CAA PAPER 93012

INTERNATIONAL CABIN WATER SPRAY RESEARCH MANAGEMENT GROUP

Conclusions of Research Programme

This paper is a summary of research and analysis conducted with the purpose of determining the feasibility and practicability of an onboard aircraft cabin spray system for extending survival time during a post crash fire. The research programme was carried out by the FAA and the CAA and managed by a Group which has included representatives of the FAA, Transport Canada, CAA, DGAC, LBA and RLD. This paper was prepared by the Research Management Group and is published in the UK by the Civil Aviation Authority.

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EXECUTIVE SUMMARY

Background

This paper is a summary of research and analysis conducted with the purpose of determining the feasibility and practicability of an onboard aircraft cabin water spray system for extending survival time during a post crash fire. The basis for this work was a series of impressive demonstrations of the effectiveness of a water spray system by the SAVE company in the UK. The 'SAVE' system was used as the baseline design at the onset of the program. The research programme was carried out by the FAA and the CAA and managed by a Group which has included representatives of the FAA, Transport Canada, CAA, DGAC, LBA and RLD.

System Effectiveness

The initial phase of the program determined the effectiveness of a SAVE type system for various fire scenarios in both narrow and wide body aircraft. The system was found to be very effective in providing two or more minutes additional escape time in all but the most severe fire conditions.

System Optimisation

Testing was conducted to study the mechanisms which made the SAVE system effective. The results showed that the system's best attributes were in slowing fire growth and reducing temperature levels in the cabin. From these results the zoned concept was developed. Testing showed that by only spraying in the area of a fire threat, as little as 8 gallons of water could provide a level of safety as great or greater than the 72 gallon SAVE type system in a narrow body aircraft. Wide body tests confirmed the ability of the zoned system in providing similar or better protection with a much reduced quantity of water.

Physiological Hazards and other Human Factors

A number of potential problems were identified and examined. A review of scientific literature and water spray test data resulted in the conclusion that, water spray of the type tested, would not add to the hazards by increasing the moisture contact of inhaled air or carrying toxic particles deeper into the lungs. The effects of water spray on evacuation was studied with full-scale trials. Results showed no difference between sprayed and non sprayed evacuation times. The reduction in visibility caused by the water spray system bringing the smoke layer down was overcome with the utilisation of the zoned system. The use of a zoned system should also minimize the number of passengers likely to be wetted and, thereby, the risk of hypothermia following evacuation.

Safety Benefit Analysis

An analysis of past accidents, updated with estimated benefits of current fire safety requirements, concluded that 14 lives per year world-wide, or 6 lives per year US/Canada/Europe would have been saved with water spray. Whilst the benefit has been presented s an average life saving per year if an accident does occur, it may involve a major loss of life.

Manufacturers' Disbenefits Studies

Studies by Airbus and Boeing concluded that the addition of such a system was possible but that some protective measures may be needed to enable the aircraft to tolerate an inadvertent water discharge. The zoned system should minimize that need.

Airworthiness Requirements

Draft airworthiness requirements were developed with industry consultation to provide a realistic basis for a cost assessment.

Cost Analysis

A cost study was commissioned to cover a range of system configurations and aircraft types. The analysis showed that for a new design wide body the annual cost to the US/Canada/Europe fleet would be in the region of \$132m to \$190m, thus giving a cost per life saved of \$22m to \$32m.

1 INTRODUCTION

The purpose of this paper is to summarise investigations into the use of water sprays for the suppression of cabin fires in aircraft on the ground. It is the report of the International Cabin Water Spray Research Management Group which was set up to manage the investigations and has included representatives of the FAA, Transport Canada, CAA, DGAC, LBA and RLD, (referred to in its report as 'the Group').

2 BACKGROUND

In 1985, soon after the accident to a Boeing 737 aircraft at Manchester, the CAA was approached by a small company with the proposal that a water spray system could be used to improve survivability in the event of an aircraft fire This has become known as the SAVE system from the name of the company.

Historically, water-based systems have been designed to extinguish fire with high flow rate jets or sprinklers, which use large quantities of water, but the essential feature of the proposal was a low flow-rate system which would produce a light spray or water mist within the cabin. The system comprised an array of nozzles which would provide spray coverage over the whole length and breadth of the cabin. This would deliver 18.75 US gallons per minute (68 litres) for a Boeing 737, equivalent to a rainfall of 0.03 inches per minute (0.8 mm). Whilst this would be insufficient to extinguish an established fire, the company's initial testing had shown that it had the potential to prevent or substantially prevent the occurrence of a 'flash' fire within the cabin by the absorption of radiant and convective heat. It also had the potential to remove water-soluble gases and particles from smoke in the cabin and, thereby. to maintain a survivable environment. This would extend the time available for safe evacuation. With this promise, the CAA agreed to sponsor a proportion of the development tests and a series of three full-scale demonstrations using a Trident aircraft at Teesside in 1988.

Following these successful demonstrations, the CAA convened a meeting of the FAA, Transport Canada and other European authorities to consider the way forward. It was agreed that the following tasks should be carried out:

(a) an evaluation of the effectiveness of the system in maintaining a survivable cabin atmosphere under a controlled range of post-crash fire conditions and a quantification of the likely increase in evacuation time available;

(b) optimisation of the system concept;

(c) an analysis of the net safety benefit which could be expected;

(d) an assessment of the potential disbenefits associated with carriage of the system and, especially any hazards due to its intentional or unintentional activation, for example, on the aircraft's systems or structure;

(e) preparation of design and performance criteria, including acceptance tests, if appropriate.

This work has been completed to the point that the question of regulation can be reviewed and the need for any further research considered.

3 SYSTEM EFFECTIVENESS

The major component in the evaluation of system effectiveness was full-scale testing carried out by the FAA's Technical Centre and by the UK Fire Research Station for the CAA. The test arrangement simulated a survivable aircraft crash involving an external fire. The fuselage structure was 'hardened' against fire to allow for multiple tests, the cabin interior comprised low heat release wall and ceiling panels and fire blocked seats. In the primary test arrangement the interior was exposed to an external fire through a door-sized aperture. The test fire was provided by igniting jet fuel in a pan at floor level (8 ft. by 10 ft. approximately) to replicate the severe thermal threat created in an accident. The effect of a wind blowing the flame into the cabin could be simulated by using an exhaust fan at an opening remote from the fire entry point. Strict control was maintained of the fuel fire conditions and the fan operation to ensure test repeatability. Other fire entry scenarios were also simulated.

In the discussion which follows reference is made to 'flashover'. In many fires this marks the point at which there is a rapid escalation in the production of toxic gases, heat and oxygen consumption. It is thus the time beyond which survival is improbable. However, the limit of survivability can also be reached without flashover and the results of a fire test can be analysed to determine the time at which the combined threat from all the individual hazards reaches a level at which survival is improbable. The results of these tests and the supporting laboratory investigation indicated that the main benefit of the system was not derived from 'scrubbing' of the fire products but, rather, that the water sprays reduced the fire penetration into the cabin and inhibited the fire spread in the cabin contents.

Narrow Body Tests

Boeing 707 fuselages were used in both the FAA and CAA tests. Test configurations and procedures were similar to ensure compatibility of results. The tests utilised 120 nozzles which discharged 24 US gallons (76 litres) per minute. Instrumentation included thermocouples, gas and particulate analyzers, smoke meters and calorimeters as well as still and video cameras. The test section of the fuselage was fitted with passenger seats, stowage bins, sidewall panels, ceiling panels and carpets.

A 'moderate wind' simulated by the exhaust fan became the standard test condition. In that case, without water spray, a flashover condition was reached between 150 and 180 seconds. The FAA tests limited spray duration to 3 minutes only, as proposed in the original design concept,and in this case flashover was delayed to 300 seconds. In the equivalent CAA test the water spray was maintained for the full duration (7 minutes) and there was no flashover. However, at a point 30 ft. from the fire entry, incapacitating levels of toxic gases were recorded after 340 seconds at which time the temperature was 96°C.

The FAA tests also included a 'zero wind' case (no exhaust fan) in which flashover was reached in 300 seconds in the absence of water spray. However, when the water spray was used no flashover was recorded even through the external fire was allowed to burn for four minutes after the water spray ceased, the total test duration being 7 minutes.

Finally, in 'high wind' tests the fire was so severe that it overwhelmed the water spray such that it became necessary to terminate the test after only 60 seconds. This suggests strongly that in some scenarios it is virtually impossible to improve survivability by design changes in the cabin.

The FAA test programme also included a 'burnthrough' scenario. The water spray proved effective when, after 60 seconds, the fire penetrated the cabin by bursting through the floor and the sidewall area. Flashover was delayed by approximately 130 seconds.

Wide Body Tests

The programme at the FAA's Technical Centre went on to examine the application of water sprays to a wide body jet. The tests were carried out in a 130 foot long hybrid consisting of a 40 foot DC-10 section married to a 90 foot cylinder. The spray configuration comprised 324 nozzles arranged in 5 rows discharging 65 US gallons (246 litres) per minute. The instrumentation was similar to that used in the narrow body tests and representative cabin furnishings were installed in the fire entry zone.

The 'moderate wind' condition was used and, as was found in the narrow body tests, significant reductions in cabin temperatures and toxic gas levels were found in the water spray test. The results indicated that a flashover condition occurred at about 210 seconds without water spray whereas, with 3 minutes of water spray, flashover was prevented throughout the 5 minute test duration.

The test programme also included an assessment of the effectiveness of the system in the event of:

- a fireball in the cabin resulting from sprayed fuel (DC-9 in collision with a Boeing 727, Detroit 3 December 1990)
- an oxygen fed fire (Boeing 737 in collision with Swearingen Metroliner, Los Angeles, 1 February 1991)

In both cases the water sprays brought about a significant improvement extending cabin survivability.

Whilst the testing confirmed the effectiveness of the SAVE system, a number of concerns remained which needed to be addressed. These included:

- The weight of water to be carried, and the associated operating penalties.
- The reduction in visibility in the cabin remote from the fire entry.
- The inhalation of hot moist air.
- The inhalation of particulate and water droplets.
- Wet evacuees and hypothermia.
- Evacuation during water spray operation.

4 SYSTEM OPTIMISATION

In the initial narrow body tests for both FAA and CAA some consideration was given to the possibility of reducing the weight penalty by restricting the spray to that part of the cabin nearest to the fire threat. Tests with only a third of the cabin sprayed showed that the spray inhibited fire penetration and spread and that there was no reduction in system effectiveness. This led FAA to carry out a more structured investigation into the effects of zoning in which the fuselage was divided into a series of spray zones each operating independently of the others. Water spray activation was dictated by thermal sensors in a particular zone, thus eliminating the wasteful and ineffective discharge of water away from the fire.

Tests were conducted with zones, each 8 feet in length, using separate thermally activated solenoid valve controlled groups of water spray nozzles. These tests utilised only 24 US gallons (91 litres) of water ($\frac{1}{3}$ of the previous tests) survival time was increased in comparison to the non zoned test results by between 35–38 seconds depending on the nozzle discharge flow rate which was varied between tests.

It was found that a flow rate of 0.35 gpm gave an optimum balance between protection duration and fire control.

A second series of tests evaluated the effectiveness of an even smaller quantity of water. It was found that with 8 US gallons (30 litres) of water survival time using the 0.35 gpm flow rate nozzles proved to be about the same for both 8 and 24 gallon quantities.

It is clear that relatively small quantities of water in a 'zoned' system can provide a significant increase in survival time compared with a full cabin discharge system. For example, 8 gallons of water in a 'zoned' system utilising 0.35 gpm flow rate nozzles provided 55 seconds additional survival time compared with the full cabin 72 gallon system.

To evaluate the effectiveness of even smaller quantities of water, a 'zoned' test using only 4 gallons of water was conducted. The 4 gallon 'zoned' test provided additional escape time but this time was less than that provided using larger quantities of water in 'zoned' or full cabin systems. Nevertheless, it is impressive that such a small quantity of water can provide a finite improvement in survival time at all.

Wide body optimisation tests used the same flow rates as the narrow body tests and a proportionally scaled array of nozzles. They confirmed the narrow body results, showing a 90 second increase in available time for evacuation.

5 PHYSIOLOGICAL HAZARDS AND OTHER HUMAN FACTORS

In evaluating system effectiveness a number of potential hazards were identified and examined, as discussed below.

Inhalation of Hot Moist Air

The inhalation of dry air at 200°C can be tolerated for a short time, from one to a few minutes. In the assessments of survival time, in Section 3 above, incapacitation due to inhalation of toxic gases always preceded temperature levels of this order. However, the possibility had to be explored that with the presence of water spray the air would become significantly moist even in the unsprayed zone (it is important to draw the distinction between the inhalation of *moist air* and *droplets* which will be considered separately below). In this context it was noted that the heat flux associated with saturated air is considerably greater than for dry air. Although human tolerance limits are not known it is considered that saturated air above about 50°C may begin to present a hazard. Measurements taken during the wide body optimisation tests, however, showed that the increase in water vapour content with time was similar for sprayed and unsprayed tests and was well below saturation at the higher temperatures. There is, consequently, no increase in hazard from this source.

Inhalation of Particulate and Water Droplets

Irritant products in unsprayed smoke exist partly as gases and partly attached to small solid particles and liquid droplets. Depending on the aqueous solubility of the gases, and the size of the particles these are capable of penetrating into and damaging the respiratory tract to a varying extent. The use of water spray was found to decrease greatly the amount of solid particles and liquid droplets capable of penetrating into the lungs, and also the irritants attached to them, thereby reducing the risk of lung damage. Although a small amount of larger, non-respirable droplets in the smoke may have been due to the water spray, these had a low dissolved acid gas content and were considered unlikely to present any additional hazard.

Wet Evacuees and Hypothermia

It is inevitable that survivors of accidents, even those occurring on an airfield, may be waiting in the open for some time. Experience has shown that this delay will be nearer to an hour than a few minutes. This raised the possibility that, in cold weather, passengers who have been subjected to a cabin water spray (due to fire or inappropriate activation) may be so wet that they would suffer from hypothermia. Indeed, the conditions under which they may be most at risk, snow and ice, may well be those in which the delay in evacuating them to a warm shelter may be the greatest. However, medical advice is that the water spray will not increase the risk of hypothermia unless the victim is wet through to the skin, and the likelihood of this is considerably reduced in the case of a zoned system as described in Section 3 above where the water spray will only operate in the immediate vicinity of the fire entry point. Further more automatic activation is likely to reduce the probability of inappropriate activation. The number of passengers sprayed will be small and, then, only lightly as they will tend to move away from the fire quickly.

Evacuation

It was recognised that there was a need for research regarding the human factors implications of cabin water spray systems. In particular, any tendency for evacuations to be adversely affected would be a matter of concern and, therefore, the CAA commissioned an experimental programme. This included an investigation into the acoustic environment. For the tests the forward section of a 707 fuselage was furnished with 45 seats and had access to one Type 1 exit. It was fitted with a full SAVE system, without zoning, and thus represented a worst case. Eight groups of volunteers (350 in all) carried out one evacuation each in a simulated take-off crash scenario. Four of the trials were sprayed and four unsprayed. The results of the investigation showed no significant adverse consequence for emergency evacuation and no effect on rates of evacuation. Wearers of glasses reported more visibility problems in the sprayed evacuations than those wearing contact lenses or no eye wear. Although volunteers reported that the evacuation commands given by cabin attendants were significantly less audible when the spray was used, there was no evidence that the evacuation was adversely affected.

Visibility

In the early research for both CAA and FAA with water spray for the full length of the cabin, it was noted that the water tends to prevent the formation of a concentrated smoke layer near the ceiling and, instead to distribute the smoke throughout the distance from the ceiling to the floor. This brought about a significant reduction in visibility in the early stages, as indicated by both light transmissivity measurements and video recordings. In the follow-on tests where only a third of the length of the cabin was sprayed it was noted that the smoke layer tended to restratify in the unsprayed part of the cabin, reforming in a concentrated layer at the ceiling. This provided a marked improvement in visibility in what can be regarded as the 'evacuation' region of the cabin. A still greater improvement has been found in the more recent optimisation tests where the sprayed area is even smaller. Volunteer's reports from the evacuation tests indicate that the spray itself does not reduce visibility so that the effects described above are entirely due to the entrained smoke.

The restratification of a buoyant smoke layer in the unsprayed 'evacuation zone' brings with it the additional benefit that the concentrations of toxic gases at lower heights are also reduced.

6 SAFETY BENEFIT ANALYSIS

A study of accidents to civil passenger aircraft over a 26 year period has been made. In this period there were 95 accidents in which fatalities and fire occurred, from an analysis of these accidents a potential life saving benefit for cabin water spray systems has been obtained.

In the analysis of past accidents the life-saving resulting from the inclusion of current mandatory safety features was first estimated. Thus the analysis attempts to calculate the benefit, as a further incremental life saving, if cabin water spray systems were to be fitted in today's standard of aircraft which incorporates all of the fire safety improvements introduced over the 26 year period. Fire test data from full-scale fire tests has been used to predict the extension in the survival time of cabin occupants as a result of the use of cabin water spray, accident hazard and evacuation profiles were used to calculate the life saving potential.

The database of 95 accidents has been used to indicate the necessary design features of a cabin water spray system, this has been achieved by studying the fire development, the aircraft damage and break-up in the accidents and the whereabouts of the crew and their condition, by this method crashworthiness objectives and preferred means of activation have been defined. An automatically activated zones system of modular design employing two or more tanks was found to offer the greatest life saving potential. Consideration has been given to the effect on the predicted cabin water spray benefits resulting from the introduction of new requirements concerning seats of enhanced crashworthiness and low heat release cabin interior materials. The expected growth in aviation and the accident trends over the 26 year period have been considered in predicting the future benefit of cabin water spray systems.

As a result of the 95 accidents which were studied in this report fire claimed 2400 fatalities, however, it is calculated that fire blocked seats, escape path lighting and improved cargo hold liners, which are now mandatory for all aircraft in operation, would if they were fitted at the time of these accidents have prevented 35% of the deaths. Cabin water sprays could have made an additional benefit of 15%, however, for nearly half the fatalities due to fire no further protection can be envisaged, these fatalities are a result of occupants, some severely injured, being engulfed in fuel fires, often when no longer within the cabin a a result of its complete destruction following impact.

There is evidence that the fire safety design changes made in recent years are fulfilling their safety objectives, this combined with the continuing reduction in accidents which result in fire leads to the conclusion that cabin water sprays would today save on average 14 lives per year world-wide. When the calculations are performed taking account of only the aircraft operated by the airlines of the nations comprising the JAA, the FAA and Transport Canada these figures reduce to 6 lives per year.

In the future it is predicted that the benefit will remain constant at this figure of average life saving per year despite the expected growth in aviation, largely as a result of the improving accident trend, cabin evacuation and fire safety improvements. The latter includes the growing use of low heat release cabin interior materials.

It should be borne in mind that the 'real world' does not conform to this idealised annual average, there is at any moment a finite risk of an accident occurring which may involve a major loss of life.

7 MANUFACTURERS' DISBENEFITS STUDIES

At the beginning of the programme, the Group agreed that 'disbenefit' studies should be carried out by aircraft manufacturers in parallel with the fire test work, principally to establish what steps might need to be taken to avoid any hazard arising from system operation including inadvertent operation. Two studies were envisaged, one with Airbus Industrie particularly directed towards the company's 'fly-by-wire' technology, and one with the Boeing Commercial Airplane Group directed towards more conventional flying controls but otherwise incorporating modern digital technology. Both studies were based on the original SAVE full-cabin spray system.

The Airbus study was funded jointly by the Commission of the European Communities, CAA and DGAC, France. It concluded that in-flight operation would have to be precluded because the cost of modifications to make this option available would be prohibitive. No serious problem was identified in relation to use on the ground, although some minor design changes were recommended. In their analysis Airbus made the pessimistic assumption that no water would be absorbed by furnishings or carpet on the main deck that that it would all find its way into the under floor area. It is unlikely however that this assumption affected the main conclusions of the analysis, specially in relation to a full duration activation.

The Boeing study sponsored by NASA and the FAA, concluded that the addition of such a system was practicable but that some protective measures may be needed to enable the aircraft to tolerate an inadvertent water discharge. The other major benefit was the possible refurbishment process that would be required following an inadvertent system discharge. However, tests conducted for the study demonstrated that the majority of sprayed water (90% or more) would be absorbed by the cabin furnishing materials.

The development of the 'zoned' system has addressed many of the potential disbenefits of the full SAVE system including those which were identified in the manufacturers' studies.

8 AIRWORTHINESS REQUIREMENTS

In addition to the joint research programme, the CAA issued a Discussion Paper in November 1988 to elicit views on the technical and regulatory issues. Comments were received from some 29 interested organisations and individuals in the UK and overseas. A digest of these comments was published in November 1989. In May 1991, a consultative conference was convened at Gatwick, England to present the results to date of the international collaborative research programmes and to further discuss the technical and regulatory issues. The comments and views expressed were published in October 1991.

Subsequently, in support of the research programme draft airworthiness requirements have been developed by the Group together with ongoing industry consultation. This material has provided a realistic basis for a cost assessment.

9 COST ANALYSIS

To assist with the process of decision making in the follow up of this research, a study was commissioned by the CAA to gather information on the likely costs of introducing water spray systems into aircraft. The study was also structured to enable the benefits of alternative options of system crashworthiness and capability to be assessed.

The system design used for the study was based on the 'optimised' system described in Section 3. Three generic aircraft types were considered; a Regional Transport aircraft (maximum 60 passengers), a Narrow Body Aircraft (174 passengers) and a Wide Body aircraft (360 passengers). Design, procurement, installation and operating costs were derived for new aircraft designs, new build aircraft and retrofit.

A summary of the cost analysis results is given below. The figures assume that water sprays would be introduced on new build aircraft only and are based on the US/Canada/Europe fleet and projected life saving. Two sets of costs are given. The reason for this is that the cost/lb used in the study was noted to be significantly different from the figure currently employed by the FAA in the assessment of new regulations. The first set of figures is based on costs/lb/year of $6.75 (Regional aircraft), $13.65 (Narrow Body) and $37.5 (Wide Body). The second set is based on a cost/lb/year of $9.30 for all aircraft types, as currently used by the FAA.

(a) Costs Based on Costs/lb/year assumed in UK study.

Aircraft Type	*Annual Cost per Aircraft*	*Annual Fleet Cost*	*Lives Saved per year*	*Cost per Life Saved*
Regional	$11.7K	$15.2m		
Narrow Body	$17.6K	$98m	6	$31.7m
Wide Body	$68.7K	$77m		

(b) Costs Based on US Average Costs/lb/year

Aircraft Type	*Annual Cost per Aircraft*	*Annual Fleet Cost*	*Lives Saved per year*	*Cost per Life Saved*
Regional	$12.8K	$16.5m		
Narrow Body	$15.2K	$84m	6	$21.9m
Wide Body	$27.9K	$31.2m		

10 OTHER APPLICATIONS FOR WATER SPRAYS

The following potential uses for cabin water sprays have been recognised by the group but they have not been researched to the point where the benefit can be defined:

Halon Replacements

Water sprays may, for example provide cargo hold, lavatory and engine fire protection.

Hull Protection

Parked aircraft are, from time to time, burnt out and water sprays may provide a means of containing a fire until the fire services are alerted and can take action.

11 CONCLUSIONS

1 Research has shown the capability for water spray systems to be an effective means of extending survivable evacuation time in a wide range of post crash fire conditions.

2 Optimisation tests have demonstrated that system effectiveness can be improved with a zoned system using much reduced quantities of water compared to the original SAVE concept.

3 A study of the potential physiological effects during evacuation in the presence of a fire has concluded that there will be no additional hazards due to the presence of water sprays.

4 The addition of a water spray system is practicable but some protective measures may be needed to enable the aircraft to tolerate an inadvertent water discharge.

5 It has been estimated that water spray would save an average of 14 lives annually world-wide or 6 lives in the US, Canada and European countries of the JAA.

6 The annual cost to the US/Canada/Europe fleet has been estimated to be in the region of $132m to $190m, thus giving a cost per life saved of $22m to $32m.

12.4 **System Optimisation**

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12.6 **Safety Benefit Analysis**

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