of Navy aircraft and provide an insight into how well the system design works. Just as SD-24, SD-8706, MIL-D-8708 and MIL-D-23222 requirements are tailored to provide design parameters for an aircraft's specific mission, so to is the fire protection requirements streamlined to meet the individual operational, environmental and performance of the aircraft.

The basic requirement for the "Protection Against Fire" is specified in SD-24, paragraph 3.2.13, as "Fire protection shall be in accordance with MIL-HDBK-221". This is the Military Handbook titled Fire Protection Design Handbook for U.S. Navy Aircraft Powered by Turbine Engines. Other paragraphs of SD-24 cross reference complementing requirements that provided tailored details of specific MIL-HDBK-221 requirements.

As part of the aircraft design proposals, vendors designate primary fire zones that require isolation, detection and extinguishing. After contract award, the designers perform a detailed analysis to determine if other fire zones exist. For the highlighted areas, the Handbook provides basic parameters to guide the designer in material selection, equipment location and use of fire detection and protection equipment. Although MIL-HDBK-221 has not been revised since 1965, and thus does not contain the latest in the state-of-the-art materials and equipment, the basic principles are still valid. An effort is currently underway to revise the Handbook, to validate and update this information.

The Handbook establishes a fire protection performance baseline that describes specific systems, their design parameters and installation requirements. To assist in the understanding of these systems, the Handbook uses illustrations to present the requirements.

2. DESIGN CONCEPTS - PREVENTION

Once the preliminary design of a new aircraft places the engines, fuel system and other flammable fluids, the the fire protection designer and/or engineer must asses and identify the various fire zones. The Handbook provides the designer with the definition of a fire zone to be a compartment which contains flammable fluid components with potential leakage and ignition sources or a compartment adjacent to a fire zone that does not have sufficient separation to minimize flame propagation.

With these guidelines, the designer must now isolate the fire zone from adjacent compartments with appropriate firewalls. MIL-HDBK-221 provides guidelines on material selection, minimum wall thickness, and even restrictions on wall perforations. In addition, it provides requirements for (a) valves to shut off the flow of flammable fluids through a fire zone to minimize feeding a fire, (b) air duct design and fabrication, (c) flammable fluid line location and installation, and (c) fire detection and extinguishing. The main power plant, auxiliary power plant, and combustion heaters are given additional protection requirements, recognizing their inherent fire hazard. Although the handbook's techniques are generic in nature, their applications are as valid today as they were in 1965.

A current problem being worked relates to an existing aircraft's environmental control systems turbine compressor unit which was not originally considered a fire source. Accordingly, fire containment, fire detection nor fire extinguishing were provided for this compartment. However, after many years of operation, these compressors are failing in such a manner that a titanium fire is initiated and has resulted in the loss of several aircraft.

An analysis of Fleet fires and system failures have identified a failure mode and a means to detect an incipient failure. The pilots have been given revised operating instructions related to the cause and effect of a compressor failure, and the maintenance personnel have specific inspection procedures. An interim solution has been the addition of an dedicated temperature switch to warn the pilot of a rise in compressor outlet temperature. This system only warns the crew of an impending problem to be verified by maintenance. The ultimate solution is the replacement of the existing compressor with a newly designed air bearing unit that eliminates the the prior failure mode and returns the compartment to a non-fire zone state.

On the Navy's newest aircraft, the tilt rotor V-22, the designers have used the fire zone containment and threat in their design of the wing-tip nacelles (figure 1). A fire wall, fire detection (figure 2) and extinguishing (figure 3) are provided for the lower half of the nacelle that houses the engine, while the upper half, which houses the hydraulic system and generators, does not have fire detection nor extinguishing (figure 1). The engineering rationale used to justify this design is that the cooling air provided to the upper nacelle has such an air velocity that there is no time nor location for a fire to dwell. Only operational experience will be able to verify this assumption.

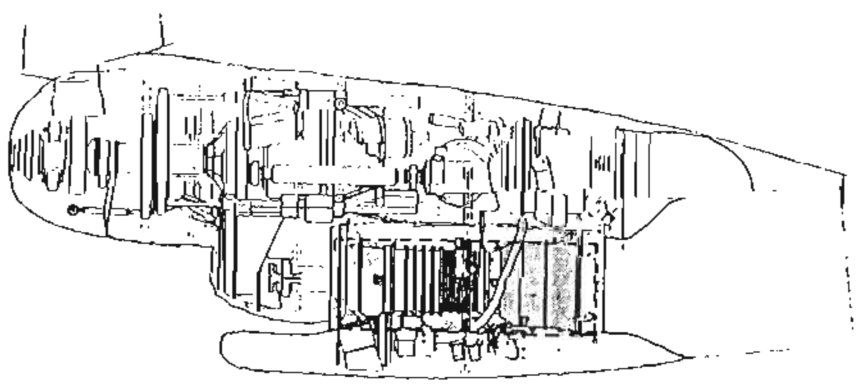

Figure 1 V-22 Nacelle Cross-Section

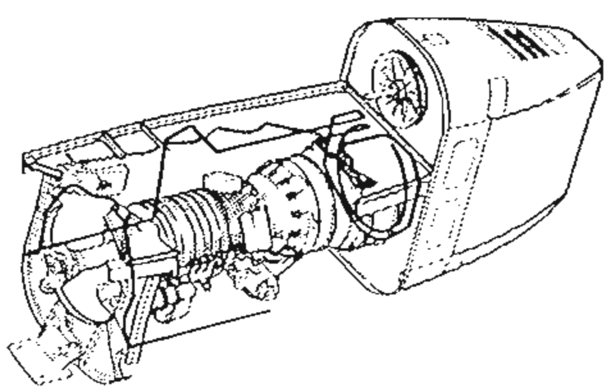

Figure 2 V-22 Nacelle Fire Detector

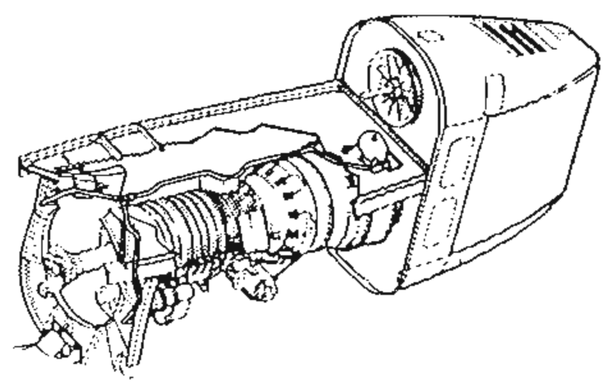

Figure 3 V-22 Nacelle Fire Extinguisher

Another innovation on the V-22 is the protection of engine bleed air lines. Rather than incorporating overheat leak detection sensors, the bleed air lines are shrouded by a line-within-a-line concept that contains any leakage. In addition, a pressure transducers measures any pressure drop in the main line to warn of a failure. This philosophy will also be subject to operational verification.

Recognizing that an aircraft will contain at least two flammable fluids, fuel and hydraulic fluid, MIL-HDBK-221 provides guidance on tank and fluid line design, construction and location. The handbook then progresses to fluid systems, ventilation, fueling and defueling requirements. By cross referencing component performance and/or design specifications, the fire protection requirements are interwoven with the system and aircraft performance requirements. Crashworthiness and combat survivability requirements for a specific aircraft are blended with existing fire protection designs to provide a modern aircraft with the best available technology and safety.

Here again, the V-22 is an example of these requirements being applied. A crashworthy fuel system is being installed to preclude fuel spillage following a crash. Not only are the fuel cells designed not to rupture on impact, they also have breakaway disconnects that seal upon separation to prevent further spillage. For combat protection, the lower third of specific fuel cells are self sealing bladder material used to minimize fuel loss after ballistic penetration. To augment this, the wing dry bays adjacent to the fuel tanks contain one of three different fire protection systems (figure 4): (a) the area around the wing ribs has void filling foam, (b) the wing leading edge area has powder filled honeycomb panels and (c) the wing trailing edge area has optically activated fire extinguishing units. The sponson fuel tank areas use void filling foam. To complete the design, the fuel cell themselves are inerting by an On Board Inert Gas Generating System (OBIGGS) which provides nitrogen enriched air that prevents an explosive over pressurization of the cell upon impact by an incindeary projectile.

Gun fire tests where run to evaluate the merits of the various protection systems, and as a result of the tests, changes where made from the proposed systems. Specifically, an Aluminum Oxide powder puffers were originally proposed for the wing trailing edge dry bay fire extinguishing, after failing to prevent a dry bay fire, a Halon 1301 filled tube with pyrotechnic fracturing system was substituted and is now on the full scale production (FSD) aircraft (figure 5).

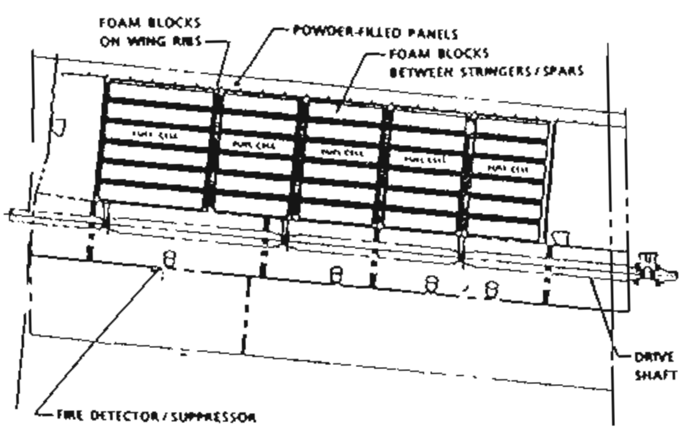

Figure 4 V-22 Wing Fire Suppression Equipment

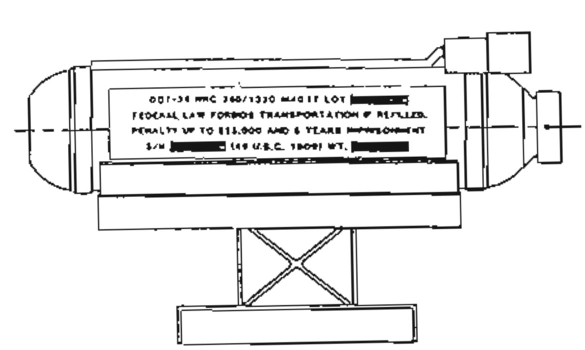

Figure 5 Systron Donner Linear Fire Extinguisher

Not only are our newest aircraft receiving these protection techniques, existing aircraft are selectively being modified and updated. An example of this is the A-6 Intruder, which is being retrofitted with dry bay fire suppressant foam and fuel tank ullage explosion protection for combat survivability. Also improvements are being made to material applications around fire zones, the addition of a discrete fire detection system, the modification of the existing overheat detection system and the addition of compartment fire extinguishing capability. In addition, many helicopters have been retrofitted with crash worthy fuel systems to improve the crews safety subsequent to a crash.

MIL-HDBK-221 deals with other systems such as electrical, bleed air and oxygen. It then goes into "hazardous systems" that are potential fire zones and explosion hazards if not properly designed and located. Hazardous systems include high speed rotating equipment such as starters, auxiliary power units and drive shafts. The design practice locates these components so that in case of their disintegration a flying fragment would not damage flammable fluid components, explosives or oxygen containers. The alternative to location is protective design, such as shrouds. Other hazardous systems are high pressure air, explosives, engine starters, guns, munitions and even landing wheel brakes. In most of these systems, MIL-HDBK-221 refers the designer to the component design specification for fire and safety parameters.

Here again, the V-22 demonstrates how these concepts are applied. The center wing gear box contains the auxiliary power unit (APU). A fire wall is provided around the hot section of the APU with its own fire detection and fire extinguishing system. Other sections of the gearbox compartment have been determined not to be a fire hazard. The

A-6 retrofit program also recognized the hazards of the APU, and has extended the aft equipment bay fire detection sensors abd fire extinguishing system around the APU compartment.

Other environmental threats, such as lighting penetration strikes into a flammable fluid system, and the ability to tolerate static electricity are also handled by the Handbook. Basic design concepts are suggested that would improve aircraft resistance to these threats. State-of-the-art fiber reinforced composite materials, used for weight reduction, have a problem with static electricity and lighting strike dissipation. As techniques are developed, these technological advances will be incorporated into MIL-HDBK-221, either by direct statements of fact or by cross referencing other specifications, so that they are applied to the next generation of advanced aircraft.

Material selection and design of other areas of the aircraft, such as the inhabited compartment, and baggage and cargo area, has seen newer and different materials being used. Their relative safety in regard to fire resistance and outgassing of noxious or toxic fumes is not addressed in the Handbook. Like electrostatic protection this materials related information either needs to be addressed directly in the Handbook or cross referenced to another document.

3. DESIGN CONCEPTS - DETECTION/EXTINGUISHING

Fire detection provisions are an example of how SD-24 cross references a design requirement. As part of MIL-HDBK-221, fire detection is described and specific design parameters are provided. However, SD-24 paragraph 3.19.4 is the contractually binding section that stipulates the requirement for fire detection. Both requirements are complimentary, except that the actual system used on an aircraft is identified in paragraph 3.19.4.

The fire detector section of MIL-HDBK-221 is an example of where the latest state-of-the-art equipment is not specifically included nor is the use of this equipment excluded. The MIL-F-7872 wire type fire detectors cover the performance requirements for the detection element and system. Where as the eutectic salt (discreet temperature) and thermistor (average temperature) type detectors meet all the specification requirements, the pneumatic (average temperature) detector does not meet the loop circuit requirement. Designs are available to back up a pneumatic system to provide coverage in case of an in-flight element fracture; this difference must be taken into consideration during design.

Optical sensor technology has improved to include dual range and combination of Ultraviolet and Infrared sensors. These reduce the potential for a sensor to give a false indication, as well as improve the responsiveness to specific threats. None of these improved sensors are covered by a specification, but their use is being encouraged because of their improvements and resistance to false warnings.

Once the aircraft is built, a temperature survey of the engine compartment is required to verify the thermodynamic predictions to insure proper activation settings for the sensors. MIL-F-7872 requires the wired sensors to be set one hundred fifty to two hundred fifty degrees Fahrenheit (150 - 250° F), eighty-three to one hundred thirty-nine degrees Centigrade (83 - 139° C) above maximum operating conditions. Some vendors suggest that their elements can be set with a tighter safety margin.

The V-22 selected the pneumatic detector for the engine nacelle and APU detectors, and a dual range optical sensor for the automatic wing aft dry bay fire extinguisher. The modification to the A-6 is using the existing thermistor sensor for overheat and adding an eutectic salt system for specific fire detection in the engine nacelle and aft equipment bay. From available data, each detection system can perform the necessary tasks. However, the individual installation can effect the systems reliability and ultimate procurement costs. Figure 3 shows how the pneumatic detector has on overlap at the rear fire wall to provide redundant coverage.

Like fire detection, fire extinguishing is specified in SD-24 paragraph 3.19.4 and also is described in MIL-HDBK-221. The specific requirements for fire extinguishing are established in the aircraft detail specification with the installation complying with the performance requirements of MIL-E-22285 and the bottles designed and tested in accordance with MIL-C-22284. Exceptions to these requirements are given when the detail design utilizes overcharged bottles or different discharge tube diameters.

MIL-E-22285 requires a demonstration that the fire extinguishing system provides six percent by volume in air or twenty-two percent by weight Halon 1301. This concentration must be maintained throughout the compartment for a minimum of one-half a second. MIL-D-8708 requires this to be demonstrated during flight. For aircraft that installation of the necessary recording equipment is not practical, the test can be performed on the ground with sufficient cooling air provided to simulate inflight conditions.

In light of the growing problem with the atmospheric ozone problem, and the controls being imposed on chlorofluorocarbons, continued use of Halons is currently not a problem. The freezing of Halon production at 1986, levels by 1992, should not effect the availbility as long as current inventories are recycled. However, if any of the few manufactures decide to discontinue manufacturing Halon, even at the established rates, a new agent will have to be found. Currently, my office is not supporting any research or development into finding alternative agents, but work is being done by the manufactures and fire fighting community.

Although we may have designed and built the perfect aircraft, it still could have a fire. The properly working detection system then notifies the pilot of the hazardous situation. Emergency Provision to cope with the situation are outlined in the Handbook. These procedures are then specified in the applicable Naval Air Training and Operating Procedures Standardization Program (NATOPS) manual for each aircraft. For the earlier mentioned environmental controls system turbine compressor problem, NATOPS were modified to alert the pilot to the potential for catastrophic failure of the flight controls as a result of the failure of the turbine and required immediate shut down of the ECS. As corrective repairs are identified and implemented, NATOPS are update accordingly.

The above addressed designing the aircraft for non-combat threats. MIL-HDBK-221 then discusses the crash and combat scenario. Here again, the basic principals are valid, but technology has brought forth systems that provide a more efficient design. Providing a fuel tank with explosion suppression, such as inerting, is not a new concept, but MIL-HDBK-221 did not provide specific design guidance. The currently available techniques such as stored liquid Nitrogen or Halon, an On Board Inert Gas Generating Systems (OBIGGS), or explosion suppressant foam can be safely used if properly sized and installed. Each system has it individual merits and problems that the designer must weigh before selecting a system.

Hand held fire extinguishers are another example of where the Handbook data has been outdated and aircraft have been modified with the later technology. MIL-HDBK-221 requires the use of Carbon Dioxide (CO_2) units, that are no longer available nor are they the best nor safest agent. The Navy has chosen a two and three fourths pound (one and one quarter kilograms) Halon 1301 extinguisher, that is purchassed in accordance with MIL-E-52031. Although the Federal Aviation Administration (FAA) has required that commercial aviation use Halon 1211 hand held units, the Navy selected Halon 1301 because a Military Specification had existed which facilitated procurement, and the higher safe exposure limits, seven percent versus 2 percent, for a confined space. Both Halons are better fire extinguishing agents and safer than the CO_2.

The A-6 fuel tank ullage explosion retrofit program is using a stored Halon system which will require recharging the system after every combat flight. While the V-22 and AH-1W are using OBIGGS systems to provide full time fuel cell pressurization and inerting. As long as the appropriate concentrations are maintained, either system will protect the aircraft from fuel tank over pressurization upon impact by an incindeary projectile.

OBIGGS currently does not have the flow rates for fighter and attack aircraft, thus limiting its application. However, work is underway with new technology permeable membrane air separation modules that may provide the improvements necessary. A technology demonstration is proposed by the Naval Weapons Center, China Lake, California, to install a permeable membrane system on an F-18 aircraft. Flight tests to determine ullage composition and inerting verification are a major portion of the program.

The Navy takes fire protection very seriously, and is concerned about the safety of all its aircraft and crews. However, some aircraft are not amenable to all the techniques as others. For example the vertical lift AV-8B Harrier, with its single engine, has fire detection but no fire extinguishing. Essentially, to fight an engine fire the first step is to shut down the engine and all fuel going to it. Once the one and only engine is shut down, it is mute to inject a fire extinguishing agent, because you are not going to restart the engine. However, fuel tank ullage explosion protection is being considered to improve combat survivability.

4. DESIGN - VERIFICATION

The Navy not only has specifications that guide the design of the aircraft, but other specifications identify the necessary component and system testing required to verify the design. Throughout the above description of the design process, there has been reference to some of this verification.

SD-8706 provides the contractual requirement to perform design analysis, trade studies and component testing. MIL-D-8708 and MIL-D-23222 are the flight test demonstration requirements for fixed wing and rotory wing aircraft. Here the requirement is to show how the design works, as a system, in an aircraft.

Hopefully the aircraft has been designed properly, and the inherent passive fire protection will prevent a fire. As such, the integrity of fire walls are not tested, but fluid leak paths are assessed to verify that flammable fluids are directed away from potential ignition sources. The integrity of the fire detection system is tested and a heat source is applied to confirm the trip settings. If possible, the fire extinguishing system should be tested during flight to verify agent concentrations, but from practical purposes, the test is performed on the ground with simulated air flow.

Systems installed for combat protection are evaluated under live fire conditions. As a result of subscale tests designs have been changed, such as the V-22 wing aft dry bay fire protection system changing from a powder extinguishing agent to Halon, and the

A-6 fuselage dry bay foams were changed from reticulated polyurethane to polyimide foam. These tests have also confirmed the design parameters, such as the duration of protection provided by A-6 Halon fuel tank inerting system.

5. SYSTEM APPLICATION

The Navy is designing its latest aircraft, using the lessons learned from from combat and routine operations, to be safer and more durable and yet not sacrifice the aircraft's performance. The costs of replacing a crew or aircraft warrant the initial expense of proper design.

Trade studies are still required to weight the cost versus performance benefit of different design parameters, such as using explosion suppressant foam versus a gas inerting system in the fuel systems. The former requires minimal maintenance and has the ability to provide multiple hit protection but increase aircraft weight and reduces usable fuel. While the latter systems require periodic (some times every flight) refilling and repair of various electrical and mechanical components.

It is not the intent of this paper to say which is the better choice, rather to identify the design philosophy the Navy is using in building new and retrofitting aircraft. MIL-HDBK-221 is the backbone of the design process, and hopefully it can be maintained current to insure future aircraft need fewer design guides to find the appropriate information.

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AIRCRAFT FIRE SAFETY IN THE CANADIAN FORCES

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Summary

Flight Safety is a prime consideration of the Canadian Forces in its approach to air operations. The aim of the Flight Safety program is to prevent the accidental loss of aviation resources and this is done by investigation of occurrences, determination of cause and implementation of preventive measures.

Aircraft fire safety is a concern not only to save lives, but resources as well. An overview of aircraft fire safety in the Canadian Forces and how fire safety is approached for the various aircraft types is presented. The transport, maritime and helicopter fleets are discussed as are procedures for the CF-18.

Another aspect of fire safety that is briefly covered is the crash, fire and rescue capability (CFR) at military airports to handle an emergency.

Introduction

Prior to discussing aircraft fire safety in the Canadian Forces, a description of the Canadian military structure is necessary. The Royal Canadian Navy, Air Force and Army were integrated in 1968 to become the Canadian Armed Forces. Prior to integration, each of the services had their own integral aviation assets including aircraft, maintenance and aircrew. With unification, all aviation resources were amalgamated under the Commander of Air Command with operational control of specific air resources being given to the land and Maritime Commanders through designated Air Groups. Although the terms Army, Navy and Air Force are being used again and there are distinctive uniforms, all aviation resources remain under the Commander of Air Command who is responsible to the Chief of the Defence Staff. As a result, the Flight Safety organization is "Air Force" and includes the responsibility for resources working in the field with the Army as well as off the decks of destroyers at sea.

The Canadian Forces Flight Safety system starts right at the top with the Chief of Defence Staff who is responsible to the Minister of National Defence. The base statement is that "accident prevention is the responsibility of the commander". From this falls the aim of the Flight Safety program: "To prevent the accidental loss of aviation resources". And this is done by investigation, determination of cause and implementation of preventive measures.

Air Command, the largest of the Canadian Forces Commands, is composed of six functional groups to meet Canada's defence commitments:

a. Fighter - CF-18, CF-5;

b. Maritime - CP140 (P-3 Orion)
CP121 (Tracker)
CH124 (Sea King) helicopters

c. 10 Tactical - providing tactical aviation support to Mobile Command (The "Army") with

CH147 Chinooks
CH135 Twin Hueys
CH136 Kiowas

d. Air Transport - CC137 (Boeing 707)
CC130 (Hercules)
CC109 Cosmopolitans (Convair 580)
Challengers
DASH 8s
Buffalos
Twin Otters

e. 14 Training - CT114 Tutor
CT133
CT134 (Musketeer)

f. Air Reserve

Aircraft fire safety is naturally a concern, not only to save the lives of passengers and crew members, but also to preserve material resources to the best extent possible. There are too few resources to start with, and with a constrained budget, the Canadian Forces must do everything possible to maintain operational strength. The concern then, regarding fire safety, encompasses not only the large transport, passenger-carrying aircraft of transport group but also the small Kiowa helicopter.

This paper presents an overview of aircraft fire safety in the Canadian Forces. The obvious "Why" has already been mentioned and "How" the different types of aircraft and operations in the Canadian Forces approach fire safety will be looked at. What actual experience the Canadian Forces have had in aircraft accidents and incidents relating to fires will also be covered and there will be a brief look at crash, fire and rescue (CFR) at Canadian Forces airports.

Transport Aircraft

Attention was focussed in recent years on several incidents involving aircraft fires that started innocently enough but ended in disaster - an L1011 at Riyadh, a DC-9 at Cincinatti and a 737 at Manchester to mention three. These accidents provoked world-wide discussion and activity regarding passenger cabin safety. Since Canadian Forces transport aircraft are designed to carry passengers as well as cargo and, similar to all commercial aircraft today, there is some compromise between safety and efficiency, obviously the Canadian Forces have concerns regarding aircraft fire safety. In particular, the light-weight materials used for cabin habitability have proven in the aforementioned accidents to be most flammable and to give off lethal gases when burned.

The Canadian Military, particularly Air Transport Group, are justificably proud of their passenger safety record. However, being not only a Government agency but military as well, it is very conscious of limited budgets. However, Transport Canada regulations are complied with where possible. Safety modifications to aircraft are being carried out that reflect current technology, but modification of some existing aircraft will not occur. Future aircraft purchases will incorporate a number of the recommended safety modifications.

Obviously, of greatest immediate concern to the Canadian Forces are our passenger-carrying fleets. Compliance has been followed with the various Transport Canada Air Navigation Orders (ANO) as indicated: (For aircraft not mentioned, the regulations were not applicable).

a. ANO #28 Fire-Blocking Materials - Seats.

The flammability of seat upholstery, fabric covers stretched over polyurethane foam, is often a major factor in the spread of an internal fire. Chemical retardants applied to the fabric can improve flame resistance but are subject to degradation from normal use. Research has shown that a fire-blocking design, a thin thermally stable fire-resistant material over the foam cushions, can be very effective in delaying the spread of fire (Figure 1) and ANO #28 calls for fire-blocking.

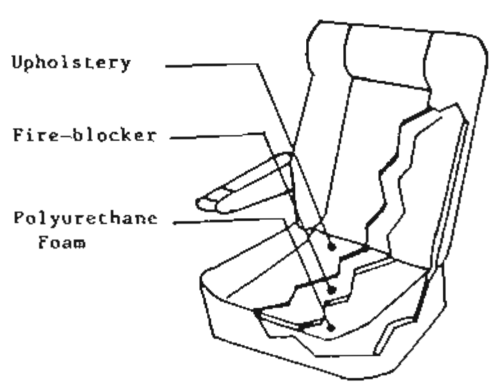

Figure 1 - Fire-blocking

CC137 Boeing -

The ANO will be complied with, but delayed due to a decision whether to replace seats entirely or just the cushion and seat cover. The target date for compliance is the summer of 1989.

CC130 Hercules -

A requirement for five pallets of extra passenger seats, 15 triple and 10 double, for the VIP role has been identified. They will be done in conjunction with the CC137 program.

DASH 8 -

All seats have been fire-blocked.

CC109 Cosmo -

New seats that have been fire-blocked will be installed by the summer of 1989.

b. ANO #29 Escape Path Marking. In an aircraft accident where there is a fire, visibility is greatly reduced very quickly. Great quantities of smoke are generated and, rising, obscure vision everywhere but near the floor. The ANO requires installation of emergency escape path marking to enable each passenger to visually identify the emergency escape path along the cabin aisle floor in finding their way to exits after leaving the cabin seat, and to enable each passenger to readily identify each exit from the emergency escape path by reference only to markings and visual features not more than four feet above the cabin floor.

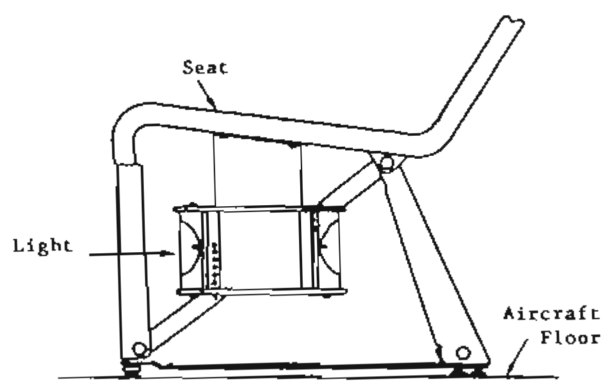

Figure 2 - Floor Proximity Lighting

CC137 Boeing -

Delays were experienced while floor track or seat mounted versions were being evaluated. The decision was for a floor proximity mounting similar to Figure 2, each unit being independent, radio-wave activated. This type of fitment is necessitated by the frequent changing of configuration from passenger to cargo versions. Fleet fitment is to be completed by the fall of 1989.

CC130 Hercules -

The VIP seating module will comply.

DASH 8 -

Lead-time delays on procurement of a system has delayed the program, but an escape path marking fitment, like Figure 2, should be installed by the summer of 1989.

CC109 Cosmo -

Fleet fitment of a floor track system as depicted in Figure 3 is to be completed by the summer of 1989.

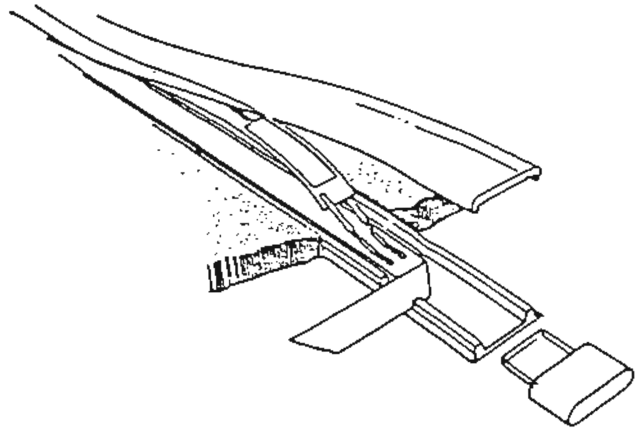

Figure 3 - Floor Track Lighting

c. ANO #30 Cabin fire protection, including labatory smoke detectors and waste receptacle extinguishers and Cabin Halon 1211 extinguishers. Lavatories are vulnerable to fires due to electrical failure or disposal of smoking material, particularly since they are not under the constant eye of the cabin crew. Transport Canada has decided that lavatory smoke detectors and waste receptacle extinguishers are required as well as portable Halon 1211 extinguishers. All Canadian Forces transport aircraft are compliant except that the Challenger fleet needs some re-design for the lavatory waste receptacle extinguishers and this won't be completed until early 1990. There is currently a study under way to determine whether the sensitivity of the installed smoke detectors can be increased; also, other types of very sensitive detectors are being considered.

d. Air Directive on lavatory flush motor circuit breaker protection.

This relates directly to the electrical vulnerability of the lavatories. The Challenger is the only aircraft not presently compliant but fleet fitment should be completed by the middle of 1989.

Other avenues leading to greater cabin protection are being investigated, such as a cabin spray system, currently being looked at by British CAA and the American FAA. This system promises more time and better conditions to evacuate from a burning aircraft by spraying a mist of water throughout the cabin. This effectively washes out smoke and toxic fumes, takes out heat and reduces fire propagation. Smoke hoods, too, have been tested by the Canadian Defence and Civil Institute of Aviation Medicine. The question of smoke hoods, though, for use in aircraft is more complicated than first thoughts would indicate. Some corporate flight operators already provide them for crew members but aviation experts remain divided over whether their deficiencies and the possible added confusion of donning them would delay passengers and counter their usefulness. Of the three basic types available - filter, breathable gas or cartridge and simple bag - each has advantages and disadvantages and there is controversy in the aviation community over what is best. However, the Directorate of Flight Safety is monitoring the smoke hood subject.

Not to be overlooked in this issue of improving aircraft fire safety, is the training and performance of the cabin crews. After all, they are the ones that must implement emergency procedures and direct/assist the passengers. The Canadian Forces Flight Attendants are thoroughly trained in safe housekeeping practices, and how to be continually alert for unsafe passenger actions and to be ready for immediate action. To counter situations involving potential fire, they undergo regular check rides and yearly hands-on, practical simulator training.

Although monitoring of the cabin area is made easier by the "No Smoking" policy on all Canadian military aircraft, particular attention is paid to lavatories and trash receptacles to ensure no smoke is present. The Flight Attendants are continually on guard for unusual, burning or electrical odours as well. Basic fire prevention is something that is trained for and practised as a metter of routine.

Topical articles in Flight Comment, our Canadian Forces Flight Safety magazine, are published regularly to heighten awareness of all in helping detection/control and protection/survivability. It is recognized that passengers, too, can contribute greatly to a safe flight.

Fire Safety on Other Aircraft

The preceding paragraphs outlined measures followed for the transport, passenger-carrying aircraft. There are other aircraft, like the CP140 Aurora (P3 Orion), that carry personnel as well. However, being military, internal fitments and materials for these operational aircraft do not have to meet the civil regulatory requirements, but since items are generally similar to commercial ones, they usually meet the requirements in effect at the time of contract.

Canadian Forces helicopters also have a measure of fire safety in that they all have "crash-worthy" fuel cells. The CH135 Twin Huey and CH136 Kiowa also have frangible fuel lines and fittings.

Even the front line fighter, the CF-18, has a measure of fire safety protection to minimize airframe and engine damage resulting from a fire. Cases of burnthrough of the engine and burnthrough penetration of the aircraft heat shield have been experienced. This has caused a fuel or hydraulic fluid fire and damage to aircraft flight control components, and has resulted in the loss of an aircraft. The burnthrough resulted from a titanium fire caused by high energy friction rub of titanium blades on the titanium case. The molten and burning titanium particles impinged and penetrated the aircraft engine heat shield. If fuel lines are broken as a result of the heat source, a secondary fuel fire results which continues until the fuel is shut off.

To counter this type of emergency, pilot procedures regarding engine shut down and fuel shut off were revised. As well, investigation revealed that the existing aircraft heat shield in the affected area had to be improved. The manufacturer conducted a series of tests and evaluations to determine how best to contain a Titanium fire, and it was determined from test results that a material called Viton was suitable. (Viton is a proprietary mix defined by a General Electric specification and manufactured by Eagle Elastomers, Stowe, Ohio.) The Canadian Forces adopted the Viton solution proposed by GE of coating the outer ducts. This, and the revised shut-down procedures, have been effective in saving several aircraft.

Actual Experiences

As to Canadian Forces experience in protection from aircraft fires, there have been several occurrences. A waste receptacle fire on the Boeing caused by a cigarette was readily detected and extinguished. There continues to be an average of one incident a month where the lavatory automatic smoke alarms detect a passenger trying to sneak a smoke.

Two recent helicopter accidents have proven the efficacy of the crash-worthy fuel cells. They were undamaged even though the aircraft were totally destroyed. As well, as just mentioned, the efficacy of the Viton coating has been demonstrated.

Crash, Fire and Rescue Capability (CFR)

Another aspect of aircraft fire safety in the Canadian Forces is the crash, fire and rescue capability at military airports to handle a declared emergency or crash. Currently, the capabilities of the military airports are under review to ensure that they are able to handle the potential problems of their regular traffic. A project is underway to provide an upgrade from Category 6 to 7 where necessary by purchasing larger capacity Crash/Fire/Rescue trucks, because it is no good being able to handle the emergency in the air and not being able to cope on the ground. Canadian Forces Bases at Shearwater, Greenwood, Edmonton, Comox and Lahr will be upgraded.

Conclusion

In conclusion, then, the Canadian Forces is very cognizant of aircraft fire safety in its broadest terms. Not only large passenger-carrying transport aircraft are considered, but measures are implemented for single-seat fighters and small helicopters. The Directorate of Flight Safety and the Aerospace Engineering and Maintenance personnel at National Defence Headquarters act as a focal point for the coordination of work on aircraft fire safety. Canada incorporates, where appropriate, the lessons learned from civil and military aviation occurrences, not only in current aircraft, but also in future buys. The Canadian Forces is justifiably proud of its passenger-carrying safety record and its steps to ensure the fire safety of all of its aircraft. However, budgets do constrain what can be done, may be more so than a commercial operation. The disasters of Cincinatti, Riyadh, and Manchester have forced Governmental regulatory agencies to take positive steps to counter potential safety hazards. The military wants to be just as safe, but the economics are different, and thus, it might take a little longer to adopt new safety measures. But the Canadian Forces can and does compensate for various constraints by more intensive training and dedicated personnel. The awareness factor of all Canadian Forces personnel who are involved in air operations is raised by a positive and active Flight Safety Program.

FIRE HARDENING OF AIRCRAFT THROUGH UPGRADES OF MATERIALS AND DESIGNS

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SUMMARY

Commercial air transportation is the safest mode of transport, because the industry and its regulators have emphasized accident avoidance along with backup fire management/control and personnel evacuation strategies when accidents do occur. Regulatory authorities set the minimum safety standards for the design, manufacture, and operation of aircraft, to which the individual manufacturers and operators add their own unilateral, self-imposed safety criteria. The evolution and status of the FAA regulatory fire safety criteria applicable to aircraft manufacturers, and the additional criteria imposed by the manufacturers on themselves such as D6-51377 for Boeing and ATS 1000.001 for AIRBUS Industrie, are discussed.

1. INTRODUCTION

Of paramount concern to an airplane manufacturer is to design the highest level of safety into his airplanes. The basic airplane design must assure that minimum mandatory standards set by regulatory authorities are satisfied. However, since regulatory requirements must by their nature represent a minimum level of safety, all manufacturers always include in airplane designs unilateral supplementary safety criteria that go beyond the regulatory minima. These complementary sets of design criteria assure the ultimate customers for the product -- the passengers who fly on the airplanes -- that the airplane design represents the highest achievements in safety.

The airlines must also assure that its operations are safe, and that the high safety level which is designed and built into the airplanes by the manufacturers are reinforced by systematic operating and maintenance procedures.

The regulatory authorities have the responsibility of assuring that the mandated minimum safety requirements are met not only by each certified airplane design, but also by each manufactured airplane. The authorities also monitor the operation of the airlines to assure that mandated airline operating standards are met.

The sum total of these efforts by the airplane manufacturers, the operating airlines, and the regulatory authorities is that commercial air travel has become by any reasonable measure far safer than any other transportation mode in history.

Notwithstanding this excellent safety record, neither the manufacturers, airlines, nor the regulators can say that no further attention need be directed toward improving safety. Such an attitude would probably lead to complacency, and would actually lower safety standards. We must always strive to improve safety.

2. FIRE SAFETY

Fire safety is one of the principal areas which have received much attention. The regulatory authorities are very sensitive to fire safety issues and always upgrade the regulations to the state-of-the-art. The manufacturers recognize the immense benefits of selecting fireworthy materials and designs, and have always placed a great deal of emphasis on their own fire safety design criteria that go beyond regulatory requirements. The reduction of risk due to fire has therefore played a very large role in the design and operation of commercial transport airplanes.

2.1 Postcrash Fires

Fire on an airplane is an extremely serious thing, particularly if it occurs during a take-off or landing accident in which jet fuel gets involved in the fire.

Fuel has to be flammable so the engines can use it, and a great deal of fuel is required for the operation of the airplane. For example, there are more than 100 gallons, or 800 pounds, of fuel carried at take-off by a long-haul airplane for each available passenger seat. The amount of heat that can be generated by burning the fuel available at take-off is about one hundred times as much as the heat that could be generated by burning all the interior furnishings plus the passengers' carry-ons and clothing. The temperatures created by a fuel fire are on the order of 1000C, and the aluminum used for the airplane structure melts about 350C below that. Less than five percent of the fuel available on take-off can produce enough heat to melt all the aluminum used in the airplane's structure.

The important conclusion that this sobering comparison reveals is that the biggest payoff in airplane fire safety is to AVOID ACCIDENTS. Crew training, airplane maintenance, and airport facilities all play a part in avoiding accidents.

2.2 In-flight and Ramp Fires

There have been fires in the past that have occurred in situations other than landing or take-off accidents. In-flight fires have been infrequent, and very rarely have been serious.

Fires have also occurred in airplanes while parked at the ramp overnight or during maintenance operations. While such "ramp fires" have not put any passengers or crew at risk, they have caused hull losses, with the resultant economic impact. A manufacturer's selection of appropriate fireworthy designs and materials can minimize the number and severity of these fires.

3. INCLUSIVE REQUIREMENTS FOR AIRPLANE DESIGN

Airplane manufacturers are required to build airplanes that meet the regulatory mandates set by government authorities. In addition to regulatory requirements, all manufacturers impose upon themselves their own safety criteria which go beyond the regulations. The design must satisfy this combination of regulatory and self-imposed, unilateral safety requirements.

There are two types of fire safety criteria: those that apply to systems (e.g., the requirements for fire extinguishers, fire stops, etc.), and those that apply to the selection of materials. It is important to recognize that material selection criteria -- regulatory and unilateral -- really apply to the performance of PARTS, which are frequently made up of several materials. How a part is constructed and processed depends on the materials it is made of; when materials change, the construction and processing of parts have to change also.

There are other things which design requirements must address that are not included in the manifold of regulatory and unilateral safety requirements. For example, the manufacturer must be able to make cost-effective, reproducible parts of some complexity that satisfy strength and weight criteria. The airlines require that cabin interiors be customizable to have the "right look" and be cleanable, durable, maintainable, and repairable.

3.1 Regulatory Requirements

In the United States, the Federal Aviation Regulations (FARs) govern the certification and operation of aircraft. For the certification of new designs of passenger airplanes, the applicable regulations are in FAR PART 25, "Airworthiness Standards: Transport Category Airplanes". The operation of airplanes by airlines is covered in FAR PART 121, "Certification and Operations: Domestic, Flag, and Supplemental Air Carriers, and Commercial Operators of Large Aircraft".

Historically, the regulations have been upgraded based on research and development both industry and the FAA. This combined research and development effort is beneficial because new technology needs to be built up on a solid foundation so that both its benefits and drawbacks are understood. In other words, it needs to be evolutionary rather than revolutionary.

The heat release rule for interior cabin liners was however developed a little bit differently. When the rule was first proposed, the intent was to proceed this way. But as time went on the driving forces became more and more non-technical. The final rule requires that new technology be developed and implemented on a fixed schedule. This has resulted in a considerable amount of chaos for both the industry and the regulatory authorities. Many problems have arisen which provide a considerable challenge to the manufacturers' commitments to meet the mandated implementation dates on schedule.

3.1.1 FAR PART 25: Certification of New Design

The first regulatory fire performance requirements covering the certification of transport category aircraft in the United States was Civil Air Regulation 4b (CAR 4b), which was issued by the Civil Aeronautics Agency (CAA) in 1945. CAR 4b required that cabin parts be subjected to a horizontal Bunsen burner test procedure; there were no vertical Bunsen burner tests required for certification at that time. The first jet transports (707, DC-8, 727, and DC-9) were certified to CAR 4b.

In 1965 the Department of Transportation (DOT) was created, and the CAA was reorganized and made a part of the DOT as the Federal Aviation Administration (FAA). Simultaneously, the existing CARs were reissued without change as FAR PARTs. CAR 4b became FAR PART 25.

Subsequent amendments to FAR PART 25 have been issued that have imposed more and more stringent flammability requirements on interior cabin furnishings. Of particular note are:

Amendment Number	Issue Date	Added Requirement
25-15	1967	12 sec vertical Bunsen burner test
25-32	1972	60 sec vertical Bunsen burner test
25-59	1984	Seat cushion fire blocking
25-61	1986	Ohio State Univ. heat release test
25-66	1988	NBS smoke release test

3.1.2 FAR PART 121: Certification of Existing Designs

New airplanes manufactured to existing, certified designs must only meet the sections of FAR 25 that were in effect when the original design was certified. For example, all current aircraft designs were certificated prior to inclusion of the new heat release rule into FAR PART 25 and are not required to meet the rule's limits. However, FAR PART 121 covers requirements airplanes must meet before the airlines can operate the airplanes in passenger service. By changing FAR PART 121, the FAA can require that all airplanes operated by the airlines be modified to meet a new requirement. The FAA changed PART 121 to require that all airplanes delivered after August 20, 1988 meet the heat release rule, regardless of their certification basis, before they could be used to carry passengers.

Since the FAA will not allow airlines to use an airplane that does not comply with FAR 121, Boeing, Douglas, and AIRBUS must incorporate new FAR PART 121 requirements into their production airplanes before the airlines will buy them. Although FAR PART 121 is not applicable to the manufacturer of airplanes, the burden of modifying new airplanes almost always falls on the airframe manufacturer.

FAR PART 121 amendments are issued and treated the same way as FAR 25 amendments. Subsequent amendments to FAR PART 121 that are of particular note for cabin interiors are:

Amendment Number	Issue Date	Added Requirement
121-184	1987	Seat cushion fire blocking
121-189	1988	Ohio State Univ. heat release test
121-198	1990	NBS smoke release test

3.2 Unilateral Requirements

The criteria imposed by a manufacturer are often as important to the design criteria for an airplane as the regulatory requirements. An example of this is what was done for the 727, 737, 747, 757, and 767 programs at Boeing. Another example is the set of ATS 1000.001 requirements imposed by AIRBUS Industrie on the A300-600, A310, A320, A330, and A340 programs.

3.2.1 Criteria Used for the 727 and 737 Programs

Research done at Boeing in the early 1960s showed that a more stringent, and preferred, flammability test involved positioning the test specimens vertically instead of horizontally. In 1961, Boeing adopted an internal requirement that parts used for commercial transports had to meet both the horizontal test required by the FAA and an additional vertical flammability test. The 727 and 737 were developed according to this requirement.

In 1966, the FAA released a Notice of Proposed Rule Making (NPRM) to incorporate a vertical flammability test in the regulations, and issued a new rule (FAR PART 25 Amendment 15) doing so in 1967.

3.2.2 Criteria Used for the 747 Program

The AIA (principally Boeing, Douglas, and Lockheed) carried out a Crashworthiness Program in 1967 and 1968. This program included large scale fire tests and the evaluation of laboratory scale test procedures involving flammability, smoke emission, flame spread rate, etc., and resulted in a set of recommendations to the FAA for future rulemaking that involved a more stringent vertical Bunsen burner flammability test.

In the development of the 747 program, potential improvements that had been identified in the AIA Crashworthiness Program were taken into account. The upgraded Bunsen burner tests that had been recommended by the AIA to the FAA for future rulemaking were required, and were in fact imposed by the FAA as Special Conditions for 747 certification in 1969.

Other criteria involving flame spread, heat release, and smoke emission were adopted, all of which exceeded the applicable regulations. Test procedures included the ASTM E84 Steiner Tunnel procedure, and the ASTM E162 Radiant Panel procedure. Acceptance criteria appropriate to the material application (sidewall panels, ceiling panels, etc.) were established.

3.2.3 Criteria Used for the 757 and 767 Programs

In the early 1970s, the FAA initiated rulemaking activities involving smoke and toxic gas emissions of interior parts. ANPRM 74-38 addressing toxic gas emissions and NPRM 75-3 addressing smoke emissions were issued. In addition, NPRM 75-31 proposed to amend FAR 121 to require all new production aircraft to meet the upgraded flammability tests introduced in FAR 25 Amendment 25-32 (1972), and required prior to that for the 747 as special conditions.

Although the FAA subsequently withdrew these proposals in 1978 in favor of a more systematic approach to upgrading the regulations (the SAFER committee was set up to recommend how to do this), industry could not afford to wait to set unilateral criteria addressing smoke, toxicity, and upgraded flammability.

Accordingly, in early 1977 Boeing established supplementary unilateral guidelines covering flammability, and the emission of smoke and toxic gases. These guidelines were used for the selection of parts in the 767 and 757 programs, which were carried out more or less simultaneously.

The guidelines for smoke emission was Ds   50 (specific optical density   50), as measured in the NBS smoke chamber. This number was selected because we thought it was probably possible, and in fact was fairly low, relative to some parts that had been used.

The guideline for flame travel rate was Is   25 (flame spread index   25) as determined by the radiant panel test in ASTM E162. This number was also selected for basically the same reasons.

The guideline for toxic gas emission was also based on the NBS smoke chamber. We knew it would be better to run bioassay (i.e., animal) tests, but the number that would have been required was hopelessly larger than anything practical. We selected the six gases shown, and set the limits to be roughly what the available literature led us to believe was approximately half the level of a 5-minute incapacitating dose.

These criteria were intended to provide guidance for material suppliers in their development of new materials for parts. The criteria were technology drivers, because more materials than were then available were certainly needed.

The results of the suppliers' efforts were gratifying. While the guidelines were not met in all cases, better materials became available for making parts. A lot of progress was made.

3.2.4 D6-51377B Used for the 747-400

In January, 1984, Boeing issued a document -- D6-51377, "Aircraft Fireworthiness Interior Design Criteria" -- which comprised a comprehensive set of interior fireworthiness criteria to be applied to a new design and to guide modifications of current production aircraft. These criteria combined the existing FAR regulations with supplementary Boeing criteria.

The guidelines establshed in 1977 for the 757 and 767 were included in D6-51377.

In addition, D6-51377 contains unilateral requirements beyond the regulatory mandates for:

- additional provisions for fire containment in cargo compartments
- fire barriers to inhibit fire from entering the passenger cabin for scenarios involving post-crash fuel-fed exterior fires,
- fire barriers/baffles to inhibit the fire spread for scenarios involving interior fires,
- shielding of possible ignition sources such as light ballasts from potential combustibles,
- protection of electrical systems.

An updated version (Revision B) of this document was issued in 1986 and used for the redesign of the 747 cabin for the 747-400. The major difference between these versions is the replacement of the initial smoke emission guidelines by a set of component-to-component requirements.

3.2.5 AIRBUS ATS 1000.001

AIRBUS Industrie set up a set of criteria similar to the Boeing guidelines in ATS 1000.001, which was released in January, 1979. It did not, however, contain a Flame Spread Index criterion. Also, in addition to the unilateral criteria, ATS 1000.001 included a more detailed description of the mandatory Bunsen burner tests in the regulations.

Whereas the Boeing guidelines had set a goal of Ds 50 for smoke emission for any and all components, the ATS 1000.001 instead adopted the same component-to-component requirements proposed by the FAA in NPRM 75-3, which were usually higher.

The limits for toxic gas emission in ATS 1000.001 were for all practical purposes the same as for the Boeing guidelines.

3.2.6 Douglas Aircraft Company Criteria

The Douglas Aircraft Company imposed smoke emission and toxic gas emission criteria that varied depending on the application of materials. The Douglas criteria, as with ATS 1000.001, do not include Flame Spread Index.

4. CURRENT AND FUTURE NEEDS

The new heat release (FAR 25-66 and FAR 121-198) rule is forcing a large number of changes to be made in cabin interiors in a very short period of time. These changes are not yet complete. There are still a lot of problems and non-optimum solutions.

4.1 Thermosets

Historically, thermoset resins - particularly epoxy - became commercially available in the 1960s and, reinforced with fiberglass, were quickly adopted for use because of their weight-saving potential. Class dividers were one of the first components to be constructed of these materials. The sidewall and ceiling panels on the 747 were a sandwich panel construction consisting of fiberglass-reinforced epoxy faces on Nomex honeycomb core, and weighed about half as much as their predecessors on the 707, 727, and 737, which were fabricated of formed aluminum.

At present phenolics are being used extensively because they have low heat-release and smoke-release characteristics. They do have, however, certain drawbacks, such as:

- low peel strength
- bleed-through of brownish stains to decorative surfaces
- sensitivity of production workers to some formulations.

The low peel strengths have forced the use of bonding-enhancers to be added to the base phenolic chemistry. These bonding aids cause an increased heat release and smoke release, both of which are undesirable.

Bleed-through of brownish stains to decorative surfaces have caused production difficulties. The problem is that the bleed-through is not uniform; if it were it would be easier to handle. It causes blotches.

Most phenolic formulations have been used successfully in production with no reported problems. However, there have been reports of adverse physical reactions of some production workers to certain "specialized" phenolic formulations. This has forced the removal of some of these specialized formulations from production usage.

4.2 Thermoplastics

Thermoplastics have been used since the 1960s. Polyvinyl chloride was one of the early thermoplastics, although its use has been essentially discontinued because of its relatively low thermal stability and high smoke emission. Polycarbonate has found a lot of utility in thermally formed and injection molded parts but is now less widely used also because of low thermal stability and high smoke emission.

Materials manufacturers are working to develop replacement thermoplastics for thermal forming and injection molding that satisfy the new heat release criteria. Encouraging progress has been made, but frustrating problems such as consistency of production material remain.

In the early 1970s for the DC-10 and L-1011 programs, some of the cabin liner panels were multiply contoured, which required the development and use of a pre-decorated flexible thermoplastic "embossing resin" that could be stretched over the contours of the panel, and then bonded. This technique was further developed for the 757 and 767 programs, using embossing resins that had very good flammability and smoke emission properties. The A310 also used such techniques.

The embossing resins that had been used on these panels showed heat release values that were very close to the new heat release rule limits, and therefore had to be changed. The various materials suppliers have developed low heat release replacement materials, but these invariably have smoke emissions that are two to three times that of their predecessors!! Although these materials meet the new regulatory smoke requirements in the final version of the heat release rule (Ds 200), materials that do not represent higher smoke emissions than those formerly used are needed.

4.3 Textile Fibers

Textiles have been used for seat upholstery, drapery, decorative murals, and decorative abrasion resistant coverings for cabin sidewalls and partitions near the floor level. Traditionally wool and specialized polyesters have been the materials of choice for textile applications. These fibers are available in an unlimited palette of colors, are durable, and lightfast.

Seat upholstery and drapery are not affected by the new heat release rules. Decorative murals and decorative abrasion resistant coverings for cabin liners and partitions must comply with these requirements. Textile constructions that have been used in the past in these applications do not meet the new requirements.

The textile industry has made progress by using more heat-resistant synthetics. There is still a long way to go, however, and some special talent needs to be applied in this area.

5. CONCLUSIONS

The design of an airplane involves criteria that encompass regulatory requirements, manufacturer requirements, and passenger requirements. All these criteria are important and must be taken into consideration simultaneously.

In the development of new technology to improve safety, it is crucial that everyone involved work together. This includes manufacturers, materials suppliers, airlines, regulators, governmental oversight committees, associations representing affected parties such as passengers, pilots and flight attendants. Only in this way can the optimum progress be made.

FIRE RESISTANCE AND BREAKDOWN OF COMPOSITE MATERIALS

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I am Lecturer in Aerodynamics and Aircraft Design at the Royal Air Force College, Cranwell. Some of my knowledge of modern materials is the result of holding this post; however, my activities in this field are conducted independently. The views I put forward are my own and do not necessarily reflect those of the Royal Air Force or U.K. Ministry of Defence.

Before joining the staff at Cranwell I had some 30 years experience in industry - with responsibilities in environmental, life support and emergency systems. I also worked in cabin furnishings and became familiar with materials used.

INTRODUCTION

For some years I have been working privately on aspects of Cabin Fire Safety and Passenger Protective Breathing Equipment, latterly with some financial assistance from the Department of Trade and Industry.

When seeking heat resistant materials it became clear that some did not conform to the new test procedures for cabin interiors effective August 1988 - yet they remain allowable for structural purposes.

The first stage in materials selection is the rejection of unsuitable ones.

COMPOSITE MATERIALS

In this context I am primarily concerned with non-metallic composites which are finding increasing use in furnishings and structures. All consist of fibrous elements to carry tensile loads embedded in solidified resins which resist compression.

Fibres tend to be Glass, Carbon, Boron or Aramid while Resins are Polyester, Epoxy or Phenolic, with developments in Polyimide, Bismaleimides and Polybenzimidazoles. Those used currently in aircraft structures are almost exclusively Carbon and Aramid in Epoxy resins; for furnishings, Glass or Aramid fibres and Phenolic resins only are now acceptable.

VIRTUES

The selection of these depends on their mechanical properties and cost benefits. (Higher material costs are more than offset by reduced labour costs in final assembly.)

The strength-to-weight ratio of Carbon/Epoxy is generally considered to reduce weight by at least 10% when compared with metal structures, and up to 25% if re-sizing of an aircraft is admissible.

Many fasteners are eliminated by wet lay-up of skin and stringer combinations, so improving exterior surface finish. This form of construction is also less subject to leaks when used for integral fuel tanks and pressure cabins.

Unlike metals, the tensile fatigue properties of carbon fibres seem almost unlimited, the compression fatigue of the resin matrix is believed to be the critical feature.

Epoxy resins are, to date, the only matrix compounds which have demonstrated repeatable mechanical strength. They do not possess fire resistant characteristics adequate for furnishings. Phenolics do, but manufacturing is more difficult while the finished product is subject to wide variations of integrity due to gaseous voids etc.

Polyester resins have not found favour in commercial aircraft.

All of these resins solidify by non-reversible chemical reactions, some at room temperature but more usually autoclaved at elevated temperatures. These are thermosets.

FUTURE TRENDS

Polyimides and Bismaleimides do not yet have the proven background needed for significant use in aircraft structures; nevertheless they are considered "promising" for non-structural applications.

Thermoplastics such as Polycarbonate, Polyethersulphone (PES) and Polyether-ether-ketone (PEEK) are already used with short fibre strand re-inforcing and it may be anticipated that, with time, long strand capability will be more fully developed.

PHILOSOPHY

In the light of the above knowledge, particularly awareness that carbon-epoxy and aramid-epoxy combinations are those whose established mechanical properties led to their selection for structural use, and that both epoxy and aramids have been rejected for furnishing purposes, it was decided to examine more closely the properties of these and other composites. Also, to determine whether appropriate specifications could be devised.

PRELIMINARY EVALUATIONS

As an engineer with limited chemical expertise first considerations were qualitative rather than quantitative. These consisted of exposures to heat and flame:-

(i) 100°C continuous
(ii) 200°C 15 minutes
(iii) 1000°C nominal 5 seconds, transient flame.

These are based on CAA Specification No. 20 for Breathing Apparatus, which has BSI and FAA equivalents.

FINDINGS

Carbon Fibre Composite

Although no visible deterioration was found at 100°C it is known that UTS at this temperature is only about 20% of its 20°C value.

Aramids (Polyamide)

Not tested independently since they require a resin matrix exactly as CFC. It is known, however, that they are no longer considered suitable for furnishings regardless of the matrix used.

Polyimides

Pass 100°C and 200°C. Performance (in film state) at 1000°C depends on thickness and manufacturer. One product was penetrated immediately, material directly in the flame vaporised with char around. Two grades from another source were tested; one behaved as above for all thicknesses available, the other showed only slight distortion without penetration provided adequate thickness was used; 40 micrometres sufficed.

Polycarbonate

Softened to a thermoformable state at 200°C, vaporised at 1000°C.

Polyethersulphone

Satisfactory at 200°C, distorted and embrittled at 1000°C.

Polyether-ether-ketone

Not tested, but known properties are:

Glass transition temperature 143°C
Melting point 332°C
Considered structurally satisfactory to 100°C

FURTHER TESTS

Epoxy Resins

Additional testing of carbon-epoxy laminates has been undertaken. Hot air at 350°C was directed onto a cured panel and it was found that the resin initially disbonded, then broke down. Gaseous products are produced.

Phenolic Resins

Phenolics exhibit superior resistance to heat; nevertheless they char readily to produce a surface layer of porous carbon. The carbon then slowly burns away, protecting inner layers by ablation.

TEST REQUIREMENTS - CURRENT

There are at present no specific burn tests required to be performed on structural materials; provided that they meet strength needs throughout the normal operating environments of BCARs/FARs/JARs etc. they are accepted.

In the writer's view a suitable test schedule can be created by combining details from a group of existing specifications relating to fire resistance.

In essence, materials used for cabin furnishings must be self-extinguishing and lose not more than a specific proportion of their weight when exposed to radiant heat for a finite time, (CAA and FAA). Airbus Industrie has maximum allowable emissions of specific toxins under essentially similar conditions.

For certain non-aircraft products emissions are also controlled, there being two methods of conducting the tests:

(i) exposed to gas flame in a chamber from which samples are extracted after the flame is extinguished (BSI, Airbus et alia)

(ii) electrically heated sample in a crucible enclosed within a tube through which air is passed. Samples taken at exit. (German DIN method)

TEST REQUIREMENTS - PROPOSALS

Objectives - Minimum standards for Passenger Compartments.

1. To establish that, if flammable, materials do not contribute significantly to the fire hazard.

2. In the combustion process toxic gases should not be emitted, If they are, then the types and quantities should be identified. (Failure to acknowledge this consideration justifies provision of breathing equipment for all occupants.)

3. Structures should afford a measure of fire containment or exclusion. For example an integral domestic garage must, in UK, be separated from residential accommodation by doors, walls, ceilings having minimum 1 hour fire check capability. (In the Manchester Boeing 737 accident, external fire penetrated the fuselage in a matter of minutes.)

4. An agreed mimimum residual static strength to remain after a timed exposure to radiant heat.

TESTS

All materials considered for use in the construction of Passenger Compartments should demonstrate adequate compliance with the above objectives.

1. Using an agreed test procedure (either the DIN or similar smoke chamber method) conduct sampling tests on emissions. The chemical composition of the material will indicate what harmful gases may be anticipated.

2. The sample to be weighed before and after the above test and percentage weight loss determined to demonstrate compliance with an agreed standard.

3. Heat transfer/fire check capability to be proven. Sample subjected to radiant heat exposure at an agreed intensity, inner surface temperature not to exceed (say) 200°C or be breached in less than 10 minutes.

4. At the end of 10 minutes exposure to the above radiant heat intensity the structure should be able to stand intact at rest, on the ground.

These suggestions are made in the light of past accident experience. Two aircraft are currently flying with composite-built pressured cabins - the AV8B/Harrier II and Beech Starship. Neither is intended for carriage of fare-paying passengers but their experience in service will doubtless be used to justify use of these same materials in future airliners.

The benefits offered by CFC and other composites justify their use. Other materials have been used for other applications and have subsequently been banned when their dangers became established. Aviation has led many technological advances in the past; let us ensure that it continues to make progress safely.

Advanced Materials for Interior and Equipment Related to Fire Safety in Aviation

by

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1. SUMMARY

The improvement of the safety of products is continuously under review by aircraft manufacturers. One of the most important fields of safety for passengers and crew members relates to improvements in connection with fires inside and outside the cabin. Naturally, several paths have to be followed simultaneously to achieve the best possible effect. First and foremost there is obviously the endeavour to avoid such accidents from the start. The training of the crew, design of the aircraft and maintenance, airport safety facilities and - last not least - the introduction of improved materials are of vital importance to reduce the danger of accidents with fires.

This presentation deals with the important aspect of material development and structural design for the interior furnishings and equipment of aircraft.

2. REGULATIONS AND REQUIREMENTS

2.1 FAA Regulations

The Federal Air Regulations (FAR's) define the certification and operation regulations.

FAR Part 25 "Airworthiness Standards: Transport Category Airplanes" applies for the certification of new passenger aircraft. The operation of aircraft by airlines is covered by FAR Part 121 "Certification and Operations: Domestic, Flag and Supplemental Air Carriers, and Commercial Operators of Large Aircraft".

In 1966 the FAA published its first "Notice of Proposed Rule Making" (NPRM) for the introduction of a vertical flammability test. The new rule (FAR Part 25, Amendment 15) was published in 1967. Further amendments affecting the cabin and cargo compartments followed later.

Issue date	Amendment	Requirement
1967	25 - 15	12 sec vertical Bunsen burner test
1972	25 - 32	60 sec vertical Bunsen burner test
1984	25 - 59	Seat cushion fire blocking test
1986	25 - 61	Ohio State University heat release test
1986	25 - 60	Cargo liner fire containment test
1988	25 - 66	NBS smoke release test

Similarly, the FAA published the FAR Part 121 Amendments concerning aircraft being manufactured.

Date of Validity	Amendment	Requirements
1986	121 - 189	Ohio State University heat release test
1987	121 - 184	Seat cushion fire blocking test
1990	121 - 198	NBS smoke release test

2.2 Manufacturer Requirements

In 1979 an additional requirement for materials and parts of the interior and equipment, the so-called ATS 1000.001 was introduced by Airbus Industrie/MBB.

This requirement which became mandatory for all Airbus aircraft limited the emission of smoke and toxic gases for all non-metallic materials used in the pressurized fuselage in addition to the FAR 25 - 32 flammability requirement valid at the time.

Six gases were named which are known to occur in the smoke gas of the materials commonly used:

- carbon monoxide CO
- hydrogen cyanide HCN
- hydrogen chloride HCl
- hydrogen fluoride HF
- sulphur dioxide $SO_2 + H_2S$
- nitrogen oxides $NO + NO_2$

The following table gives the allowable limit values for the most important parts of the interior and equipment as valid at present. These values are measured in the NBS chamber.

<u>Gas Limits</u>

- hydrogen fluoride (HF) : 50 ppm after 1,5 min and 4 min
- hydrogen chloride (HCl) : 50 ppm after 1,5 min and 500 ppm after 4 min.
- hydrogen cyanid (HCN) : 100 ppm after 1,5 min and 150 ppm after 4 min.
- sulphur dioxide (SO_2+H_2S) : 50 ppm after 1,5 min and 100 ppm after 4 min.
- carbon monoxide (CO) : 3000 ppm after 1,5 min and 3500 ppm after 4 min.
- nitrous gases ($NO+NO_2$) : 50 ppm after 1,5 min and 100 ppm after 4 min.

Smoke Limits

parts	D_s after 90 sec.	D_s after 4 minutes
textiles	--	100
floor covering		
draperies		
upholstery		
air ducting	--	100
insulation	--	100
major panels	100	200
ceiling panels		
wall panels		
sidewalls		
stowage compartments		
partitions		

Following the publication of Amendment 25 - 66 / 121 - 189, the revision of ATS 1000.001, issue 4 has now got under way, the most important change being a further reduction in smoke gas emission for the major panels of the cabin. The revised version, issue 5, is to be published immediately.

Boeing and McDonnel Douglas have introduced similar in-house requirements.

Boeing:	D6 - 51377	Smoke and Toxicity
McDonnel Douglas:	DMS 1500	Smoke
	DMS 2294	Toxicity

Apart from a few exceptions, the standards of all these requirements are comparable, going beyond the stringency of the existing regulations of the authorities in terms of the smoke emission requirements.

3. HISTORY OF MATERIAL DEVELOPMENT OF AIRBUS AIRCRAFT WITH REFERENCE TO THE REGULATIONS AND ATS 1000.001

The materials mainly used for the interior of the Airbus A300 (1974) were epoxy glass sandwiches, ABS, polycarbonates and PVC. On introduction of the ATS 1000.001 the ABS and PVC parts were eliminated and replaced by polycarbonate parts and phenolic glass sandwiches. Above all, the smoke intensive epoxy resin was replaced by phenolic resin which produces little smoke. The Airbus (A310 - 1981) corresponded to this standard.

Following the publication of Amendment 25 - 61 / 121 - 189, it was primarily necessary to replace the polycarbonate injection moulding parts used for large surfaces in the passenger service units by thermoplastic materials with low heat release characteristics. Polyetherimide (PEI) and polyethersulphone (PES) were introduced to meet the requirements 100/100 kW/m^2 and $kW\ min/m^2$. It was possible to process these materials in the same injection moulds after minor changes. The problem of higher shrinkage due to the approx. 50 to 100 °C higher processing temperature was controlled by up to 10 % short glass fiber contents.

Normally, such injection moulding parts are dyed directly. However, there are considerable problems of colour constancy with fiber glass reinforced parts and it is also hardly possible to achieve an acceptable colour equivalence between PEI and PES parts. This has meant that such parts have had to be provided with a paint coating which gives rise to extra costs and weight.

Another aspect which is unsatisfactory is the high brittleness especially of highly pigmented light colourings. The natural amber colour is particularly problematic in this connection. Considerable efforts were required to adjust the decorative surface systems -encompassing decorative varnishes, decorative foils and decorative textiles - to the new Heat Release Requirement (100/100). In all three cases totally new products had to be developed and qualified within a very short period in order to be able to deliver on August 20th 1988 aircraft meeting the values 100/100 kW/m^2 and kW min/m^2 in compliance with Amendment 25 - 61 / 121 - 189.

In the case of the varnishes, it has been possible to decrease the heat release (peak) to the order of 80 kW/m^2 by developing a new filler which has a blocking effect and by reducing and further limiting the polymer layer thicknesses. The integral values are in the order of up to 80 kW min/m^2.

As regards the decorative foils which consist of two Tedlar foils (PVF), intermediate embossing resin (structure and colouring) as well as a layer of adhesive, it has been possible to reduce the heat release sufficiently by means of new Tedlar foils with reduced heat release, new flame-inhibiting embossing resin and new adhesives. However, an increase in smoke emission had to be accepted.

The situation with decorative textiles for wall coverings is unsatisfactory. MBB currently has a qualified product on PBI basis which, when applied to phenolic glass sandwich material, is only minimally under the 100/100 limit therefore providing insufficient tolerance and constantly causing problems in production.

4. MATERIALS FOR COMPLIANCE WITH AMENDMENT 25 - 66/ 121 - 198

Now, what is the situation as regards compliance with the second stage of the Heat Release Rule, Amendment 25 - 66 / 121 - 198 with the values 65/65 kW/m^2 and kW min/m^2 (peak and 2 minutes total heat release)? We are currently in the course of development and qualification of materials for this stage. In order to be able to deliver aircraft on 20th August 1990 which meet these regulations the materials will have to be defined by the middle of this year.

Phenolic glass sandwich material with a Nomex honeycomb will remain the basis for major panels (sidewalls, partitions, ceilings, hatrack doors and walls for galleys and toilets).

New generations of decorative foils, paint systems and textiles will be used to decorate these panels.

Decorative foils from various suppliers - resulting from the first stage of the Heat Release Rule - are being qualified.

As regards Airbus components which are provided with decorative varnishes, a new spray filler and a new top coat of a supplier are currently at the qualification stage.

Both these decorative systems (foil and varnish) will make it possible to meet the 65/65 requirements in future.

As far as textile decorations are concerned, only the wall coverings are affected by the Heat Release Rule. There are no adequately developed textiles for fulfillment of the 65/65 requirement today. Core spun yarns which are undergoing investigation offer a certain potential. Some of the most important are listed below:

- polyamidimid
- polyetherimid
- polyamid
- polyester, FR
- polybenzimidazole
- wool, FR

These textiles are governed not only by the Heat Release Rule but also the relevant smoke emission (NBS), toxic fume emission (NBS) and flammability test (Bunsen burner) requirements, which is a particular challenge if color fastness, cleanability, abrasion and corrosion resistance are to be kept within specified limits.

Qualification activities for thermoplastic injection moulding parts of the passenger service units are focussed on polyetherimides (PEI) for the time being. However, for some dyes there are certain problems in obtaining an adequate safety margin for the 65/65 heat release values. It may prove necessary to stop dying these parts and to coat them with varnishes instead. Besides the use of PEI, second source development work also encompasses investigations into the use of modified polyethersulfone (PES) and polyphenylsulfone (PPSU).

The use of these materials partly results in considerable additional expenditure due to the need to provide completely new injection moulds.

5. FUTURE DEVELOPMENTS

As already indicated, current development and qualification activities do not provide satisfactory solutions for fulfillment of the Heat Release Rule for 1990 in every case. This will be the major task for materials development engineers and aircraft producers in the immediate future. The most important activities will have to be in the following areas:

- availability of a thermoplastic injection moulding material for the PSU's with better dying characteristics, less brittleness, lower solvent sensitivity and good processability, as well as low heat release values. HR $\leq$ 55/55

- development of decorative foils with smoke emission values of less than Ds = 100.

- availability of a textile wall covering material with heat release values of less than HR $\leq$ 55/55 in an applied condition on phenolic resin sandwich components.

In addition, important activities for the further development of materials for equipment and furnishings will focus on the following areas.

In order to reduce weight and cost, milled aluminium parts and aluminium castings will increasingly be replaced by short fiber reinforced thermoplastic injection moulding parts for interior equipment and furnishings. Polyetherimides (PEI) and polyetheretherketone (PEEK) with short glass and carbon fiber reinforcement (up to 30%) are primarily used. In some cases, weight savings of up to 50% are possible and at small quantities per aircraft considerable cost savings are possible - especially by comparison with milled aluminium parts.

Intensive development activities are under way in the field of fabric-reinforced thermoplastics at many of the major manufacturers and processors of thermoplastic materials. This group of materials is entering into competition with the fabric-reinforced phenolic resin systems widely used today. At the present stage, aircraft manufacturers see no essential technical requirement making the use of this new group of materials compulsory on the short term. Even the latest regulations regarding fire-safety can be met with today's phenolic resin systems. However, modern fiber-reinforced thermoplastics may possibly offer a cost reduction potential making the partial use of such materials in the interior and for equipment attractive. Such potential cost advantages will, however, have to be demonstrated first. The potential relates to:

- the low cycle times
- better surface quality and thus reduced decoration effort
- possibility of producing integral components by welding
- possibility of deep drawing and pressing processes.

The major disadvantages at present are the two to three times higher material costs than phenolic resin semi-finished products.

As far as plane sandwich structures in the cargo hold and passenger compartment are concerned, it is fair to assume that there will be suppliers of continuously produced sandwich panels with fabric-reinforced thermoplastic materials in the near future. These could certainly compete with fabric-reinforced phenolic resin sandwich panels.

6. CONCLUSION

Working towards on improvement in the safety of passengers in commercial aircraft, it is not really possible to achieve a target. Constant efforts must be made to protect the health and safety of passengers in the event of an accident which can never be completely ruled out. It is therefore always only possible to reach intermediate targets.

It is the responsibility of the aircraft manufacturers, material developers and suppliers, certification authorities, airlines, aircraft crews, airports and further organizations to jointly work towards this end. There can be no standstill.

NEW MATERIALS FOR CIVIL AIRCRAFT FURNISHING

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SUMMARY

In order to improve aircraft safety with respect to fire, in the last few years the authorities have issued several regulations relative to the fire resistance of organic materials used in civil aircraft commercial furnishing, in particular FAR 25 Amendment 61 and FAR 121 Amendment 189. Their purpose is to to limit the heat release of the materials used for passenger cabin furnishing.

These regulations to be applied on aircraft delivered as soon as August 88 are very severe as they prohibit the use of most of the materials which have been used up to now.

The purpose of this paper is to present the various investigations on new materials made at Aérospatiale together with the development of new technologies.

1. INTRODUCTION

In order to improve aircraft safety with respect to fire, in the last few years the authorities have issued several regulations relative to the fire resistance of organic materials used in civil aircraft commercial furnishing, in particular FAR 25 Amendment 61, FAR 121 Amendment 189; their purpose is to limit the heat release of the materials used for passenger cabin furnishing.

These criteria imposed are extremely severe as they prohibit the use of most of the materials which have been used up to now such as ABS, PVC, PC, Aramid, Prepregs.

Manufacturers and material suppliers are faced with a real challenge to develop new materials and launch them in series production in a very short period of time in order to meet the regulations.

The purpose of this paper is to present the various investigations on new materials made at Aérospatiale together with the development of new technologies in order to improve the level of safety board aircraft constantly.

2. THE NEW REGULATION

The new regulation consists in testing the samples representative of the various commercial furnishing panels with their decoration by subjecting them to the old tests to which new tests have been added.

FAR 25 Amendment 32 : Bunsen Burner Test
(burnt length - extinguishing time)
FAR 25 Amendment 61 : OSU Chamber Test : HR heat release and HRR Heat release rate

FAR 25 Amendment 66 : NSB Chamber Test
(Opacity of smoke after 4 min.)

The test causing the greates number of constraints and which is the most difficult to conduct is the one in the OSU chamber because todate very few laboratories are equipped with OSU chambers and the regulation is still not precise as regards the adjustment parameters to be respected and the procedures for validating this test.

3. MATERIALS RECOMMENDED BY THE FAA

To meet this new regulation the FAA propose to use the fibre glass/phenolic resin prepreg lay up. The FAA base their proposal on the results of full scale tests which were performed on a C 133 which showed that when fibre glass/phenolic resin was used the flash over occurred after 240 sec., whereas with the other industrial materials tested it occurred earlier.

Aerospatiale are very familiar with the fibre glass/phenolic resin prepreg lay up technology since it has been used in their workshops for more than 20 years. Concorde was already equipped with panels produced using fibre glass/phenolic resin prepregs; this means that Aérospatiale know the advantages and disavantages of this solution well.

Advantages	Disadvantages
- Provides good safety as regards risks of fire - good mechanical characteristics in particular good stiffness - cheap prepreg	- tack still badly controlled which makes lay up more or less difficult - limited shelf life - storage in cold chamber - high density (d = 2.5) - long implementation which is thus expensive although operations have been automatized - safety and health problems due to the free phenols released.

4. AEROSPATIALE OBJECTIVES

Considering the short time we had to meet the criteria imposed we have to fixe the objectives :

- to keep the same design so as to use the existing tools
- not to increase weight

The materials implemented today correspond to these objectives and are provided in para 5.

In the future, we intend to :

- change the design to reduce manufacturing costs
- work with materials that are more flexible to implement
- continue improvements as regards safety with respect to fire

Investigations have been initiated at Aerospatiale and are provided in para 6.

5. NEW MATERIALS IMPLEMENTED AT AEROSPATIALE TO MEET THE LATEST REGULATIONS : (without changing the design).

5.1. Thermo setting prepreg lay up :

Most of our furnishings are produced by laying up thermosetting prepregs. The idea of creating a carbon fibre glass/phenolic resin hybrid was born when analysing the carbon fibre/phenolic resin prepreg heat release which is just below that of the fibre glass/phenolic resin prepreg.

The hybrid we are using at the present time is made up of :

. 33 % of carbon fibre which gives it very good stiffness; the carbon fiber used is a large mesh material.
. 66 % of textured fibre glass which is thus light, to complete the weave and achieve relative sealing.
. impregnation of modified phenolic resin.

With respect to the fibre glass/phenolic resin prepregs :

. the weight saving is about 30 %, i.e. 8 kg for an Airbus A320 cockpit lining
. the behaviour to respect to fire is similar
. the mechanical characteristics are not absolutely equivalent but the presence of carbon provides good stiffness which is determining factor for furnishing
. implementation is easier as a result of better lay up possibilities and better surface appearance.

5.2. PES plate thermo setting

A certain number of components were produced by thermo setting polycarbonate plate.

When the new regulation appeared we had to chose thermoplastics which were not thermostable such as polyetherimid (P.E.I.) or polyethersulfone (P.E.S.).

The first product available on the market was ULTEM 1613 produced by G.E., but this material did not allow light shades and the desired texture to be obtained easily. This is why we chose a P.E.S. thermoplastic : Europlix Ultrason E produced by a german company, Rhom, on the basis of B.A.S.F. raw material, and which has recently changed to Europlex Ultrason EQ7 in order to guarantee the heat release 65/65 criteria required in the official regulation.

Although implementation of these thermoplastic plates is more complex than that of the polycarbonate plates, it requires high thermo setting temperatures and differential heating temperatures which have to be optimized according to the shape of the part, but it has been possible to keep the existing tools.

6. DEVELOPMENTS OF NEW TECHNOLOGIES AND NEW MATERIALS :

Aerospatiale is looking towards new technologies to reduce production costs, use materials that are more flexible to implement, and improve safety.

6.1. Reinforced thermoplastic stamping (without flow) :

This process is similar to die forging for metallic materials; it is performed in three stages :

(1) a laminate is made up with a certain number of plies determined when the part is designed
(2) the laminate is pre-heated
(3) it is stamped using a cold mould made up of a metal upper die and bottom die on a conventional press.

To apply this process, Aérospatiale has acquired a "bay" which pre-heats the laminate and prevents the laminate from cooling between operation (2) and operation (3).

The pressures exerted are about 2 to 5 Mpa. Aérospatiale has worked with different types of P.E.I., P.E.S. and P.P.S base materials and different reinforcements : fiberglass, carbon/fibreglass hybrid, with conventional weaves and deformable weaves.

This technology is perfectly well suited to constant thickness developable shapes and small or medium size parts.

As the resin is thermoplastic, no curing is required; storage duration is unlimited at ambient temperature, and the resin only has to be softened before use.

Implementation costs are 30 to 50 % less according to the parts.

6.2. Powder impregnated phenolic thermo setting composite stamping :

Phenolics for their parts, are evolving. We are using a stamping process for powder phenolic impregnated carbon-fibreglass hybrid plates. This method eliminates the problems caused by thickness and the presence of volatile contents.

The shaping is performed on a semi-finished product which is a rigid sheet, stored at ambient temperature.

The technology can be used for the same type of part as the one described in 6.1. Its implementation involves more constraints as a hot mould is used instead of a cold one, and the cure time is a little longer. The base material, on the other hand, is cheaper.

A value analysis must be made for each part in order to choose between 6.1 and 6.2

6.3. Compression moulding with flow :

The process can be compared to forging for metallic parts. It requires :

. a heating installation capable of heating the material to a temperature at which it can be moulded
. a quick-close press capable of maintaining the pressure until the resin has stopped flowing
. a metallic mould (upper die/bottom die)

The semi-finished product is a sheet reinforced with fibreglass or carbon fibres (cut fibres or mat) or a carbon/fibreglass hybrid imprenagted with a thermoplastic resin (P.E.I. or P.E.S) : G.M.T. or a non acid phenolic resin : S.M.C.

The sheets, which have the same weight as the part to be moulded, are placed inside the lower half of the mould. the press is then activated. The two halves of the mould come together quickly and exert a pressure on the reinforcement of the semi-finished product.

The material which initially covered only a part of the mould will flow and fill the whole space in a few seconds without shearing. Fibre length is thus almost totally unaffected by the moulding operation.

As it is the reinforcement fibres that carry most of the load in a composite, fibre arrangement in the finished part plays a predominant part in obtaining the mechanical properties. It is thus necessary to check the regularity of the fibre arrangement on the first parts by dissection, particularly if the geometry is complex.

This technology makes it possible to obtain parts with complicated geometries and variations in thickness, ribs, etc. ...

The pressures required depend on the complexity of the shape of the part, but they are typically in order of 20 MPa. Aérospatiale has chosen to design the ATR 42/72 luggage rack door and side panels using this technology.

6.4. Resin transfer moulding (R.T.M.)

This process consists in thermo-forming a special reinforcement to the exact shapes and size of the part, in the mould, and then injecting a liquid phenolic resin under low pressure or vacuum.

Resin tranfer moulding is carried out in several phases :

(1) cutting out the reinforcements

(2) positioning the reinforcemants, generally one above the other, in a frame or retaining plate retaining the reinforcement peripherally. The tension of this retaining plate must be adjusted in order to permit relative slippage of the plies towards the centre of the mould. A large part of resin transfer moulding know how resides in good design and good adjustement of the retaining plate.

(3) heating in an oven to soften the reinforcement binder.

(4) forming the reinforcement in the press.

(5) cooling in the mould to set the binder which makes it possible to conserve the shapes.

(6) cutting the preliminary shape to the exact dimensions of the part to be moulded.

(7) placing the preformed reinforcement, cut the size of the part, in a closed mould sealed in around the periphery.

After injecting, the excess resin required to expel the air initially present in the mould is removed via vent holes perpendicular to the plane of the mould.

This technology also makes it possible to reduce production costs and obtain parts that have an excellent surface condition and do not require a surface treatment operation before being painted.

7. CONCLUSION

Aerospatiale are on the point of adapting new technologies to put them in a even better position with respect to the existing regulations and enable them to produce parts at less cost. But to be able to do so, future regulations must be realistic, i.e take account of industrial reality from the point of view of test methods, criteria to be met and available industrial materials. What do tomorrow's regulations have in store for us ? Toxicity requirements ? Burnt through requirements ? It would be desirable for the intended directions to be announced early enough to enable the necessary developments to be prepared. The position of an aircraft manufacturer such as Aerospatiale is very difficult today, as modifications to the regulations are often made hastily and therefore lack consistency.

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HEAT RELEASE RATE MEASUREMENT FOR EVALUATING THE FLAMMABILITY OF AIRCRAFT MATERIALS

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Summary

With the goal of improving fire safety in passenger aircraft, the FAA and Transport Canada have adopted a new test method to evaluate the flammability of aircraft interior materials. The method uses a modified ASTM E906 release rate test apparatus. Experiments have shown that the test is affected by small variations in such factors as the pattern of airflow in the combustion chamber, the number and position of pilot flames and certain characteristics of the sample such as flame retardancy and physical construction. The author discusses the various factors affecting the test. Of particular interest is a comparison between the thermal method and the oxygen consumption method of HRR measurement. The oxygen consumption method is recommended.

Introduction

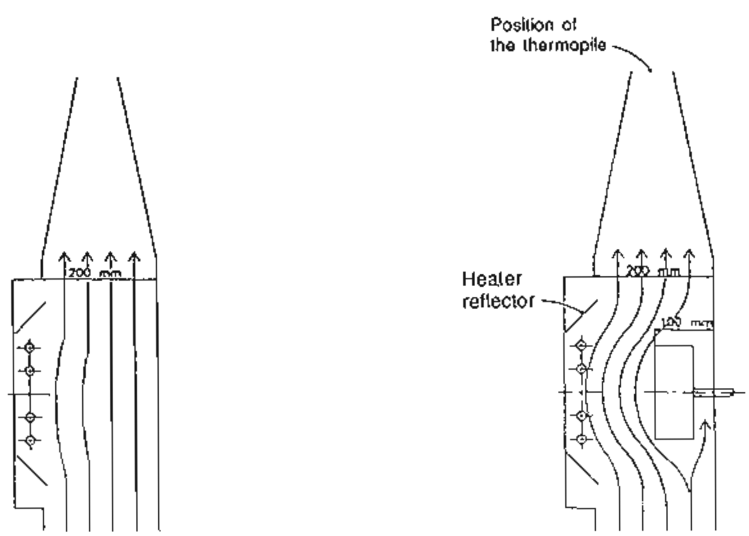
To upgrade the fire safety standards for cabin interior materials in transport category airplanes, the Federal Aviation Administration (FAA) started a program in the late 1970s to establish a method for testing flammability under an imposed radiant heat representative of the post-crash fire environment. A standard test method of the American Society of Testing and Materials (ASTM), ASTM E906(1), was adopted as the most suitable method for the purpose. The E906 standard test was originally developed for testing the flammability of building materials which generally have HRR's between 150 and 400 kW/m^2. For aircraft materials, HRR's below 100 kW/m^2, or ideally below 65 kW/m^2 were being sought. To measure such small values of HRR accurately, the current FAA test was developed from the ASTM E906 test by improving the sensitivity of measurement and by precisely defining the test conditions.

The Fire Research Section of the Institute for Research in Construction, National Research Council of Canada (NRCC) has been involved in establishing the FAA test in Canada under the supervision of Transport Canada since 1985. The facility and the testing method were successfully inspected by the Technical Center of the FAA in 1987, and since April 1988 tests have been performed both for certification and development purposes.

The purpose of this paper is to share acquired technical information with other international testing laboratories which have developed, or are developing, their own testing facilities for the FAA test with the goal of upgrading the testing methods and thus improving fire safety of aircraft materials.

PATTERN OF AIR FLOW IN THE COMBUSTION CHAMBER

Fig. 1 Cross section of the combustion chamber and the pattern of air flow
(a) Before sample injection (b) After sample injection



Heat flux density on the specimen surface must be uniform and within 5% variation as described in the regulation(2). To get uniformity, a diamond shaped mask plate is used in front of heater bars and also, the slopes of the edges of heater reflector plate are adjusted(2). Adjusting the slopes, however, may change the pattern of air flow in the combustion chamber and the HRR measurement may be significantly affected. When a specimen of no heat output is injected into the testing position, mV output of the thermopile may be expected to fall because of the heat absorption by the cool specimen and the specimen holder. Actually, the mV output increases because more air flows towards hot heater bars as shown in Fig. 1. This increase could be as high as 1.5 mV depending on the angle of the slope; 1.5 mV corresponds to about 18 kW/m² in HRR measurement. When a particular testing apparatus constantly shows higher values than others, this effect should be examined.

PILOT FLAME PROBLEMS

The FAA has ruled that both the upper and lower pilot flames should remain lighted at all times during tests, but the pilot flames occasionally are extinguished. When a material treated with flame retardants is tested, the evolved gas may extinguish some of the upper pilot flames. As well, the lower pilot flame may be physically smothered by swelling of the front surface of a specimen.

The upper pilot

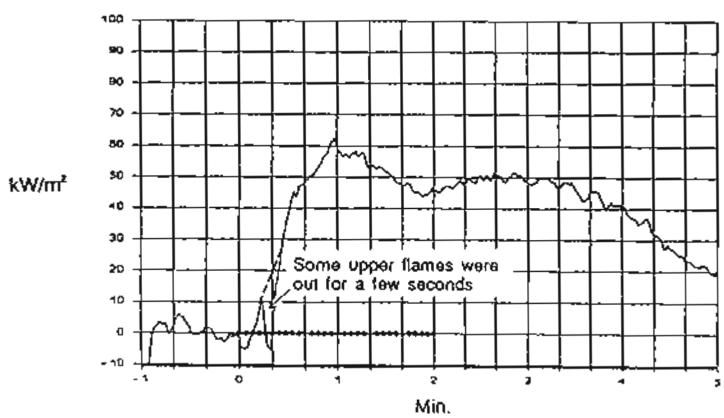
The original design of the upper pilot burner had three flames 60 mm apart. Once a flame was extinguished, it did not reignite. When the upper pilot flames are off, combustion of gaseous decomposition products is less efficient and a dip appears on the release rate curve. To alleviate this, the burner has been redesigned to have 14 flames 12.7 mm apart.

Even with the new design, some of the flames may still be extinguished but they are easily reignited by adjacent flames. The problem has been mitigated, yet some dips still appear on release rate curves as shown in Fig 2. The dip reduces the value of accumulated heat release. The reduction may be corrected by integrating the area below the broken line in Fig. 2, or alternatively, the dip can be left as it is since generation of flame extinguishing gases may be a desirable characteristic of the material.

The lower pilot

Smothering the lower pilot flame could occur in testing a material with a honey-comb structure. The built-up pressure in the honey-comb makes the heat softened front surface swell thus blocking the lower pilot. When the lower pilot flame is off, flaming of a specimen could cease completely. Installation of a reigniter has been suggested to cope with this problem. One suggested design is a spark ignition gap installed immediately in front of the pilot burner. The high voltage of a spark source, however, may produce noise in the data system or cause unpleasant electric shocks to the operator. At NRCC, a hot platinum wire igniter has been used.

Fig. 2 HRR trace when some of the upper pilot flames extinguished



It has been noted that installing a hot wire igniter prevented smothering of the pilot flame by providing a physical barrier in front of the pilot flame. A simple guard and not a reigniter may solve the lower pilot problem in most cases. Another suggestion is to install crossed wires on the surface of the specimen attached to the edge of the specimen holder; this will prevent swelling of the specimen surface at the position of the lower pilot burner.

AIR TIGHTNESS OF THE COMBUSTION CHAMBER

The FAA test apparatus loses its air tightness upon repeated use, especially around the heater bar fixture, and supply air may leak out of the combustion chamber. The air leak results in larger values for the calibration constant. The air tightness can be checked visually by placing a smoke generator in the combustion chamber or by flowing nitrogen instead of air and measuring the decay of oxygen concentration at the chimney. The latter method can be performed conveniently in the oxygen consumption method of HRR measurement, which will be discussed later in this paper.

SURFACE AREA OF A SPECIMEN

The specimen holder has front dimensions of 0.156 m X 0.156 m with a 6 mm wide edge. The exposed surface of a specimen is then 0.144 m X 0.144 m =0.02074 m^2. The FAA rule requires that 0.02323 m^2 surface area be used for HRR calculations. The difference from the exposed surface area is approximately 12%.

STATISTICS OF TEST DATA

Small variability of test data is desirable in a test for better control of the quality of materials to be tested. The quantitative measure of the variability is the standard deviation. Variability of test results in the FAA test has been studied in two different ways. One was a repeated test of a control sample over a period of 8 months and the other was statistical analysis of actual test data.

The variability of data in repeated tests is mainly caused by variation of test conditions. Variability in triplicate test data is variation of the specimens and of test conditions specifically related to the material, such as instability of pilot flames.

Repeated tests of a control sample in an 8 month-period

Specimens of a control sample were tested 17 times over a period of 8 months. Means and standard deviations are as shown in Table 1.

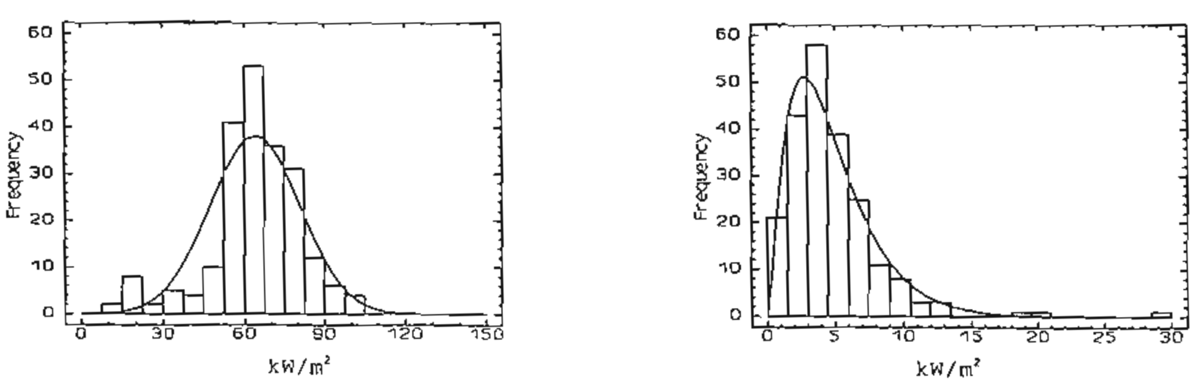
Table 1 Repeated test of a control sample in an 8 month-period

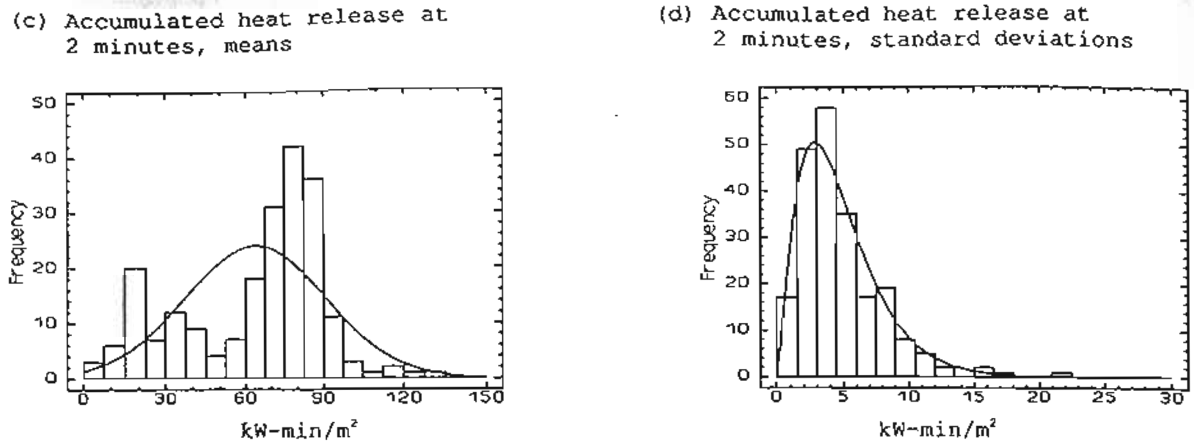
	Number of tests	Mean	Standard deviation
Max. HRR	17	70.9 kW/m^2	6.52 kW/m^2
Accum. HR	17	73.3 kW-min/m^2	7.52 kW-min/m^2

Statistics of actual samples tested in an 8 month-period

From March to October 1988, 214 materials were tested. Means and unbiased standard deviations for each triplicated run are shown in Figure 3 (a), (b), (c), and (d).

Figure 3 Histograms of test results
(a) Maximum rate of heat release, means
(b) Maximum rate of heat release, standard deviations





Each histogram contains 214 data points. Curves have been drawn assuming a normal distribution for means and a chi-square distribution for standard deviations. It is notable that peak values of the standard deviation for accumulated HR and maximum HRR are about 3 while those of the control sample were about 7 as shown in Table 3. The results indicate that variation in test conditions over a long time period is significant; relative standard deviation was about 10 %.

THERMAL METHOD VS. OXYGEN CONSUMPTION METHOD

There have been two generic types of heat release rate measurement: the thermal method and the oxygen consumption method. The thermal method measures increases in the temperature of the exhaust air by a thermopile; the current FAA heat release test(2) and ASTM E906(1) are examples of the thermal method. The oxygen consumption method measures oxygen content of exhaust air, and calculates HRR based on the fact that a constant amount of heat is generated per unit quantity of oxygen consumed. An example of the oxygen consumption method is ASTM E-5 proposed Cone calorimeter test(3).

Blomqvist compared the oxygen consumption method and thermal method using an ASTM E906 apparatus with a compensated thermopile(4). Tests of a polyvinyl chloride (PVC) wall covering gave a HRR which changed rapidly with time; the thermal method gave only 60% of the peak value of the oxygen method. The discrepancy can be explained by the large thermal inertia in the thermal method.

The present author compared the two methods using an ASTM E906 apparatus in a previous study, and concluded that the oxygen consumption method was advantageous because it was free from thermal inertia which is caused mainly by absorbing and desorbing of heat by the walls of the apparatus(5).

The other advantage of the oxygen consumption method is a non-biased measurement of both convective and radiative heat release. A thermopile, the temperature sensor used in the thermal method, measures the convective heat release but may not measure the radiative heat release. For the purposes of fire safety, the HRR including both convective and radiative heat release should be measured. In the FAA test or ASTM E906, the apparatus is calibrated with burning methane. A methane flame is less bright, having a smaller radiative/convective ratio than a propane flame or wood flame. When a test sample has a flame of higher emissivity than the methane flame, the measured HRR value is biased and is recorded as smaller than it actually is. In the oxygen consumption method, both convective heat and radiative heat are measured without bias.

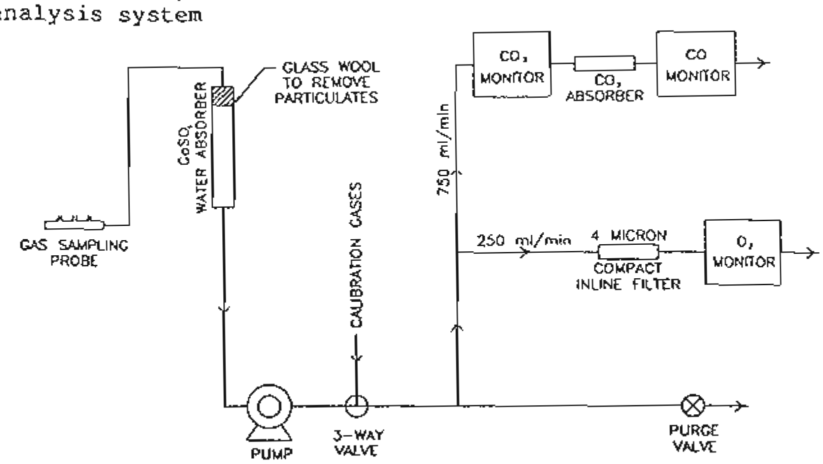
EXPERIMENTAL STUDIES OF O_2 CONSUMPTION METHOD IN THE FAA TEST APPARATUS

The standard FAA heat release test has been modified to measure HRR by the thermal method and oxygen consumption method simultaneously. The modification included the addition of a gas sampling line and gas analyzers as shown in Figure 4. The gas sampling probe was placed 4 cm below the level of the bypass air opening in order to sample gases only from the combustion chamber flow.

High baseline of the thermal method

Figure 5 shows millivolt outputs of the thermopile and oxygen analyzer when a control sample was tested. Differences between the two curves are obvious; the thermal output curve is characterized with a large baseline value and relatively small signal values.

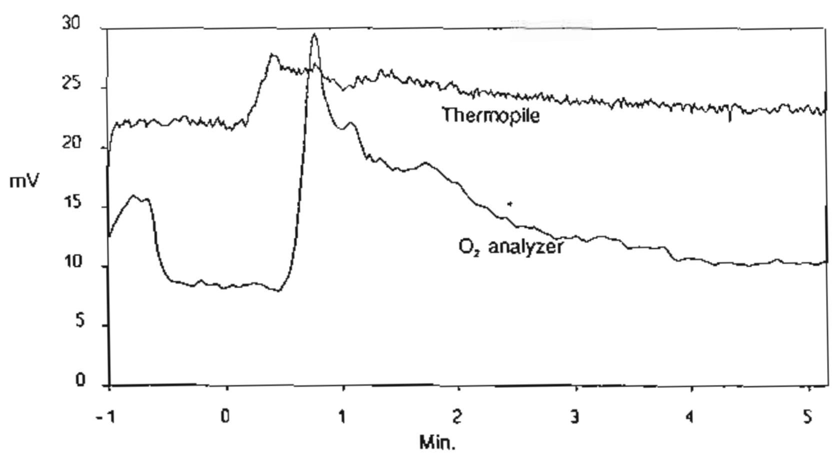
Fig. 4 Gas analysis system



The large baseline value is caused by the output from electric heating bars; it does not appear in the oxygen consumption method. The baseline value is subtracted from measured millivolt values to calculate heat output in the FAA test. In any measurement a large baseline value is not desirable; poor signal/noise ratio results and also fluctuation of the baseline value reduces accuracy of measurements more significantly than in a case with small base line value. The small baseline value is another advantage of the oxygen consumption method.

It is also obvious in Figure 5 that the peak shape compared to the long tailing part of the curve is much steeper in the output of the oxygen analyzer than that of the thermopile. The difference is caused by thermal inertia as discussed earlier.

Fig. 5 Output signals from the thermopile and oxygen analyzer



The output signals from the O_2 analyzer were delayed about 25 seconds from the thermopile outputs. The delay was caused by the gas sample flow path from the sampling probe to the exit of the O_2 analyzer. The delay had no effect on the value of HRR.

HRR values measured by both thermal method and oxygen consumption method

Five different methods were used to calculate HRR in the modified FAA test:
1. Standard thermal method(2)
2. Modified standard thermal method using propane as the calibration gas
3. O_2 consumption method with the apparatus constant measured by burning known flow rates of methane
4. Same as #3 but propane was used in place of methane
5. Normal oxygen consumption method using the accepted heat release value for unit quantity of O_2 consumption.

In #2 above, propane was burnt in a similar way but with smaller flow rates than methane flow rates in the standard method. In #3 and #4, methane and propane calculated in kW/O_2%. HRR for the combustion of test samples is calculated by multiplying the constant with the O_2 consumption percent. In this method, the flow rate of air in the calibration and test runs should be kept constant but the value is not required. Two different gases were used in calibration to investigate the effect of brightness of flames.

In #5, a heat release value of 13.1 KJ/(gram O_2)=18.70 KJ/(m^3 O_2) suggested by Hugget(6) was used. Flow rates of air to the combustion chamber and to the bypass were measured by a hot wire anemometer method(7) in the 39 mm id. air supply pipes. The standard air flow, whose rate was 0.04 m^3/sec measured by a rotameter, was found to split in a ratio of chamber/bypass=1/1.62.

Four different calibration constants (Kh) are shown in Table 2 and results of five different methods of HRR measurements are shown in Table 3.

Table 2 Calibration constants

Thermal method Kh, kW/mV		Oxygen consumption method Kh, kW/%	
#1	#2	#3	#4
with CH_4	with C_3H_8	with CH_4	with C_3H_8
0.282	0.369	2.375	2.456
1.62*	1.72*	0.99*	1.03*

* Relative standard deviation in duplicate runs, %

Table 3 HRR of control sample

	Thermal method		Oxygen consumption method		
	#1	#2	#3	#4	#5
	CH_4 Kh	C_3H_8 Kh	CH_4 Kh	C_3H_8 Kh	Common method
Max. HRR*	78.3	102.7	123.9	128.1	105.4
Accum.HR**	50.8	66.6	58.9	60.9	50.2

* The maximum HRR in the 5 minute test period, kW/m^2
**The accumulated HR at 2 minutes, kW-min/m^2

In Table 2, values of relative standard deviation of the oxygen consumption method were smaller than those of the thermal method; the oxygen consumption method had better reproducibility. The larger value of the calibration constant measured with propane than with methane, in the thermal method, is accounted for by the larger radiative/convective ratio of the propane flame. In Table 3, the standard FAA test method (thermal, with methane calibration) resulted in the smallest value of HRR for the control sample. In comparing the oxygen consumption methods and thermal methods, the lower values of maximum HRR in the thermal method result from greater thermal inertia in the thermal method. The thermal inertia should have no effect on the accumulated HR and there is no significant difference between measured accumulated HR of the two groups in Table 3. It is obvious that the standard method (#1) gives a lower value of the maximum HRR than other methods. The oxygen consumption methods, #3 and #4, methane and propane calibration respectively, agreed well. Values obtained by the common method are lower than those measured in #3 and #4 methods; more accurate measurement of the chamber air flow may be required.

THE STANDARD AIR FLOW RATE

The standard air flow rate 0.04 m^3/s is in excess of that needed for complete combustion of materials to be tested. In the above experiments, the maximum oxygen depletion was 2% and 1.3% respectively in the methane calibration and in testing a control sample. Concentrations of CO were less than 0.01% and 0.2% respectively. The air flow rate can be reduced by 1/2 or 1/3 of the standard rate without much increase in CO concentration, which is an indicator of incomplete combustion. The reduction of flow rate will increase O_2 consumption percent. MV output will also be increased resulting in improved signal/noise ratio both in the oxygen consumption method and the thermal method.

Conclusion

The measurement of HRR by the standard FAA test method is affected by air flow pattern, pilot flame stability, air tightness, and consideration of the surface area of samples. Close control of these factors is essential for a valid measurement. The magnitude of variability of data that were obtained in the author's experiments has been discussed;

relative standard deviation in tests of a control sample in a 8 month period was about 10 %.

The oxygen consumption method and the thermal method were compared by adding a gas analysis system to the standard FAA test apparatus. The oxygen consumption method is a better method and it is recommended for use in place of the present thermal method. The thermal method results in less accurate HRR values by giving: 1) a small maximum HRR value because of the thermal inertia of the apparatus, 2) lower than actual HRR values in testing materials with flames of higher emissivity than methane flame, 3) higher base line values and 4) less reproducible data. The signal/noise ratio can be improved further by reducing the air flow rate.

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(6) C. Hugget, Estimation of rate of heat release by means of oxygen consumption measurements, Fire & Materials 4, 61 (1980)
(7) Air Velocity Meter, commercially available, range 3-30m/sec, accuracy 5%

Acknowledgement

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PASSENGER BEHAVIOUR IN AIRCRAFT EMERGENCIES INVOLVING SMOKE AND FIRE

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A review of the accident literature has indicated that in aircraft emergencies involving smoke and fire both environmental and behavioural factors will influence passenger survival rates. These factors include the number of operational exits, the presence of toxic fumes, the extent to which anxiety, disorientation, feelings of depersonalization, panic and behavioural inaction occur among the passengers. Furthermore, in situations in which life is placed under severe threat, in addition to the experience of fear, people will compete with each other in order to survive. As a consequence the orderly process of evacuation for which passengers are briefed, frequently breaks down and the behaviour of passengers appears to be confused and disorderly.

In an experimental programme, a series of evacuation exercises were performed, in which incentive payments were made in order to introduce the element of competition which is known to lead to a disorderly evacuation in some aircraft accidents.

Using this technique six configurations at the vestibule prior to the Type I exits, and seven seating configurations adjacent to the overwing exit have been investigated.

INTRODUCTION

Aircraft accidents may be classifed according to a number of criteria, the most critical of which being whether the accident was survivable. Utilising this classificatory system, it is possible to assign accidents to one of three groups:

(a) those which are FATAL or NON-SURVIVABLE. Accidents in which none of the passengers or crew survive (for example: the Air India 747 in 1985 and the Pan Am 747 in 1988, in which the crash forces were of such severity that all onboard were killed instantly)

(b) the NON FATAL or SURVIVABLE, in which all the passengers and crew survive (for example: the Tristar which overran the runway in 1985 at Leeds-Bradford Airport)

(c) the TECHNICALLY SURVIVABLE, a grouping which includes the British Airtours 737 accident at Manchester Airport in 1985, and the British Midland 737 which crashed onto the M1 near East Midlands Airport in January 1989. Accidents in which some of the passengers or crew survive.

The world wide accident statistics indicate that the number of accidents in all three categories has decreased over the last two decades (Re: Figure 1). Despite this the proportion of passengers and crew who survive aircraft accidents has not improved, even when the data from those accidents considered to be non-survivable has been removed (Re: Figure 2). Thus, although the likelihood of being involved in an accident has diminished, the chances of successful egress has not increased to a significant extent.

Since approximately 90% of aircraft accidents are categorised as survivable or technically survivable, recently steps have been taken by the UK's CAA and the FAA in the United States in an attempt to reduce the number of fatalities. These improvements have included the introduction of floor proximity lighting and fire blocking materials. The behaviour of passengers and their impact on emergency evacuations has also come under scrutiny. It is anticipated that with a comprehensive understanding of behaviour in highly stressful and disorientating conditions, steps can be taken to improve the probability of a successful evacuation of all passengers from the aircraft.

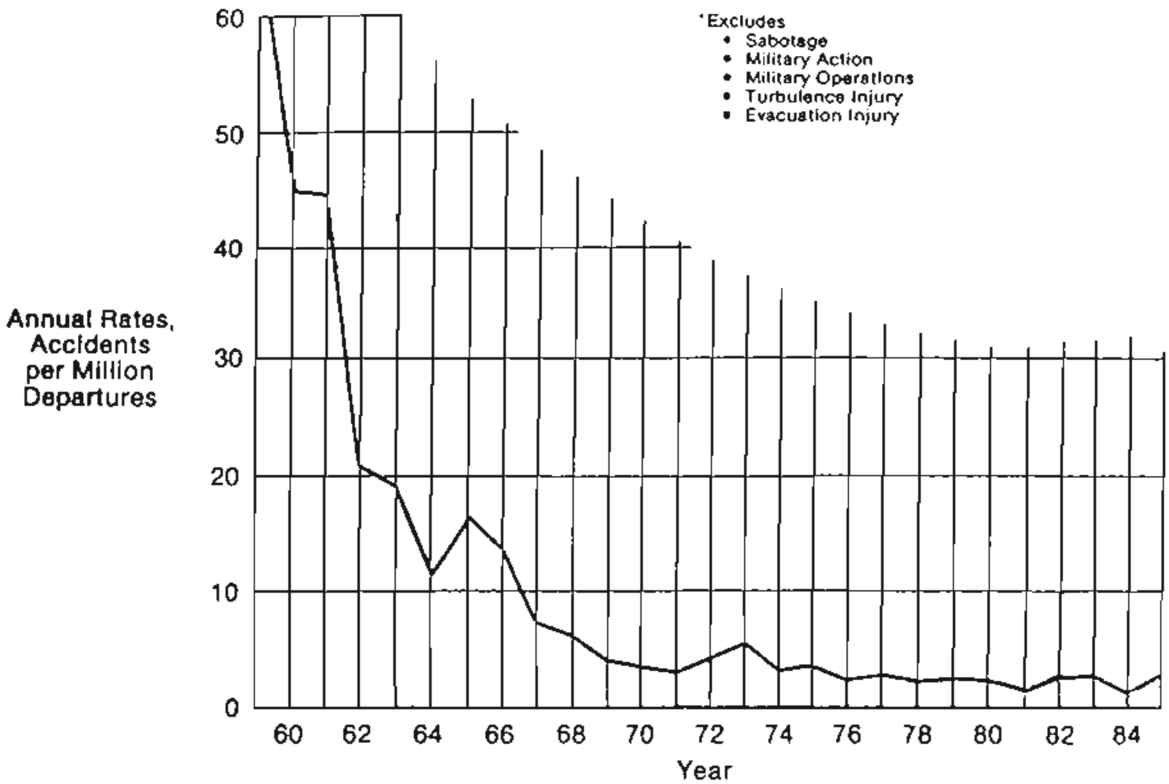
As yet little research effort has centred on the impact of passenger behaviour on aircraft emergencies. However, it has been possible to extrapolate information from other disaster situations, such as building fires and earthquakes. This information, along with reports from survivors of recent aircraft accidents, has been used to build up a representation of the types of responses which passengers adopt and the impact of such behaviours within the cabin, particularly in those emergencies which involve smoke and fire.

Information obtained from accident experience suggests that fire and smoke are the most serious environmental factors to affect an aircraft accident. The presence of either is one of the primary reasons for initiating an evacuation, for example: the Air Canada DC-9 descended into Cincinnati Airport in 1983 following the discovery of an inflight fire in the aft lavatory. Equally, post impact fire has a dramatic effect on

Figure 1

All Accidents

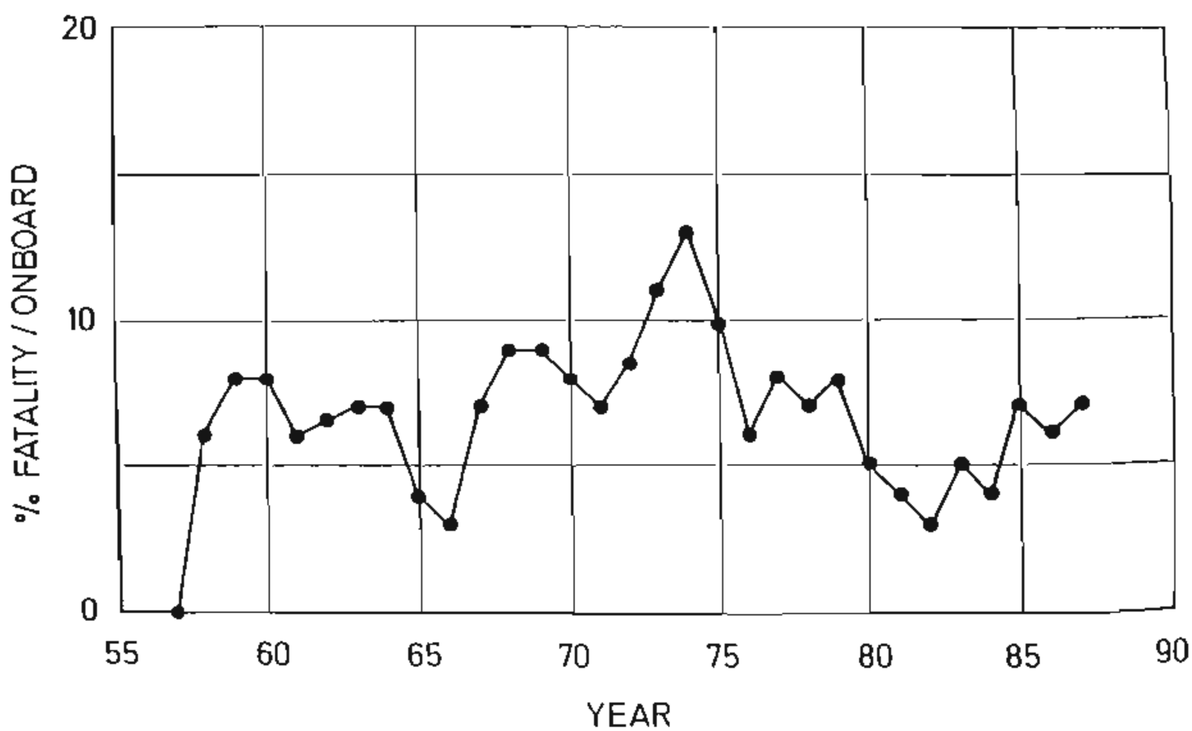
Worldwide Commercial Jet Fleet



Source: Statistical Summary of Commercial Jet Aircraft Accidents (1959 - 1985) Boeing Commercial Airplane Company

Figure 2

FATALITY RATE IN ALL SURVIVABLE ACCIDENTS



Source: Civil Aviation Authority World Airline Accident Summary (1957 - 1987) the efficiency of the evacuation and the types of behaviours displayed by passengers.

Smoke and fire have the potential to limit the number of exits available for egress and produce toxic fumes, factors which will consequently induce certain behavioural responses.

(a) Limited Number of Exits

If smoke and fire are outside the aircraft when an evacuation is initiated the number of exits is often limited, as cabin staff are trained not to open exits which may allow fire or smoke to enter the cabin. Equally, passengers are directed away from areas within the cabin in which fire and smoke are present.

A limited number of exits obviously increases the demand on available escape routes. Accounts from survivors of the British Airtours Boeing 737 at Manchester in August 1985 indicate that passengers egressed over seat backs and forcibly pushed themselves towards exits. Only to be confronted with a mass of bodies pushing forward to the doors. It was noted that human blockages occurred adjacent to the overwing exit and at the vestibule area of the galley. Blockages which dramatically decreased the efficiency of the evacuation, as passengers were overcome by smoke and trampled by others in the anxiety ridden push to the exits.

(b) Toxic Fumes

If fire or smoke are present in the cabin and are allowed to persist they create an environment which impairs breathing and vision. Equally the combinations of toxic fumes which emulate from cabin fires also have the potential to influence psychological functioning, which may, in turn, affect the behavioural responses of individuals in an emergency evacuation.

In addition to the specific impact of smoke and fire, toxic fumes can also lead to a number of behavioural responses which include disorientation, anxiety and depersonalization.

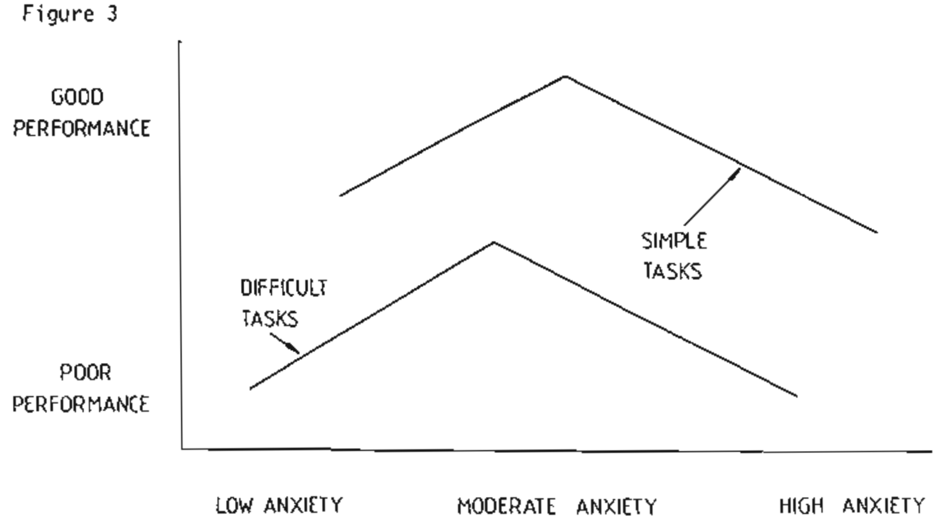
(i) Disorientation

Smoke generated from aircraft fire is normally dense and black, consequently reducing visibility and inducing disorientation. This reduction in visibility has a two-fold effect, it will increase levels of anxiety and passengers may enter areas of the aircraft from which there is no escape.

(ii) Anxiety

Passengers in an emergency situation are required to make a series of novel and difficult responses, in a situation which is potentially life threatening. It is hardly surprising that optimum egress does not occur, especially in view of the effect of anxiety on performance which has long been known to exist. The level of performance attained on a task being dependent on the level of anxiety and the complexity of the task (Re. Figure 3).

Figure 3



THE RELATIONSHIP BETWEEN LEVELS OF ANXIETY AND PERFORMANCE FOR BOTH SIMPLE AND DIFFICULT TASKS

Yerkes-Dodson (1908)

Simple tasks such as unfastening the lap belt become more difficult in emergency situations. In fact, many passengers revert to actions which would release a car seat belt. Fear, it seems, increases the likelihood that the most frequently used response is made.

(iii) Depersonalization

A sense of fear and reduction in performance are not alone in being a characteristic response to an emergency situation which involves fire. People who have encountered life threatening events often say that the passage of time slows while mental activity increases. Although by detaching themselves from the actual situation, and acting as an "observer", they seem better able to think and respond effectively.

Such depersonalization may account for the reactions of passengers during the period prior to three premeditated evacuations, studied by Robson in 1973. Of the 268 individuals, cabin staff classified 35% as calm, 47% as mildly agitated, 2% as very agitated with less than 1% exhibiting signs of uncontrolled panic.

Such a breakdown may give an indication of the patterns of behavioural response exhibited by passengers during actual emergency situations. The types of response frequently cited in literature from other situations, such as building fires,and borne out in survivors statements are: Fear-Flight, Panic, Behavioural Inaction and Affiliative Behaviour.

Fear-Flight

The fear response is the dominant reaction when survival is threatened. Anxiety and its physical concomitants are familiar - racing heart,tenseness of muscle etc.

Earliest psychological investigations of fear identified two responses, one of "flight" from the area ie. escape, and one of "fight", ie. attacking the agent of harm. It is unlikely that passengers would respond to an emergency onboard by attacking the agent of harm. However, fear-flight may be of some relevance.

In fact it may be possible to sub-divide the fear-flight reaction. Behavioural reaction to a small cabin fire, whose origins may be a seat, may be flight from a specific area. In comparison, if the threat to a passenger's well-being is more intense, the flight response may be more dramatic. Even to the extent of disregarding the advice of cabin staff and attempting to escape before the aircraft comes to rest.

Fear, it should be noted, underlies all the behavioural responses to aircraft emergencies.

Panic

According to the panic scenario, people threatened with entrapment compete in an animalistic manner for limited access to an escape route.

The term panic has been used to such an extent that we anticipate that we will act accordingly in a disaster and will also expect others to respond in a corresponding manner. It is therefore surprising to find that Robson in 1973 indicated that less than one percent of passengers displayed responses akin to uncontrollable panic. A result which is borne out in widespread analysis of disaster situations.

The incidence of panic may increase with the severity of the accident, being at its highest in accidents which involve considerable fire and smoke.

Incidences of panic may be explained if behaviour is viewed as a reflection of an individual's appraisal of the high stress situation. Lack of familiarity with the aircraft interior in the presence of smoke may lead to blockages at certain exits. Such blockages may appear to be highly irrational to someone who learns after the event that other exits were available. To the individual, in the situation, who does not recognise or observe the existence of these alternatives, attempting to fight his way to the exit may seem a very logical choice as opposed to burning to death.

Behavioural Inaction

Unlike panic, behavioural inaction has received little attention, yet evidence from disaster situations seems to indicate that it is a more likely response than that of panic in a high stress situation.

The analysis of four disasters, led Allerton (1964) to conclude that between 10 and 25% of people did little or nothing to escape from danger. This totally inappropriate response has also been observed in aircraft accidents. A number of fatalities on the Air Canada DC-9 accident in 1983 were located in seats which had been allocated to them before take-off. Equally, a number of passengers onboard the taxiing Boeing 747 at Teneriffe in 1977 were judged by their fellow passengers to make little attempt to escape from the burning aircraft.

It is suggested that individuals do little or nothing to escape as they are uncertain of what action is the most appropriate. A response which is hardly surprising in view of the rapidly changing events in a highly dangerous situation.

Affiliative Behaviour

Affiliative behaviour is characterised by movement towards the familiar. The direction of escape, it seems, will be related not only to the location of the threat but also the location and degree of familiarity of the individual with the place and other people.

Although of direct relevance to behaviour in building fires, it may also be applicable to aircraft emergency situations. Movement towards the familiar in terms of people will be minimal, as friends and family are usually seated together. The attraction of the door of embarkation, ie. the familiar, has been noted in many emergencies.

Escape behaviour displayed by passengers does indicate that attachment, again the familiar, has survival value. Individuals tend to act in an altruistic manner ensuring the safety of family and friends, while disregarding others who are unknown.

In addition, passengers attachment to their hand luggage has often been observed, ie. many passengers insist on taking their personal belongings with them when undertaking an emergency evacuation. It seems the perceived value of the contents obviously outweighs the risk they believe they will encounter if they take it with them.

The way in which passengers react to any emergency will be a reflection of their appraisal of the situation. This appraisal is influenced by many factors including their age, sex, cultural origins, previous experience and their consumption of alcohol prior to the event. The effectiveness of these responses differ, and consequently differentials exist in survival rates between groupings.

At the present time, reliance has to be placed on the statistics which relate to deaths, which leads to the assumption that those who die during their attempts to escape, respond in an ineffective or inappropriate manner.

At this point, one can only suggest that the old and young are at a disadvantage, especially in accidents in which speed, strength and agility play a dominant role. However, past experience, knowledge and a mental plan of how to escape seem to aid egress even in the presence of dense smoke.

SUMMARY

The evidence available from aircraft accidents and other situations in which life is under severe threat, suggests that people are (a) very frightened and (b) will compete in order to survive. A scenario which is particularly pertinent to accidents which involve smoke and fire within the cabin, such as the British Airtours 737 accident.

In such situations, the orderly evacuation which is seen in the 90 second aircraft certification demonstration breaks down. Rather than working in collaboration to get everyone out of the aircraft as quickly as possible, the threat to life is perceived to be so intense that each individual's behaviour is directed towards survival. In some instances the objective may extend to include the survival of members of their family.

The resultant egress is disorganised, with passengers travelling past open exits, others near exits not surviving the accident and in some instances, blockages occurring in aisles and surrounding exits.

CRANFIELD EVACUATION TRIALS

In response to a request from the UK CAA, the Applied Psychology Unit at Cranfield initiated an experimental programme which attempted to investigate the effects of passenger behaviour on flow rates during emergency evacuations. The objective being to assess the optimum width of the bulkhead prior to the Type I exit, and the seating configuration adjacent to the Type III (overwing) exit. The following configurations have been under review:

Bulkhead width

- (i) A width between the galley units of 20"
- (ii) A width between the galley units of 24"
- (iii) A width between the galley units of 27"
- (iv) A width between the galley units of 30"
- (v) A width between the galley units of 36"
- (vi) Port galley unit removed

Overwing seating configuration

- (i) The CAA minimum prior to Airworthiness Notice 79, with a seat pitch of 29"
- (ii) A configuration with a seat pitch of 29"
- (iii) The CAA alternative standard in Airworthiness Notice 79, in which the seat row located in line with the exit has the out board seat removed. The seat fore and aft being at normal seat pitch of 32"
- (iv) The CAA standard, specified in Airworthiness Notice 79, with a seat pitch of 39"
- (v) A configuration with a seat pitch of 44"
- (vi) A configuration with a seat pitch of 51"
- (vii) A configuration with a seat pitch of 60"

N.B. In conditions (ii) to (vii) the seat rows bounding the exit routes should have limited recline or break-forward

Re: Appendix A and B

In order to make the evaluations as realistic as possible a system of incentive payments was introduced. This technique has been utilised successfully in laboratory work in the behavioural sciences, in an attempt to influence the motivation and performance of individuals and groups. In the Cranfield experimental programme, the scheme was adopted in order to introduce an element of competition between the participants.

Volunteers were asked to perform four evacuations, for which they were paid a £10 attendance fee, with a bonus of £5 paid to the first half of the volunteers to exit the aircraft on each evacuation.

Participants were aware of the incentive payment scheme prior to undertaking the first evacuation, in order to reproduce the competition. Volunteers were not, however, given any information regarding the exits or configurations under review.

On each of the 28 test days, four of the thirteen configurations were assessed, two through the bulkhead and two via the overwing exit. The design of the experiment was such that twelve of the configurations were undertaken a minimum of eight times.

The programme aimed to achieve as much realism as safety would allow, thus the evacuations took place in a Trident aircraft parked on the airfield at Cranfield. In addition the volunteers were given a standard pre-flight briefing prior to each evacuation by members of the research team trained and dressed as cabin staff. The volunteers heard taped noise of the engine start up, taxi down the runway, which were followed by a series of unexpected noises and the call to evacuate.

To ensure that the cabin configurations were evaluated rather than other extraneous variables, the exits were opened by members of the research team and subjects egressed via ramps mounted outside the doors rather than chutes.

Each evacuation was recorded using video cameras (with time bases) mounted in the interior of the aircraft and outside the exits. Volunteers were also asked to complete questionnaires at the conclusion of each evacuation.

RESULTS

Over 1550 volunteers took part in the trial series, an average of 55 volunteers on each trial day. For safety purposes these individuals were between the ages of 20 and 50, and passed fit by the doctor present at the evacuation site. Of these 71% were male, with the mean age of participants being 28.8 years (sd.7.6).

At the conclusion of the 28 trial days, 111 evacuations had been performed (deteriorating weather conditions made it hazardous to initiate the final evacuation on one day). On 7 occasions it was necessary to halt an evacuation, as the number of volunteers attempting to pass through the exit led to a situation in which individuals were physically stuck in the aperture or individuals were at risk of being trampled by others. Consequently, the safety officer considered it dangerous to continue.

With the quantitative and qualitative data which has been gathered, it is anticipated that it will be possible to specify the optimum seating configuration adjacent to the Type III exit and the dimension of the bulkhead prior to Type I exit. At the present time the analysis of the results is at a preliminary stage.

The video and questionnaire data from the trials has also provided an insight into the dynamics of behaviour within the cabin in an actual emergency. Aisles and exits have been blocked by the sheer numbers of people trying to egress, volunteers have walked over others, many have searched for friends and families before making attempts to egress, although not seated in the same vicinity. Similarly, some participants managed to bypass others and come from the back to the front of the aircraft, some volunteers near operational exits did not achieve the bonus payments and a percentage of volunteers had problems undoing seatbelts. Within the trials, the instances of panic have been negligible whilst there was a notable number of volunteers who were unable to move ie. behaviourably inactive.

On a trial by trial basis, the variation in terms of aggression, types of behaviour displayed and consequently evacuation times, was great. This indicates the need in evaluations of this type, for a considerable number of repetitions to achieve reliable and valid results.

In addition, the trials have indicated that the introduction of incentive payments could be of great value. The technique has the potential to provide statistical data, required for the assessment of design options or safety procedures for use in emergency situations.

Since the volunteers in the trials do not represent a cross-section of the travelling public, it must be argued that in a real emergency the problems highlighted by the findings could only be worse.

In 1989 the programme of research is to be extended to include investigations of:

(a) The influence of the configuration at the Type I and Type III in orderly evacuations, akin to those in aircraft certification demonstrations.

(b) The influence of non-toxic smoke on the behaviour of passengers in the assessment of the configuration at both the Type I and Type III exit.

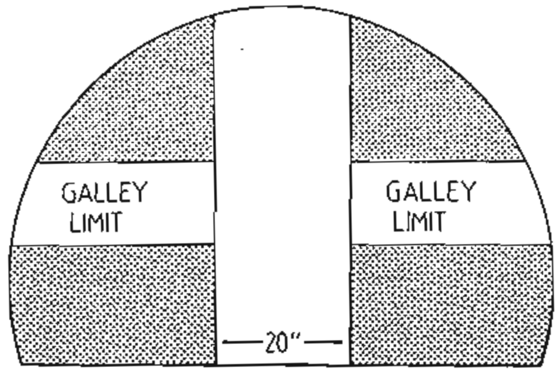
It will therefore be possible to assess the impact of passenger behaviour on exit routes when (i) passengers are exiting in an orderly manner, (ii) motivated to compete to egress and (iii) in conditions involving smoke.

REFERENCES

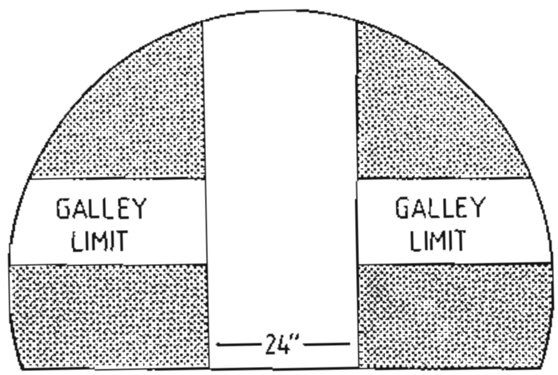
1. Marrison, Muir and Taylor - "Passenger Evacuation - A Literature Review" (1987)

2. Robson - "Passenger Behaviour in Aircraft Emergencies" (1973) Royal Aircraft Establishment Technical Report No. 73106.

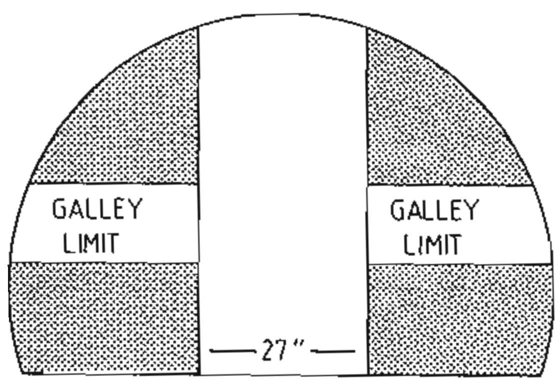
APPENDIX A.



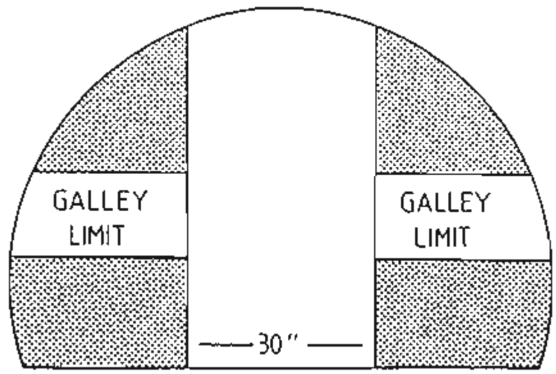
TEST 1 WIDTH BETWEEN THE GALLEY LIMITS
= 20 INCHES



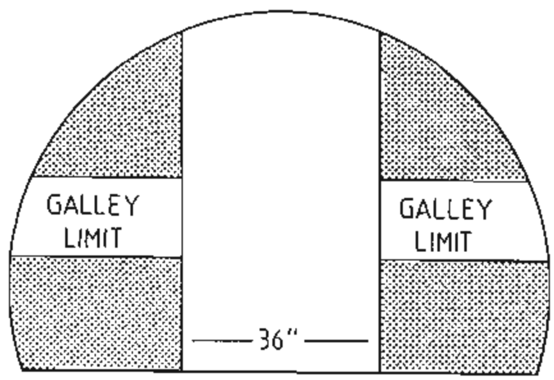
TEST 2 WIDTH BETWEEN THE GALLEY LIMITS
= 24 INCHES



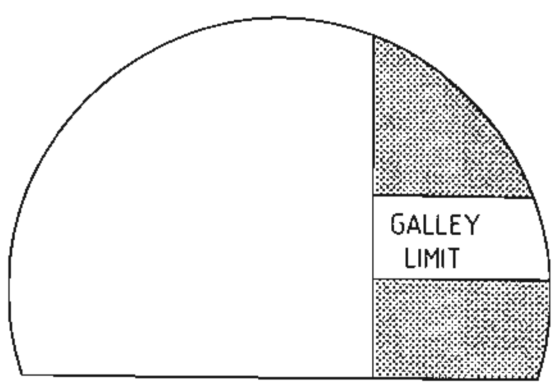
TEST 3 WIDTH BETWEEN THE GALLEY LIMITS
= 27 INCHES



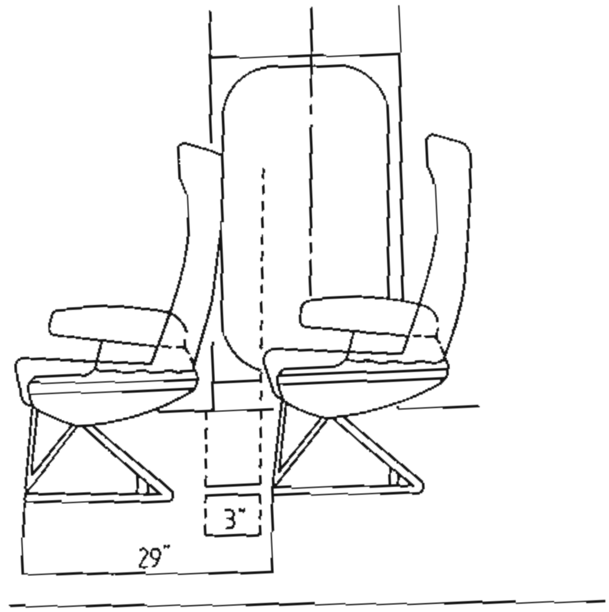
TEST 4 WIDTH BETWEEN THE GALLEY LIMITS
= 30 INCHES



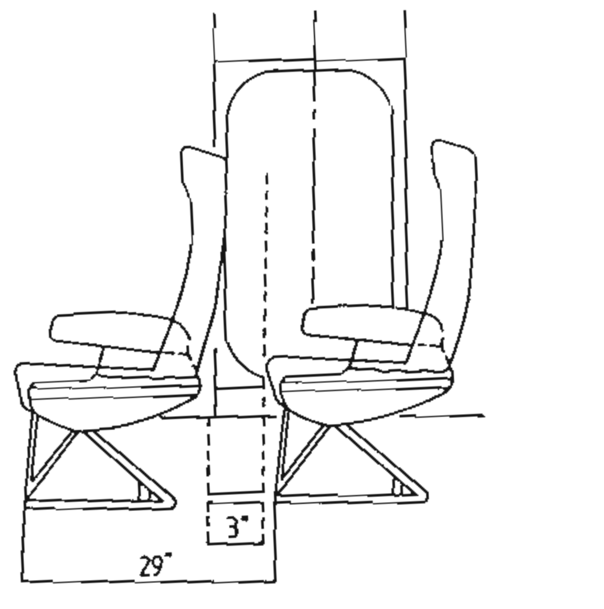
TEST 5 WIDTH BETWEEN THE GALLEY LIMITS
= 36 INCHES



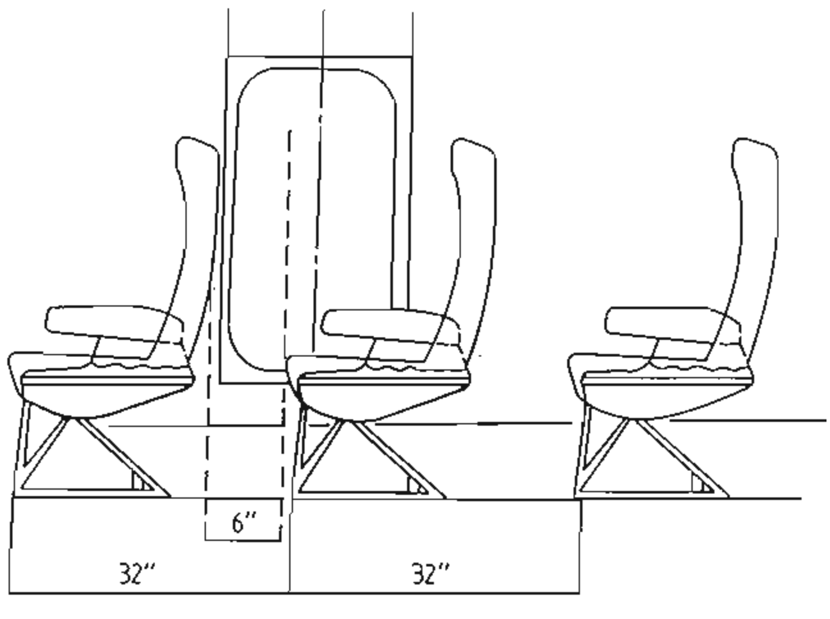
TEST 6 LEFT SIDE GALLEY LIMIT REMOVED



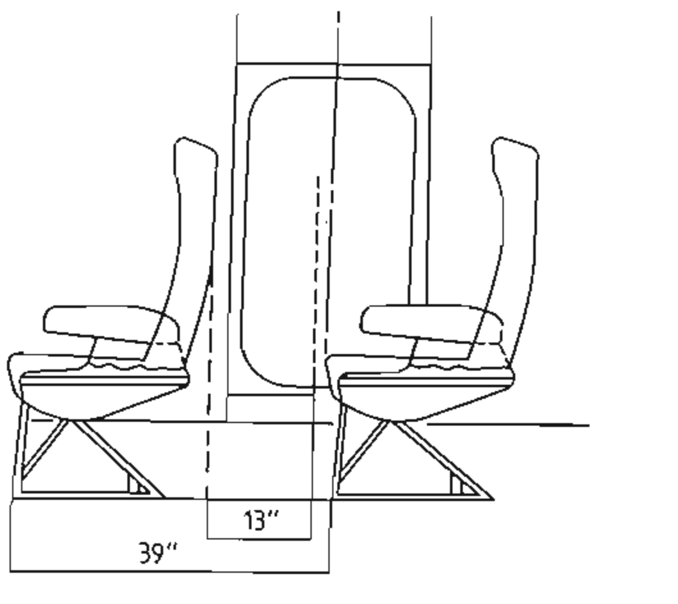
TEST 1A SEAT PITCH - 29 INCHES
VERTICAL PROJECTION - 3 INCHES



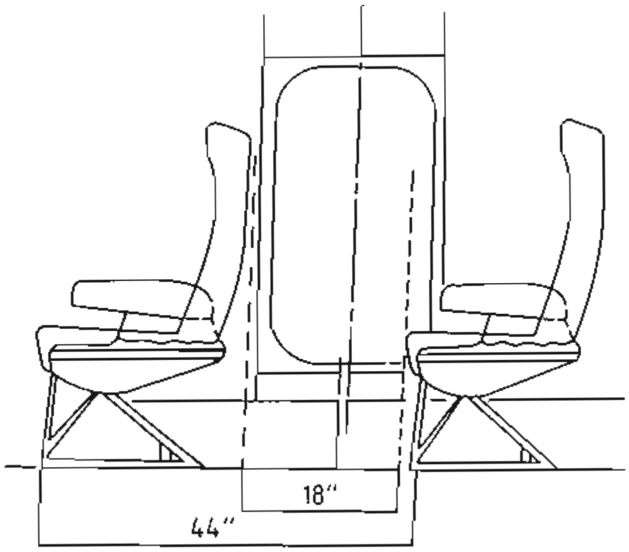
TEST 1B SEAT PITCH - 29 INCHES
VERTICAL PROJECTION - 3 INCHES
(SEAT BACKS TO REMAIN IN A RIGID POSITION)



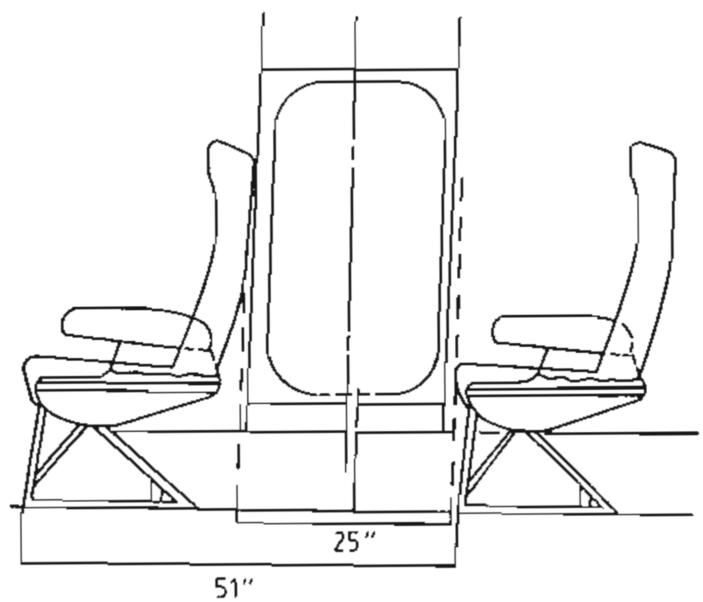
TEST 2 SEAT PITCH - 32 INCHES
VERTICAL PROJECTION - 6 INCHES
EQUIVALENT TO AN 79 REQUIREMENTS
WITH OUTBOARD SEAT REMOVED



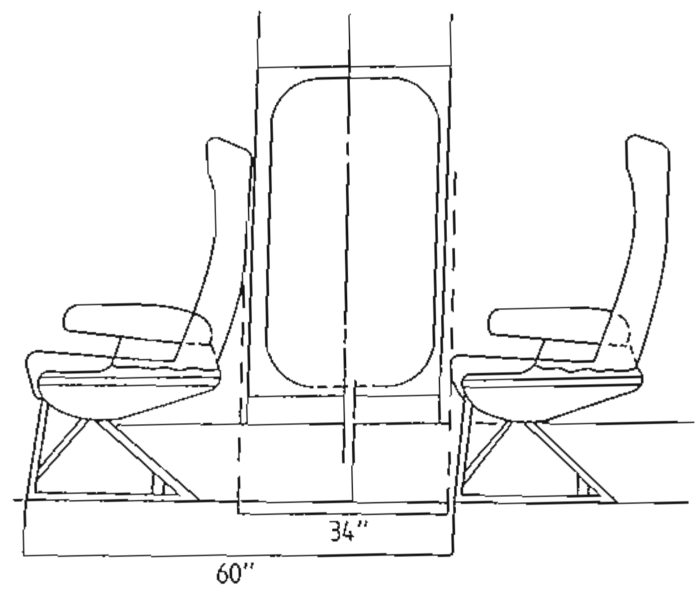
TEST 3 SEAT PITCH - 39" INCHES
VERTICAL PROJECTION - 13 INCHES
EQUIVALENT TO AN 79 REQUIREMENTS



TEST 4 SEAT PITCH - 44 INCHES
VERTICAL PROJECTION - 18 INCHES



TEST 5 SEAT PITCH - 51 INCHES
VERTICAL PROJECTION - 25 INCHES



TEST 6 SEAT PITCH - 60 INCHES
VERTICAL PROJECTION - 34" INCHES

SMOKEHOODS DONNED QUICKLY - THE IMPACT OF DONNING SMOKEHOODS ON EVACUATION TIMES

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SUMMARY

765 volunteers aged between 18 and 50 took part in 9 simulated emergency evacuations in clear air and smoke with and without ventilated smoke hoods. Analysis of differences between the experimental conditions, age, sex, seat location, exit and test run showed that the key factor was seat location. While the wearing of hoods and the presence of smoke both increased the evacuation times the interaction between these separate factors was negative, indicating that the use of hoods in the presence of smoke was less than the sum of the additional times attributable to 'smoke' and 'hood'. A quadratic response surface model enabled the evacuation time for each seat to be predicted for each condition and show that evacuation time increases with the distance from an exit and the aisle. It was concluded that the wearing of smoke hoods should not significantly impede the ability of passengers to evacuate an aircraft cabin in an emergency.

SECTION ONE - THE INVESTIGATION

THE STUDY

The aim of the study was to observe and record the effects, if any, on timings and passenger behaviour of donning smoke hoods during a simulated emergency evacuation of an aircraft passenger cabin in both clear air and smoke; to report upon these observations and draw conclusions therefrom. It was planned that four evacuations would take place in clear air (2 with and 2 without smoke hoods) and that six would be undertaken in 'smoke' (2 without smoke hoods, 2 with smoke hoods and 2 in an in-flight fire situation using smoke hoods). Therefore, the investigation centred on the impact that the donning of smoke hoods might make on the overall timings of such events.

In terms of money and resources the overall cost of this study was in the region of £250,000. Funds and materials were donated by firms, local authorities, airline operators, trade unions, commercial radio, television services and individuals in North America, the Pacific Basin, Australia, Europe and the United Kingdom. In excess of 1,500 individuals freely gave their time to fulfil the role of support staff and as participants in the tests. The Civil Aviation Authority contributed £12 ,000 to cover the direct costs of the in-flight fire tests; the regulatory authority extended its existing insurance arrangements to include the event and provided a time-expired engineless Trident III aircraft from those located at the Civil Aviation Authority Fire School, Tees-side.

The test method was developed from the aborted take off evacuation demonstration procedures used by operators and as many variables as possible were eliminated. It was agreed with representative of the Civil Aviation Authority that the timing of individual tests commenced when the signal to evacuate the cabin was given to the cabin crew by the controller and ended when the last participant crossed an exit threshold. Individual timings were treated in the same manner. Thus it was possible to substitute ramps for slides as a means of descending from the aircraft fuselage to the ground; this was seen to be a significant factor by the Medical Ethics Committee concerned and those providing insurance cover. Furthermore, it was possible to ensure that the timings of the evacuations were in no way clouded by participants hesitating at the threshold of slides.

The participants fulfilling the role of passenger, for the tests which took place from the 27th of April to the 2nd of May, 1987, used the rear cabin of the time-expired engineless Trident III aircraft. The front cabin, stripped of seats, was used for observation and the siting of special equipment. The seating configuration was standard six-abreast Coach/ Economy, all of which were fitted with seat belts. Eight five of the one hundred seats (appropriately identified) were used to seat participants in the tests. The remaining fifteen seats were utilised for safety monitors/first aid assistants and the siting of safety equipment. Seating was provided for two cabin attendants. However, it was not possible to obtain shoulder harnesses for their use. A third cabin attendant was stationed at the public address microphone located alongside the centre left entrance. The standard aircraft public address system was used.

Only the left centre and right rear exits were used for egress. Participants boarded the aircraft [illegible]

No attempts were made to disguise the exits to be used during the tests. For reasons of safety the unused overwing exits were sealed with protective tape.

PASSENGER SMOKE PROTECTION EQUIPMENT

Du Point PELS type smoke hoods were used for the study. While the design incorporates a breathable gas supply, for the purposes of the tests the gas cylinder was a dummy and unobtrusive ventilation holes were provided. This hood gives all round visibility so that no specific orientation to the face was needed. The cabin crew did not use smoke hoods.

The smoke hoods were individually packed in yellow vinyl pouches taped on the rear of the passenger seats above passenger serving trays. Where seats faced a bulkhead the pouches were taped to the bulkhead at a similar level. The flaps of the vinyl pouches were retained by a velcro fastener and therefore extraction of the smoke hood was simple and easy.

SMOKE

The choking and irritant smoke encountered in aviation fires could not reasonably be applied to those taking part in the Tees-side tests. Therefore, with the intention of bringing about a change in behaviour on the part of participants, non-toxic theatrical white smoke, generated from six units placed at selected points in the cabin overhead stowage lockers, was used.

The signatory to the application to the Medical Ethics Committee, the observer from the Federal Aviation Authority, the Exercise Controller, the Site Coordinator and the Safety Officer met on board the aircraft to decide the appropriate level of smoke to be applied. Smoke was discharged at a number of timed durations ranging from five to thirty seconds. In turn these discharges were related to the time required on each occasion to ventilate the cabin and regain an acceptable level of visibility. In addition, a check was made to ascertain that, within a reasonable time limit, the fall of smoke within the cabin was uniform. A ten second discharge of smoke proved to be the maximum that could be produced while still achieving the time span set, by the Civil Aviation Authority Safety Officer, for regaining adequate visibility in the cabin (i.e. visibility of all the participants in 25 seconds and 90% of all smoke exhausted within a minute).

In order to ensure that the condition in the "smoke with hoods"tests would gain acceptance by the Federal Aviation Administration in the United States of America, it was agreed with their observer that the cabin crew's direction to don hoods would be as the falling smoke reached the top of the seat backs. This decision - influenced by the belief that in situations where smoke protection was available this was likely to be the longest period of time passengers would tolerate smoke without donning hoods - was conveyed in a statement made to the Medical Ethics Committee.

PARTICIPANTS

The requirements for insurance cover and the needs of the Medical Ethics Committee called for participants to be within the age range of 18 to 50. Nevertheless, within such constraints endeavours were made to align the volunteers, as far as practicable, to the North Atlantic passenger pattern; It was intended that 30% of each cabin load would be female and that no simulated infants would be carried.

Eighty five participants took part in each test. They were volunteers from the North East of England recruited through local radio broadcasts and other direct arrangements by Community Service Volunteers (CSV). Almost all came from outside the aviation community and many had never flown. None had participated in an escape simulation within the previous six months and none took part in more than one test.

Only 900 of the 1295 men and women recruited through the radio phone-in programme could be related to the test requirements and difficulties were noted in readily obtaining male volunteers solely by this means. A shortage of participants on the first day brought about the cancellation of the second test due to be undertaken on the 27th April, 1987. Subsequent participant shortfalls, while not critical, impacted to some degree on the intended participant profile. However, it will be seen from the statistical analysis that the effects of sex and age were not found to be significant and therefore it was possible to exclude these variables.

Prior to being medically screened, all participants were given a general briefing on the event; thereafter they were offered, should they wish to do so, the opportunity to withdraw from the tests. Participants were also required to complete a form of informed consent.

Participants were asked to complete questionnaires following the tests in an endeavour to determine their attitude towards the smoke hood, solicit comments that might disclose general problems in relation to the equipment and indicate the retention of the pre-flight safety instructions that were applied.

CABIN CREW

Three British Airways cabin attendants familiar with the Trident III and the operation of its doors volunteered to take part in the tests; they were briefed on the exits to be used and the manner in which the tests were to be run. They also contributed to the modification of the pre-flight briefings for "smoke hoods". No flight deck crew were provided. A standby cabin crew was made available by the French Cabin Attendents' trade union.

PRE-FLIGHT BRIEFING

The standard pre-flight safety briefing was given with the addition, where appropriate, of smoke hood information. Reference was made to the briefing cards which had been realistically adapted to show the cabin layout for the aircraft utilised. Two sets were provided; one with the necessary smoke hood access and donning procedures, and another without such smoke hood material for use in situations of clear air and smoke without hoods.

After the safety briefing, cabin attendants checked to ensure that seat belts were fastened and handed out newspapers to those who wanted them. Thereafter, recorded engine noise was applied and time was provided for the participants to settle down in the cabin.

TEST DURATION & THE EVACUATION

Each test and timing started on a predetermined signal from the Exercise Controller to the cabin attendant located in the area of the left centre exit. This member of the cabin crew then issued the command over the public address system to the participants to evacuate the aircraft in a predetermined instructions which chimed with those currently used by British Airways. The format of the commands used related to each of the test situations. As has been indicated the timings of each test ended when the last participant left through either of the exits.

Six closed circuit television cameras and one heat seeking camera were used to provide a record of the tests. Two of the cameras covered the exit externally at the left centre and right rear exits to the aircraft; a further two cameras covered these exits from inside the aircraft and two other cameras covered internal longitudinal views from each end of the rear cabin. A heat seeking camera also provided a longitudinal view down the cabin towards the rear of the aircraft. The heat seeking camera was utilised to monitor participants during the tests utilising smoke as well as to maintain a CCTV record of such events for insurance purposes. The CCTV recorders used were able to set out the passage of time at the bottom of the frame of the picture. This information provided the basis for timing the tests as well as the individual times that each participant left the cabin.

SAFETY

Able bodied volunteers, drawn from the Durham County Fire Service, undertook the roles of safety monitors/first aid assistants. During the tests eight were seated and dispersed throughout the length of the cabin; a further four were located at each of the two exits - two inside and two outside. As a secondary role these men and women were asked to endeavour to observe the behaviour of participants and the manner in which hoods were donned. Those positioned outside the exits in use provided a back up timing record for the evacuation rate on a ten second interval basis with stop watches.

The Civil Aviation Authority Divisional Fire Officer undertaking the role of Safety Officer worked with the Exercise Controller and had ultimate authority over all matters of safety. In this context he had absolute discretion to (1) require anything to be done or not to be done, before, during, or after any test and to (2) abort any test should he deem this to be necessary at any time. He was required to satisfy himself that the Exercise Controller and the safety monitors/ first aid assistants understood their safety responsibilities, and ensure that an ambulance, fire tender and medical officer were always available during the tests. He used the heat seeking camera to assist him in monitoring events in conditions of smoke. It fell to the Safety Officer to personally undertake a search of the cabin at the end of each test to ensure that it was clear of participants.

Floor level lighting was installed in the rear cabin of the aircraft for use in each of the tests. While the established cabin ventilation systems on the aircraft operated satisfactorily, two high powered electric fans, appropriately sited, were made available to ensure the rapid extraction of the 'smoke' used in specific simulated emergencies. Suitable fire extinguishers were unobtrusively placed in both cabins on the aircraft. Similarly, fire extinguishers were made available at the test site support centre, Dinsdale Hall, where they could be readily seen. Light weight resuscitation units were made available for immediate use on the aircraft and sited alongside the positions occupied by the safety monitors/first aid assistants. Smoking was not permitted on or alongside the aircraft.

Whenever the tests took place, fire cover, provided by a crewed tender from Tees- side Airport, was sited alongside the aircraft. Two medical officers were always present during each of the tests; they were supported by members of St. John's Ambulance Brigade and two of the Brigade's crewed ambulances.

ORGANISATION & ADMINISTRATION

Establishing the test facilities at Tees-side Airport called for the involvement and collaboration of a wide range of organisations, authorities and contractors in the North East of England and elsewhere. Thus, over a four month period it was necessary for specific members of the research team, based on Linacre College, Oxford, to frequently visit Tees-side in order to progress the necessary arrangements. The very able support of two members of the Media Action staff, drawn from the Newcastle Office of the Community Service Volunteers, provided continuity at the locations in the North East of England and made sure that the operational calender established for the event was rigidly maintained.

The test site at Tees-side Airport was supported by an assembly area located some three and a half miles distant at Dinsdale Hall. It was here that participants (who had travelled by coaches from locations near their homes) were briefed about the event, medically screened to ensure they were physically fit to take part in the tests, received a main meal and completed both their forms of informed consent and the post-test questionnaires.

The collection and return of the participants was organised by Community Service Volunteers drawn from Newcastle who also provided "escorts" for each coach. The support for the medical screening of participants was provided by nursing sisters and members of St. John's ambulance Brigade under the control of their Area Surgeon. Briefing and the application of the post-test questionnaires was carried out by members of the research team while the payment of participants expenses, at the rate of £5.00 each, was very ably undertaken by the Chief Executive of one of the sponsor companies.

The distribution of tea, coffee, biscuits and mid-day meals at Dinsdale Hall and at the Tees-side Airport dispersal site was undertaken by the Women's Royal Voluntary Service. Their members also provided a sympathetic ear for those participants who felt an immediate need to talk to someone about their experience.

The immediate daily organisation of the aircraft at Tees-side revolved around the Exercise Controller and the Site Coordinator. The Exercise Controller, a senior officer from the Offshore Fire Training Centre at Montrose, supervised the operation of the tests. He was responsible for everything occurring on the area of the dispersal ground and inside the aircraft; also for the safe conduct of each test. He gave the orders for the boarding of the participants, commencement of the tests and the subsequent movement of the participants back to the support centre, Dinsdale Hall. This member of the team was also responsible for the control of smoke generation; he was required to take direct control of any real emergency and was authorised to abort a test whenever he judged this to be necessary. On the completion of each test the Exercise Controller supervised the preparation at the test site for the following event. In particular he ensured that the aircraft was clear of volunteers; the cabin had been valeted after each test and, where appropriate, the passenger safety briefing cards had been changed.

The supervision of the support function was undertaken by a further senior officer from the Offshore Fire Training Centre at Montrose who fulfilled the role of the Site Coordinator. He was charged with undertaking all those tasks which were not the direct responsibility of the Exercise Controller such as the reception, marshalling and movement of participants, securing the availability of the necessary facilities other than those under the control of specialist groups e.g. CCTV, contractors, etc., together with the issue and return and safe custody of stores and equipment. When advised that a test was due to commence the Site Coordinator was required to marshal all the external support staff needed at the aircraft and while a test was underway he was responsible for all aspects of safety outside the aircraft.

In terms of their roles, the Exercise Controller and the Site Coordinator were the initial focal points for the safety monitors/first aid assistants, members of St. John's Ambulance and those members of the Woman's Royal Voluntary Service at the aircraft site.

TEST PROCEDURE

Within the framework of the test method and organisational arrangements the following test procedure was developed:

(a) In accordance with the CSV postal notifications participants are taken by coach from predetermined locations to the assembly centre at Dinsdale Hall.

(b) Participants receive general briefing on the tests.

(c) Participants are medically screened and complete form of "informed consent".

(d) Participants issued with identification numbers (which are worn over their clothing) and thereafter they are transported by coaches from Dinsdale Hall to the Trident III site at Tees-side Airport.

(e) Eighty five participants are randomly seated in the rear cabin, by the cabin crew. The Exercise Controller checks, by visual inspection from his location at the centre exit, that the eighty five participants are present and advised the CCTV mobile studio that this is so. Cabin crew close, but do not lock, the exits.

(f) Participants are given the appropriate pre-flight briefing (i.e. with or without smoke hood information).

(g) Cabin crew check to see that all seat belts are fastened and record the seating positions of each of the participants.

(h) Recorded engine noise started and newspapers issued, by cabin crew, to participants at their seats.

(i) Test started with predetermined signal and timings commenced on the aircraft by the Exercise Controller, with a stop watch, and at the CCTV mobile studio by resetting the timing record.

(j) Cabin crew act in accordance with British Airways routine safety procedures and announcements; in test environments using the ventilated smoke hoods, the cabin crew inform participants when to don the hoods.

(k) Timing of the test ends when the last participant leaves the aircraft across either of the cabin exits.

(l) Participants reboard the coaches and return to Dinsdale Hall.

(m) Post-test questionnaires distributed and completed by participants who are also verbally debriefed.

(n) Participants receive standard expenses payment, sign the appropriate receipt together with a statement that they did not incur any injury while participating in the test.

(o) Participants return, by coach, to the locations previously utilised for their collection.

SECTION TWO - STATISTICAL ANALYSIS

THE DATA

Two sources of material were available for statistical analysis. The Closed Circuit Television tapes provided the times that each of the tests commenced together with the times that the participants crossed the thresholds of the front and rear exits. The questionnaires completed by the participants after they had taken part in the tests provided a series of responses which could in most cases be related to the individual's evacuation performance.

In a number of instances it was found to be very difficult to accurately identify the numbers worn by specific participants as they crossed the thresholds of the exits and left the aircraft. Therefore it was necessary for British Aerospace plc, who had made the recording at Tees-side, to undertake an appropriate listing, against times of egress for all runs, from the U-matic master copies then held by the company at Warton, near Preston.

It had been planned to duplicate each of the tests covering the five different conditions. However, as has been mentioned earlier, with the shortage of participants on the first day it was only feasible to undertake the following nine tests:

DAY	RUN	CONDITION
1	1	Clear air without hoods
2	2	Smoke with hoods
2	3	In-flight fire
3	4	Smoke without hoods
3	5	Clear air with hoods
4	6	Smoke with hoods
4	7	Smoke without hoods
5	8	In flight fire
5	9	Smoke with hoods

The second run, 'smoke with hoods', was discarded from the analysis because the smoke on this occasion was discharged for only seven seconds. A change in the wind at the time of the ninth run resulted in smoke being blown back into the cabin when the rear exit was opened. This brought with it a slow evacuation time at this exit. Initially, a safety monitor/first aid assistant attributed the increased density of the smoke to the delay in 'firing' of a smoke generator, forgetting that with electrically controlled switching all such generators were shut down together. Nevertheless, the outcome was the creation of a condition that did not chime with the others employed at Tees-side and the data it provided could only be utilised in a relatively small portion of the analysis.

A review of the CCTV tapes from the Tees-side tests showed that in the six tests using smoke hoods only two participants were not wearing them when they left the aircraft. It is known that one of these participants was seated by an exit and therefore saw no reason to don such equipment prior to evacuating the aircraft and the other had apparently consumed a considerable quantity of alcohol between the time of medical examination and the commencement of the test and was intoxicated. As the ventilated smoke hoods had been readily donned without significant difficulties, and with recognition that only limited funds were available, the initial analysis of the participants answers to the post test questionnaire was restricted to those concerned with claustrophobia - a task involving the collation of more than 2,000 responses.

THE STATISTICAL ANALYSIS OF EVACUATION TIME DATA*

The following analysis was conducted using a data set provided by Dr J H B Vant which contained the age, sex, seat occupied, exit used, exit order, claustrophiobic status and evacuation time of each participant in each of the experimental conditions. As explained in the text of this report, there were problems with the experimental conditions of runs 2 and 9 and these are not included in the present analysis.

As a preliminary to the main analysis of the data the effects of the experimental conditions, the location of seat within the aircraft, the exit used, the age and sex of the participants on the evacuation times were examined. The effects of sex and age were analysed after removing the effects of seat location, exit used and run and neither was found to be significant. In the further analysis of the differences between the runs, exit used and location of seat in aircraft therefore, the variables sex and age were excluded. Furthermore, after taking account of the location of the seat in the aircraft the exit used was not significant indicating that the latter was almost completely determined by the former. For the these reasons, the analysis of the differences between the experimental conditions which follows concentrates on the key factor, the location of the seat occupied.

For the purposes of this analysis, the location of each seat was designated by two numbers: x, the row position counting from front to rear and y, the position in row counting from left to right, so that the front row is row 1 and the last row, row 17. In each row, therefore positions 1 and 6 were window seats and 3 and 4 aisle seats.

The main analysis considered the evacuation times measured for each individual in each run under the four main different experimental conditions, excluding for the moment inflight fire. This analysis allows for the separate estimation of effects of smoke (S) and hoods (H) and the interaction (S x H) between these factors. In order to balance

*Kindly undertaken by R W Hioms, M.A., PhD., FIMA, FBCS, Fellow of Linacre College.
(At the request of the majority of the sponsors, the data set has been retained at Oxford.)

the design for this analysis, four of the runs were used, one each in clear air with hoods and without hoods and one each in smoke with and without hoods. These runs were numbers 1, 4, 5 and 6, respectively. (Examining the times for the occupants of corresponding seats in runs 4 and 7 and performing pairwise tests showed no significant difference and as runs 4 and 7 were similar, run 4 was used in this part of the analysis to represent the condition with smoke and hoods both present).

The results of this analysis indicate that the wearing of hoods and the presence of the smoke both increase the evacuation times. The effects of these main factors, were very highly significant. The interaction between these factors was significant and negative, indicating that the use of hoods in the presence of smoke had an effect on evacuation time which was less than the sum of the additional times attributable to the separate factors 'smoke' and 'hood'.

Table 1: Estimated additions to evacuation times

Effects:	hoods (H)	smoke (S)	Interaction (S x H)
	5.12 (1.84)	6.25 (1.84)	-3.73 (1. 84)

The values shown are the estimated additions to the evacuation times (in secs.) caused by the presence of smoke and hoods separately and the combination of both these conditions, as they were experienced in runs 1,4,5 and 6. The numbers in brackets are approximate standard errors for these estimates.

Another approach to the determination of the effects of the two factors, using a quadratic response surface model, enables the evacuation time for each seat position to be predicted for each condition. Unlike the balanced design analysis employed above, this analysis can make use of all the experimental runs (except runs 2 and 9 as explained above). The time taken to evacuate increases with distance from an exit and consequently the time increases from the front towards the middle rows and also from the rear towards the middle rows. Likewise the time increases from the window seat towards the aisle seats. The model is a best fitting quadratic surface model using the row and position within a row as coordinates.

The fitted model equation for prediction of the evacuation time, t (in secs.) is

$$t = C + 10.87\,x - 7.96\,y - 0.59\,x^2 + 1.13\,y^2$$

where x is the row (from front to rear) and y is the position in a row (from left to right) and C is a constant determined as indicated below:

clear air	0.102
clear air with hood	7.091
smoke	8.214
smoke with hood	11.469
in flight fire	5.393

The above values were obtained by an analysis of covariance applied to all runs except run 9 using x and y in the quadratic response surface model as concomitant variables. These results confirm the estimates obtained from the balanced design analysis above which showed the increased times due to the presence of the hood and smoke factors in the experimental conditions. The details of the calculations are given below:

smoke effect	= ((8.214 - 0.102) + (11.469 - 7.091))/2 = 6.245
hood effect	= ((7.091 - 0.102) + (11.469 - 8.214))/2 = 5.122
smoke x hood interaction	= -(8.214 - 0.102) + (11.469 - 7.091) = -3.734

The standard errors for these estimates are, however slightly higher (2.53 instead of 1.84) than those for that analysis in view of the addition of the variability about the overall fitted surface to the residual variance in the analysis. The former estimates, with their smaller standard errors, may be preferred for making interpretations of the effects of the different factors.

The analysis of the subjects by claustrophobic group showed that there was no over-representation of claustrophobics in any particular run, nor did they have higher evacuation times than others. Table 2 shows the evacuation times for those runs in which hoods were worn by claustrophobic group.

Table 2: Claustrophobic category

Run		Not at all	Slightly	Moderately	Very
Run 3	time	32.3	31.3	32.3	16.4
	no.	55	16	1	1
Run 5	time	32.4	39.8	_	23.4
	no.	76	7	0	1
Run 6	time	34.7	45.9	35.3	57.2
	no.	65	16	1	1
Run 8	time	38.0	40.0	38.9	50.6
	no.	56	20	6	2

The mean evacuation times (t) are shown together with the number (n) in each category of claustrophobia.

SECTION THREE - DISCUSSION

PERCEPTION OF THE TEST ENVIRONMENT

There may be some similarities but nearly every aviation accident has a different cause. Fire and smoke are effects common to many aviation accidents. Nevertheless, the impact of choking and irritant smoke, together with the heat and the terror experienced by passengers in situations of aviation fire can never be effectively reproduced in test situations involving human beings. Therefore it must be accepted that the effects of these factors can not be readily assessed by the tests employed in this study. However, with the carefully defined aim it is possible to gain a significant measurement of the impact of wearing hoods on the overall evacuation times in clear air and smoke; thus, the product of a study of this nature can do much to dispel misconceptions and contribute the preservation of life in the future.

The general effect of the smoke* was that the harder the participants found it to see in this condition, the longer the

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*Immediate Reactions to the Smoke: During Operation Exit a number of observations were made by participants. A man taking part in run 2, "Smoke with Hoods", which was discounted for purposes of the investigation because the discharge of smoke only lasted seven seconds, wrote:

"Professional Observations which may be of use (Safety Practitioner)

Noted many people waiting for instructions to put on hood even though they were sitting in dense smoke.

I automatically kept low in the smoke, and was able to see amber lights in the floor of the aisle (presumed to be lead-out lights) I could not communicate to others around to lead out of the dense smoke (see Q.35). Your observation may show a time gap between myself and the person in front exiting from the plane. I stopped to investigate a pair of legs (casualty) about 4 seats from the front and turned out to be an observer (I hope!) Very embarrassing - I tried to leave my seat without unfastening the belt."

Another participant, after taking part in a test employing the same condition, wrote, " .... by the time we were out of our seats it was impossible for us to see a hand in front of us". Others reported participants climbing over the backs of the seats fumbling to release seat belts and getting in their way as they endeavoured to reach an exit.

A further comment regarding the selected level of smoke was made on behalf of the Chief Inspector of Accidents, Accident Investigation Branch, Department of Transport, by Mr E J Trimble, who wrote " ... in the large scale Tees-side tests using naive subjects this particular question had to be approached with the utmost care due to the possible effects of isolated or more general adverse reaction by those participating in the evacuation in "smoke"." He went on to express the view that the level selected was absolutely correct and added that" ..it would have been difficult to contend with any degree of certainty that (a) much reduced visibility would have seriously affected donning time of the smoke hoods, the prime focus of Operation Exit, since their stowage was directly in front of each "passenger" in arms reach " evacuation times. A relatively small number of participants reported that they encountered difficulty in breathing in conditions where the smoke was applied. It is possible that this may have caused by a combination of stress and the "musk" odour of the smoke used at Tees-side. The reaction by some participants to the smoke and the reports of sensations of claustrophobia (covered earlier in the statistical analysis) chime with those emanating from people who have been confronted by fire and the associated toxic fumes and gases. During some evacuations it was noted that a number of individuals had difficulty in releasing their seat belts; some observed a small number of participants climbing over seats in their efforts to leave the cabin while a number of participants encountered others getting in their way as they tried to leave the aircraft.

STATISTICAL ANALYSIS

The preliminary statistical analysis concentrated on the effects of the experimental conditions, the location of seat within the aircraft cabin, the exit used, the age and sex of the participants on the evacuation times. This identified the location of the seat as the key factor and provided a firm indication of the direction to be taken for further statistical work. Thus the main analysis, utilising a balanced design, considered the evacuation times under the four different experimental conditions, excluding for the moment inflight fire. The separate estimates obtained for the effects of smoke and hoods and for the interaction between these factors, indicate that the wearing of hoods and the presence of the smoke both increase the evacuation times. However, the interaction between these factors was negative, indicating that the use of hoods in the presence of the smoke had an effect on the evacuation time which was less than the sum of the additional times attributable to the separate factors 'smoke' and 'hood'.

It will be recalled that when participants donned the ventilated smoke hoods in conditions of smoke, their subsequent evacuation, observed by monitors, support staff and others, was much more orderly than during an evacuation taking place in smoke without hoods. Comments made by a number of the participants, after taking part in tests involving the donning of the smoke hoods in a condition of smoke, indicated that they were unaware that the equipment was ventilated. The view is held that because participants felt that the ventilated smoke hoods gave protection from the smoke the confidence this gave them brought about a more orderly and therefore quicker evacuation.

A further approach - adopted by Dr. Hiorns to determine the effects of the two factors, used a quadratic response surface model and made use of all the experimental runs except 2 and 9. This enabled the evacuation time for each seat position to be predicted for each condition and showed that the time taken to evacuate increases with distance from an exit and an aisle. The model is a best fitting quadratic surface model using the row and position within the row as coordinates. In turn, it was possible to proffer the fitted model equation for prediction of evacuation times.

The statistical analysis undertaken for the study differs from the traditional method, based on an analysis of basic evacuation times. It is felt that the utilisation of such an approach could offer information of value for those seeking to review evacuation tests.

HOOD DONNING

At the outset it was clear that some saw a specific hood donning time as a necessary outcome of the Tees-side tests. However, the aim of the study set out in the test protocol developed with the Civil Aviation Authority, and subsequently approved by this regulatory authority, was related to observing and recording the effects, if any, on timings and passenger behaviour of the donning of smoke hoods during simulated evacuations of an aircraft passenger cabin in conditions of clear air and smoke. Thus, the investigation centred on the impact that smoke hoods might make on the overall timings of such events rather than to provide measures of hood donning time.

As has been mentioned earlier only two out of 510 people required to wear ventilated smoke hoods during the tests left the aircraft without donning a hood. While safety monitors/ first aid assistants noted that some were a little slower than others in placing the hoods over their heads, the participants did not appear to encounter significant difficulties when donning the ventilated smoke hoods used in the tests.

Some of the participants were reported to have donned the ventilated smoke hoods on first sight of the smoke rather than wait for the directions of cabin staff. It will be recalled that the evidence provided by the Air Accidents Investigation Branch of the Department of Transport, at the inquest on those who died at Manchester nearly three and a half years ago, indicated that it was necessary that smoke hoods should be close at hand and under the control of passengers. Clearly the participants behaviour during this study confirmed that in circumstances where smoke hoods are thus, it can be argued that hood donning time lacks the significance that many attribute to it.

Nevertheless, hood donning plays a part in the development of the specification for passenger protective breathing equipment and the data drawn from the Tees- side tests reveals the increased times due to the presence of the 'hood' and the 'smoke' factors. Study of the CCTV tapes from the Tees-side study, where the equipment was with easy reach of the participants, leads one to believe that the majority of the participants donned the ventilated smoke hoods within some ten seconds.

In turn, the Tees-side study has shown that the speed at which smoke hoods are donned is influenced by the motivation of the individual to don the equipment, the ease at which such equipment can be worn and the effectiveness of the instruction provided during the passenger safety briefing. These factors are taken into account in the Civil Aviation Authority specification number 20 (Specification for Passenger Protective Breathing Equipment (PPBE - Smoke Hoods).

SECTION FOUR - CONCLUSIONS

As a preliminary to the main analysis of the data, the effects of the experimental conditions, the location of seat within the aircraft, the exit used, the age and sex of the participants were examined. The effects of sex and age were analysed after removing the effects of seat location, exit used and run; neither were found to be of significance. Therefore it is concluded that the inability to maintain the exact recruitment targets did not impact on the findings of the study.

After taking into account the location of the seat in the aircraft used, the exit used was not significant indicating that the latter (i.e exit) was almost completely determined by the former (seat location). For this reason, and that the effect of age and sex were not significant, it was concluded that the analysis of the differences between the experimental conditions should concentrate on the key factor, the location of the seat occupied.

Statistical methods concentrating on the key factor encountered in an evacuation study permit the application of techniques based on quadratic response surface models. It is concluded that such models provide a very much more useful information than the statistical methods based on the analysis of evacuation times.

The smoke used at Tees-side could not reproduce the choking and irritant characteristics of the smoke encountered in aviation fires, a factor which is likely to increase the time taken by those trying to evacuate an aircraft cabin in the condition smoke without hoods. It is expected that in such a condition the difference between evacuation times would be wider. Nevertheless, the application of the smoke did bring about a measurable behavioral change in terms of extending the evacuation times. It is therefore concluded that for the purpose of the study the form of smoke used was satisfactory.

Five hundred and ten individuals were called upon to don ventilated smoke hoods during the course of the study. As has been stated, only two people left the aircraft without a hood; one was seated alongside an exit and saw no need for a smoke hood in such a location at the time of the evacuation, while the other had apparently consumed a considerable quantity of alcohol between the time of medical examination and the commencement of the test. Therefore it was concluded that the preflight briefing devised for passenger protective breathing equipment was satisfactory and that the ventilated smoke hoods used for the study were easy to don.

A number of people taking part in the tests in conditions where ventilated smoke hoods were worn reported some feeling of claustrophobia. However, these participants together with others who did not experience this phobia left the aircraft in an orderly manner. Analysis of subjects by claustrophobic group showed that there was no over representation of the claustrophobics in any particular run, nor did they have higher evacuation times than others. It is concluded that this phobia was not an inhibiting factor in the case of those taking part in the Tees-side tests.

It was observed that on donning smoke hoods in conditions of smoke a more orderly evacuation took place than in a condition of smoke without hoods. It is therefore concluded that the donning of the ventilated smoke hoods gave the participants a feeling of protection from the smoke and the confidence they gained from this act brought about a more orderly evacuation.

The study centred on the impact that donning of ventilated smoke hoods might make on simulated emergency evacuations of an aircraft passenger cabin in conditions of clear air and smoke rather than to provide measures of hood donning time. In circumstances where passenger smoke hoods are near to hand, hood donning time lacks the significance that many attribute to it. Nevertheless, hood donning time plays a part in the development of specifications for passenger protective breathing equipment and data drawn from the Tees-side tests provides the increased times due to the presence of the hood and the smoke.

The statistical analysis indicates that the wearing of smoke hoods and the presence of smoke both increase the evacuation times (Smoke hoods 5.12 and Smoke effect 6.25 with standard errors of 1.84). The effect of these main factors were highly significant. Nevertheless, the interaction between these factors was significant and negative. (-3.73 with a standard error of 1.84), indicating that the use of the hoods in the presence of smoke had an effect on evacuation time which was less that the sum of the additional times attributable to the separate factors 'smoke' and 'hood'. The ventilated smoke hoods were located within easy reach of the participants. It is known that on first sight of smoke some donned the ventilated smoke hoods prior to receiving directions from the cabin attendants and many may have perceived that the ventilated smoke hoods afforded protection, in turn, bringing with it a more orderly evacuation. For these reasons it is concluded that the wearing of smoke hoods should not significantly impede passengers, ability to evacuate an aircraft cabin in an emergency.

It is suggested that the preoccupation with evacuation times, with and without smoke hoods, has led to the main point being missed. The tests show, as did those undertaken by the Federal Aviation Administration in 1969, that evacuation in conditions of smoke takes much longer and thus protection is necessary from smoke particles, toxic fumes and gasses for some passengers to survive.

FLIGHT CREW TRAINING FOR FIRE FIGHTING

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SUMMARY

This paper contains a description of Lufthansa emergency training aspects for flight-and cabin crews in respect to fire fighting. It addresses topics as preventive measures, on board fire fighting equipment, measures in case of an on board fire, training for actual fire fighting and future developments.

INTRODUCTION

The emergency training of flight and cabin crews deals with a variety of important topics such as passenger evacuation, decompression, sea survival after airplane ditching or survival in arctic or desert regions. If questioned, however, most crewmembers will state that an inflight fire poses the highest threat to aviation. This is a scenario which crews fear most. There have occurred some fatal accidents which we well remember, e.g. the Saudia L-1011 case in Riyadh, the Air Canada DC-9 burning out after landing in Cincinnati and - lately - the Main Deck Cargo Fire on the South African B747 Combi resulting in a crash near the island of Mauritius. One thing, however, should be made quite clear from the beginning:

Flight- and Cabin Crews have only the facilities to fight fires in an early phase. No one in an airplane presently has a chance to fight successfully a fire which has already spread into an inferno. One important aspect of flight crew training therefore consists also of prevention rather than on fire fighting only.

1. PREVENTIVE MEASURES

1.1. Irregularities during Flight

Our flight attendants are trained that any unusual observations, malfunctions or any defects related to electrical equipment have to be reported to the cockpit crew. Also resetting of circuit breakers is forbidden, until the cause for the malfunction has been clearly determined and the situation has been corrected.
How important flight attendants are in this respect, may be illustrated by the following example. During landing a flight attendant had the impression of some light flashes coming from the galley area. Since the sun was shining through the window it might have been a wrong observation. After removal of some galley installations a wiring was detected with partly missing insulation. The light flashes which the cabin attendant was not sure of were produced by the sparks of the intermittent short circuits produced by the faulty wire. A good example for prevention?

1.2. Observation of Cabin

Smokers aboard an airplane are undoubtedly a risk factor, for instance when falling asleep while smoking, disposing cigarettes on trays or in waste boxes, or when smoking in restricted areas as toilets. It is the duty of cabin attendants to keep an eye to all possible risk factors expecially during night.

1.3. B747 Main Deck Cargo

Lufthansa is the largest operator of B747 Combi airplanes. These airplanes are able to carry up to seven 10 ft containers in an aft section of the airplane. Instead of containers very often freight is transported on pallets. What prevention can be done here?

It is our procedure that the fire fighting crew is selected by the captain before departure and that a visual inspection of the loading in the cargo area is performed before takeoff. These preventive measures can be done without any time pressure and under optimum visibility condition, whereas with a spreading fire time is short and visibility may be impaired by dense smoke.

1.4. Technical Equipment

1.4.1. Smoke Detectors

The areas in a passenger airplane, where a fire may not be detected in time or areas which are not accessible, are usually equipped with smoke detectors. They are installed in lavatories, cargo holds or also in the Main Deck Cargo Compartments. When properly maintained, these systems provide a warning in most cases earlier than the human senses. However all those warning systems are useless if due to wrong wiring the fire is really existing in a different area than the warning is indicating. You will rememeber some of these findings after the British Midland B737 crash.

1.4.2. Fire Extinguishing Systems

Generally those areas, which are not accessible or which have proven to present a high fire risk, are equipped with extinguishing systems, that are activated either manually from the cockpit (after receipt of warning) or automatically by melting of a temperature fuse. When passengers put their cigarettes into the toilet waste boxes and caused there some fires, we started to install in the waste boxes automatic fire extinguishing systems which are activated if temperature exceeds 80 degrees Celsius. Cargo hold area fire extinguishing agents are controlled manually from the cockpit. The agent is Halon 1301 for those stationary systems. Halon is one of the most effective fire fighting substances we know. For the B747-400 Main Deck Cargo Compartment probably the FAA will require a Halon fire knock down system.

2. ON BOARD FIRE FIGHTING EQUIPMENT

Lufthansa has spent considerable time some years ago for Emergency Equipment- and Procedure Standardization. Due to that work all cabin attendant stations on our different airplane models are equipped identically. Each cabin attendant station has a 1 kg Halon 1211 fire extinguisher and for fire fighting under dense and toxic smoke conditions an oxygen bottle with corresponding full face mask. More than the minimum required number of fire extinguishers is carried, e.g. ten 1 kg Halon fire extinguishers are on board a Lufthansa B747 Combi airplane.

In addition one 2,5 kg Halon extinguisher is carried in the Electronic Equipment Compartment and one 7,5 kg Halon extinguisher in the B747 Main Deck Cargo Compartment. No other types of fire extinguishers (water etc.) are carried, so that crews do not have a selection problem.
In order to enable the flight deck crew to perform their duties even under smoke or toxic fumes, there are full face masks or - on newer airplanes - combined quick donning and full face masks available.
Useful other equipment for fire fighting such as crash axe, crow bar, protective gloves, smoke goggles and a safety rope (B747 Main Deck Cargo Compartment only) is distributed throughout the airplane cabin and the cockpit.

3. MEASURES IN CASE OF AN ON BOARD FIRE

3.1. Cabin Fire Procedure

Each standard cabin attendant station is equipped with the Cabin Fire Procedure (Figure 1). The area enclosed by thick black lines has to be known by heart. The most important aspect for successful fire fighting is to localize the source of a fire and then to fight it. To empty a fire extinguisher for instance into a smoke filled toilet without hitting the fire source is of no use at all. If needed for e.g. toilet fire fighting a full face mask and oxygen bottle have to be used. An important task of the fire fighting attendant - called first CA in our procedure - is to call a second flight attendant. This attendant has to inform the purser and the rest of the cabin crew, so that necessary other steps are initiated without delay. Some of these are:

- Communication of all relevant information to cockpit crew through purser
- Switching off all electric connections in affected area
- Directing passengers away near fire location
- Ensure availability of reserve fire extinguishers and oxygen bottles, but removal of all oxygen bottles near fire location.
- Directing passengers to breath through wet cloth
- Watching affected area closely for reignition after successfull fire fighting.

For the underfloor galley of our Condor DC-10 we have a special procedure as well as for B747 Main Deck Cargo Fire fighting. The procedure in figure 2 has been changed short time ago after a test of our old Main Deck Cargo Fire procedure. Primary points of concern were:

- Consumption of too much time before cargo compartment was entered for fire fighting
- Difficulties with safety rope (gordian knot and problems to move freely for the fire fighting attendant)
- Problems with oxygen bottle and full face mask (hindering movement, too little endurance time with approximately 10 minutes of oxygen, no direct communication e.t.c.)

Our goal is to equip our B747 Combi airplanes earlier than the complete fleet with smoke hoods and to integrate mike and earphone into te hood for verbal communication of the fire fighters with the purser outside of the cargo compartment. The purser then will be responsible for communication with the cockpit.

3.2. Cabin to Cockpit Communication

Many accidents have proven, how vital communication is between cabin and cockpit personel. For this reason cabin and cockpit crews are trained together at Lufthansa. In our annual emergency refresher training we have lately used a film with the title "Flash Fire" that was produced by Lufthansa based on the NTSB report of the Air Canada DC-9 accident in Cincinnati. If somebody is interested in that film, it may be viewed at a suitable time after the meeting. The lessons we have learned from that accident are:

- in case of fire no time shall be wasted for preparation of an emergency landing
- fire extinguishers shall only be used after localization of fire source.
- conflicting informations to cockpit crew such as "I think the situation is under control since the smoke is clearing away" shall be avoided
- circuit breakers shall not be resetted without verification of the malfunction.

4. TRAINING FOR ACTUAL FIRE FIGHTING

4.1. Mockup Training

In all of our training mockups in Frankfurt we have the possibility to generate smoke, to light artificial fires and to check if a crew member has determined the fire source and extinguished the fire successfully. The artificial smoke we use is a cosmetic smoke as used in theatres or in discotheques and it is nontoxic according to manufacturer and laboratory findings. The disadvantage of that smoke is that it is "white smoke" and that it tends to stay on the ground when no airdisturbances exist. This is in conflict to real fires, where the smoke is extending from the ceiling to the bottom.

The fire simulation is done by some yellow and red flickering lights. With smoke present it provides a fairly good impression of a real fire. The fire fighting action is simulated with original fire extinguishers filled with air. If the airstream coming out of the nozzle is correctly directed to the flickering bulbs, it passes a heated resistor. When this resistor is cooled off sufficiently, the fire goes out. It lights up automatically after a selectable time interval in order to save the reset switching for the instructor if another crew member is trained.
The locations for these fire simulations are in the cabin, in the toilet (with the need to open access panels) and in waste boxes. A speciality in fire training is our Main Deck Cargo Compartment mockup, where the respective fire fighting procedure can be trained (donning of full face mask, opening crash net, getting necessary equipment, locate and extinguish artificial fires under smoke environment). We will change this facility to better simulate real airplane conditions (especially simulating the confined space).

5.2. Real Fire Fighting

In order to gain confidence in oneself and the equipment we think it is essential that crews extinguish real fires from time to time. As most airlines we have a fire training place where we light up a pan filled with fuel. Only correct handling of an extinguisher will guarantee success in the fire fighting. Most mistakes you may observe are holding the fire extinguisher not in an upright position, attacking fire from too far or too near distance, directing Halon not to the fire base and overestimating the spray time of an extinguisher (around 6 sec for 1 kg Halon extinguisher). I would like to point out all those airlines in possession of a fire fighting house such as e.g. Air France, KLM and Swiss Air, since their training is independant from weather. Since Halon, however, belongs to these substances which damage the Ozon layer on earth, we have to find solutions for realistic training without environmental pollution. Presently the fire fighting houses need tremendous maintenance efforts due to the aggressive combustion products when using Halon. Also the problem of accidents from acid drops falling eventually on trainees or trainers seems not to be solved successfully. In the meanwhile we have changed the times for fire fighting exercises from a two year to a three year basis for environmental reasons.

6. FUTURE DEVELOPMENTS

6.1. Smoke Hoods

Our company has tested the smoke hoods of 7 manufacturers under typical conditions during fire fighting. Though the German legislation does not yet require these smoke hoods on board of our airplanes, we have seen that these hoods offer considerable advantages such as longer oxygen duration, quicker donning, better communication and free movement capability.

6.2. Better Flammability Standards

The new FAA requirements will further enhance survivability in accidents related to fires and are an important step into improved cabin safety.

6.3. Cockpit Equipment

The combination of quick donning and full face mask is a step into the right direction to replace in future smoke goggles and quick donning masks.

6.4. Smoke Hoods for Passengers

It is uncertain, if these devices will be introduced and if they generally may help to save lives. Being familiar with several kinds of emergencies I as an individual person would be in favour for such an equipment, because it would improve my chances for survival. For Lufthansa a solution would be preferable which combines the usability of present masks for decompression and passenger smoke hoods. This would, however, need a complete redesign, since masks should be detachable and should no longer have the design feature to mix air (or fume in case of fire) into the supplied oxygen.

CABIN FIRE PROCEDURE

Fire or smoke	LOCALIZE FIRE SOURCE AND CALL SECOND CA	First CA
Fire source	FIGHT IMMEDIATELY	First CA
Oxygen bottle and full face mask ...	PUT ON IF NECESSARY	First CA
Cockpit- and Cabin Crew	INFORM	Second CA
Additional fire extinguishers	AS BACKUP TO FIRE SOURCE	Other CA's
Communication with Cockpit Crew..	MAINTAIN	Purser

> Attention: In case of a lavatory fire keep the door closed until full face masks have been put on and the fire can be fought with several extinguishers simultaneously

Oxygen bottles near fire	REMOVE	Other CA's
Electric switches and circuit breakers in danger area	SWITCH OFF/PULL	Other CA's
Passengers near fire	SEND AWAY	Other CA's
Handluggage near fire	REMOVE	Other CA's
Oxygen bottles and .... full face masks	PROVIDE AS RESERVE	Other CA's
Air vents near fire	CLOSE	Other CA's
Blankets and extinguishing liquids	KEEP READY	Other CA's
Provtective gloves, crash axe, crow bar	KEEP READY	Other CA's
Announcement for smoke	CLOTH OVER MOUTH AND NOSE	Purser
Fire extinguished	WATCH FOR RENEWED FLARE-UP	All CA's

FIGURE 1.