DOT/FAA/AR-09/17

Air Traffic Organization
NextGen & Operations Planning
Office of Research and
Technology Development
Washington, DC 20591

A Cost-Benefit Analysis for the Installation of Fire Suppression Systems in Cargo Compartments of Cargo Airplanes

April 2009

Final Report

U.S. Department of Transportation
Federal Aviation Administration

United Kingdom
Civil Aviation Authority

NOTICE

This research was jointly sponsored by FAA and the Civil Aviation Authority of the United Kingdom by means of the Memorandum of Cooperation regarding Civil Aviation Research and Development between the Civil Aviation Authority of the United Kingdom and the FAA. This activity has been carried out in cooperation with Transport Canada and the Civil Aviation Authority of the United Kingdom under the auspices of the International Cabin Safety Research Technical Group whose goal is to enhance the effectiveness and timeliness of cabin safety research.

Technical Report Documentation Page

1. Report No. DOT/FAA/AR-09/17	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle A COST-BENEFIT ANALYSIS FOR THE INSTALLATION OF FIRE SUPPRESSION SYSTEMS IN CARGO COMPARTMENTS OF CARGO AIRPLANES	5. Report Date April 2009 6. Performing Organization Code
7. Author(s) R.G.W. Cherry & Associates Limited	8. Performing Organization Report No.
9. Performing Organization Name and Address R.G.W. Cherry & Associates Limited The Priory, High Street Ware, Hertfordshire. SG12 9AL United Kingdom	10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration Air Traffic Organization NextGen & Operations Planning Office of Research and Technology Development Washington, DC 20591	13. Type of Report and Period Covered 14. Sponsoring Agency Code ANM-115

15. Supplementary Notes

The Federal Aviation Administration Airport and Aircraft Safety R&D Division Technical Monitor was Richard Hill.

16. Abstract

The National Transportation Safety Board has recommended that fire suppression systems be installed in the cargo compartments of all cargo airplanes operating under 14 CFR Part 121. Currently, Class E cargo compartments, which are the primary cargo compartment type used in US cargo airplanes, do not require fire suppression systems. In response to this recommendation, FAA has requested that a cost/benefit analysis be carried out relating to the installation of on-board fire detection and extinguishment systems in cargo airplanes. This report contains the results of this analysis and a description of the methodology used.

The analysis assessed whether fire suppression systems, fitted to the cargo bays of cargo airplanes, type certificated to FAR Part 25 and operating under FAR Part 121, are likely to be cost beneficial. Potential benefits will result from a reduction in Injuries (Fatal and Serious) to personnel, a reduction in the damage incurred to the aircraft and its cargo, and a reduction in the damage that might be incurred to property on the ground. Potential costs are those that might be incurred from the installation and operation of fire suppression systems.

A mathematical model has been developed to assess the benefit. The model utilizes statistical distributions derived from data on in-service airplanes and accident information. Cost assessments were made for modifying cargo aircraft to the new Type F Cargo Compartment being considered for combi aircraft. These cost assessments were based on the installation of a Halon type fire suppression system together with suitable cargo compartment liners. The data used in the cost assessment was based on that contained in the ARAC document relating to main deck class B cargo compartments.

The results of the study suggest that crew injuries (Fatal and Serious combined) and the loss of the aircraft and cargo in freighter fire accidents are likely to be a significant factor in the prediction of benefit. Collateral ground damage does not appear to contribute significantly to the prediction of benefit. It is concluded that Halon fire suppression systems, or alternatives that are likely to be developed for below floor cargo compartments, are unlikely to be cost beneficial for the cargo compartments of cargo aircraft. Fire suppression systems, of the kind currently being considered for the cargo compartments of combi aircraft, may prove to be cost beneficial, particularly on larger cargo aircraft.

17. Key Words Fire suppression systems, Cargo compartments, Cost benefit analysis	18. Distribution Statement This document is available to the U.S. public through the National Technical Information Service (NTIS), Springfield, Virginia 22161.

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 61	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

ARAC	Aviation Rulemaking Advisory Committee
CSRTG	Cabin Safety Research Technical Group
EASA	European Aviation Safety Agency
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
MAIS	Maximum Abbreviated Injury Scale
NTSB	National Transportation Safety Board (USA)
RTM	Revenue Ton Miles

EXECUTIVE SUMMARY

The National Transportation Safety Board has recommended that fire suppression systems be installed in the cargo compartments of all cargo airplanes operating under 14 CFR Part 121. Currently, Class E cargo compartments, which are the primary cargo compartment type used in US cargo airplanes, do not require fire suppression systems.

In response to this recommendation, FAA has requested that a cost/benefit analysis be carried out relating to the installation of on-board fire detection and extinguishment systems in cargo airplanes. This report contains the results of this analysis and a description of the methodology used.

The analysis assessed whether fire suppression systems, fitted to the cargo bays of cargo airplanes, type certificated to FAR Part 25 and operating under FAR Part 121, are likely to be cost beneficial.

Potential benefits will result from a reduction in Injuries (Fatal and Serious) to personnel, a reduction in the damage incurred to the aircraft and its cargo, and a reduction in the damage that might be incurred to property on the ground. Potential costs are those that might be incurred from the installation and operation of fire suppression systems.

A mathematical model has been developed to assess the benefit. The model utilizes statistical distributions derived from data on in-service airplanes and accident information. Cost assessments were made for modifying cargo aircraft to the new Type F Cargo Compartment being considered for combi aircraft. These cost assessments were based on the installation of a Halon type fire suppression system together with suitable cargo compartment liners. The data used in the cost assessment was based on that contained in the ARAC document relating to main deck class B cargo compartments.

The results of the study suggest that crew injuries (Fatal and Serious combined) and the loss of the aircraft and cargo in freighter fire accidents are likely to be a significant factor in the prediction of benefit. Collateral ground damage does not appear to contribute significantly to the prediction of benefit.

It is concluded that Halon fire suppression systems, or alternatives that are likely to be developed for below floor cargo compartments, are unlikely to be cost beneficial for the cargo compartments of cargo aircraft.

Fire suppression systems, of the kind currently being considered for the cargo compartments of combi aircraft, may prove to be cost beneficial, particularly on larger cargo aircraft.

1. INTRODUCTION.

1.1 BACKGROUND.

The National Transportation Safety Board (NTSB) has issued the following recommendation:

> (A-07-99)
>
> *"The Safety Board believes that the FAA should require that fire suppression systems be installed in the cargo compartments of all cargo airplanes operating under 14 CFR Part 121".*

In response to this recommendation, one of the FAA's fire safety R&D activities was to

> *"Conduct a cost/benefit analysis of the installation of on-board fire detection and extinguishment systems in cargos" [US Department of Transport, "Enterprise Battery Action Plan for 2008" - draft].*

Currently, Class E cargo compartments, which are the primary cargo compartment type used on the US fleet of cargo airplanes, do not require fire suppression systems. Instead, these compartments rely on the ability to control the airflow to the compartment by depressurizing the airplane following a cargo fire.

1.2 SCOPE & OBJECTIVES.

The primary objective of this analysis is to assess whether fire suppression systems, fitted to the cargo bays of cargo airplanes, type certificated to FAR Part 25 and operating under FAR Part 121, are likely to be cost beneficial. Airplanes below 12,500 lb are excluded from the study.

Benefits calculated in Section 2 are expressed in US dollars (2007) and are based on a reduction in:

- Injuries (Fatal and Serious) to crew and ground personnel
- Damage to the aircraft and its cargo
- Damage that might be incurred to property on the ground

Costs used in Section 3 are also expressed in US dollars (2007) and are those that might be incurred from the installation and operation of fire suppression systems on the US fleet of cargo airplanes. These costs are limited to Rough Order of Magnitude assessments.

1.3 AIRCRAFT WEIGHT CATEGORIES.

The benefit and cost likely to accrue from fitting fire suppression systems to cargo aircraft is likely to vary significantly with aircraft size. Cargo airplane types, considered in this analysis, have been assigned a weight category based on the sub divisions of Maximum Take-off Weights shown in Table 1.

Table 1. Aircraft Weight Categories

WEIGHT CATEGORY	AIRCRAFT MAXIMUM TAKE-OFF WEIGHT
B	**12,500 lb to 100,000 lb**
C	**100,000 lb to 250,000 lb**
D	**250,000 lb to 400,000 lb**
E	**Greater than 400,000 lb**

2. BENEFIT ANALYSIS.

2.1 METHODOLOGY.

A mathematical model has been developed to assess the benefit from the installation of fire suppression systems in the cargo compartments of US registered cargo airplanes. The model is based on the "Monte Carlo Simulation" methodology utilizing statistical distributions derived from data on in-service airplanes.

Monte-Carlo simulation is a method where variables are randomly chosen based on their probability of occurrence. The variables are then combined to determine the required output – in this case the benefit that might accrue from the installation of fire suppression systems on the US fleet of cargo airplanes.

By running the model many thousands of times, a distribution of the predicted benefit may be generated. The working of the model and the statistical distributions utilized are explained in this section of the report.

The mathematical model used in this analysis works on the premise of predicting the number of cargo fire related accidents that are likely to occur over one year, for each weight category of aircraft, and multiplying it by a prediction of the cost of such an accident.

This is calculated based upon the following formula:

Benefit per year = Prediction of number of accidents x Cost of accident

The predicted number of accidents for a particular year is calculated from the accident rate multiplied by the accumulated usage over that selected year.

Benefit per year = (Accident rate x Usage per year) x Cost of accident

In this analysis, usage has been expressed in terms of Revenue Ton Miles (RTM), which is the weight of revenue generating cargo multiplied by the number of miles the cargo is carried. This has been used in favor of hours or number of flights as it seems reasonable that the probability of a cargo fire occurring is related to both the quantity of cargo carried and the duration for which it is carried. RTM gives a representation of both of these units and is a usage value that is routinely recorded and used by the air transport industry. Incorporating these usage terms into the above equation gives the following:

$$\frac{Benefit}{Year} = \frac{Accidents}{RTM} \text{ x } \frac{RTM}{Year} \text{ x } \frac{Cost}{Accident}$$

The RTM accumulated by the US cargo fleet in 2007 was selected for the *RTM/Year*, as this is the latest complete data available to this study. As 2007 has been selected for the usage term, the *Benefit/Year* predicted is the benefit that could have been obtained based upon the 2007 fleet if cargo fire suppression systems had been installed (assuming that they are 100% effective).

In summary, the benefit for the year 2007 appropriate to each weight category in the US cargo fleet can be calculated from the product of:

- The predicted cargo fire accident rate per Revenue Ton Mile for the US cargo fleet [1]
- The total Revenue Ton Miles accumulated by the weight category of aircraft in the US cargo fleet in 2007
- The predicted cost per accident for the weight category.

By using probability distributions of these values, the model can be used to generate a distribution of the predicted benefit per year for each aircraft weight category. The total benefit per year is obtained by summing the individual benefits calculated for each weight category.

The structure of the "Monte Carlo Simulation" model is shown in Figure 1. Details of the workings of the model and the statistical data used are provided in Sections 2.1.1 to 2.1.8.

---

[1] The accident rate per Revenue Ton Mile is assumed to be similar for all weight category aircraft.

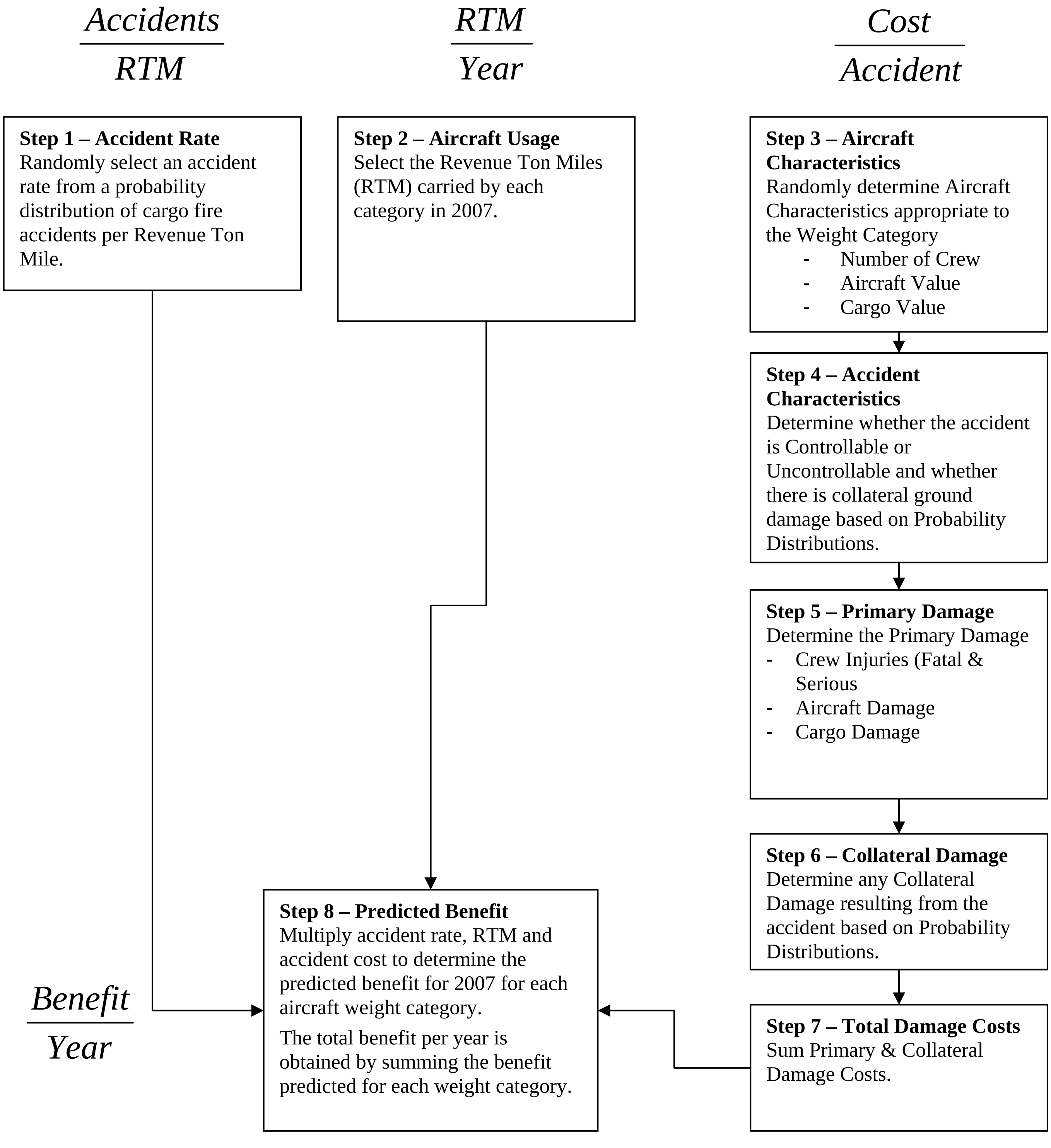

Figure 1. “Monte Carlo Simulation” Model Structure

2.1.1 Derivation of Accident Rate.

2.1.1.1 Data.

2.1.1.1.1 Cargo Fire Accidents.

The CSRTG Accident Database (Reference 1) was searched to identify all cargo fire related accidents on US registered cargo operations over the period 1967 to 2007. The following criteria were used for the selection of accidents:

- Accident date between 1967 and 2007 (inclusive)
- US registered aircraft (N registration)
- Cargo only operation
- Fire related accidents involving fire or smoke from the cargo compartment

Only aircraft accidents conforming to the ICAO definition[2] were included in the analysis. The prevention of occurrences in which there were no serious or fatal injuries to personnel or any substantial damage to the airframe is unlikely to result in significant benefit.

The NTSB Database (Reference 2) was also searched for cargo fire accidents and Boeing Aircraft Company supplied a listing of accidents involving cargo fires. These data sources identified the following cargo fire accidents to US registered aircraft over the period 1967 to 2007:

1. **Accident Ref: 20060207A**

Date:	7th February 2006
Operator:	United Parcel Service (UPS)
Aircraft:	DC8 (Registration N748UP)
Location:	Philadelphia, Pennsylvania, USA
Aircraft Damage:	Substantial
Crew Injuries:	None

> *"The cause of the in-flight fire could not be determined in the UPS accident. However, the presence of a significant quantity of electronic equipment in the containers where the fire most likely originated led the Safety Board to closely examine safety issues involving the transportation of rechargeable lithium batteries on commercial aircraft, including batteries in airline passengers' laptop computers and other personal electronic devices."*

---

[2] *"An accident is an occurrence during the operation of an aircraft, that entails:*
1) A fatality or serious injury;
2) Substantial damage to the aircraft involving structural failure or requiring major repair of the aircraft; or
3) The aircraft is missing." ICAO

2. **Accident Ref: 20040427A**

Date:	27th April 2004
Operator:	Mountain Air Cargo
Aircraft:	F27-500 (Registration N715FE)
Location:	Melo, Uruguay
Aircraft Damage:	Destroyed
Crew Injuries:	None

"A FedEx flight operated by Mountain Air Cargo. The flight diverted after discovery of a fire in the cargo bay. The cause of the fire was unknown."

3. **Accident Ref: 19960905B**

Date:	5th September 1996
Operator:	Federal Express Corporation (FedEx)
Aircraft:	DC10-10CF (Registration N68055)
Location:	Newburgh/Stewart, New York, USA
Aircraft Damage:	Destroyed
Crew Injuries:	None

"The National Transportation Safety Board determines that the probable cause of this accident was an in-flight cargo fire of undetermined origin."

4. **Accident Ref: 19731103B**

Date:	3rd November 1973
Operator:	Pan American World Airways
Aircraft:	B707 (Registration N458PA)
Location:	Boston Massachusetts
Aircraft Damage:	Destroyed
Crew Injuries:	All Fatal—3 Crew Members

"About 30 minutes after the aircraft departed from JFK, the flight crew reported smoke in the cockpit. The flight was diverted to Logan International Airport where it crashed just short of runway 33 during final approach. Although the source of the smoke could not be established conclusively, the NTSB believes that the spontaneous chemical reaction between leaking nitric acid, improperly packaged and stowed and the improper sawdust packing surrounding the acid's package initiated the accident sequence."

2.1.1.2 Cargo Fire Accident Rate.

Accident rate, based on in-service data, is not a precise number but rather a distribution of confidence level associated with a given number of accidents occurring over a given period. As previously explained, for this analysis, "the period" or usage is expressed in terms of Revenue Ton Miles (RTM).

The assessment of the number of Revenue Ton Miles accumulated by the US fleet of cargo airplanes per annum to 2007 is based on the data shown in Figure 2.

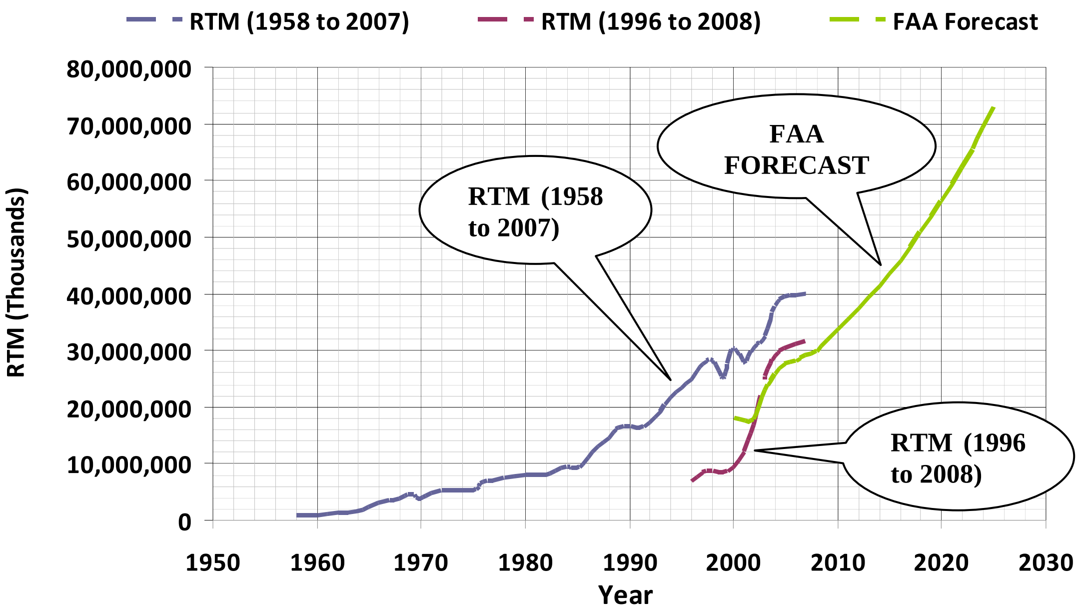

Figure 2. Assessment of the Number of Revenue Ton Miles per Annum for the US Fleet—All Data Sources

The curves annotated as "RTM (1996-2008)" and "RTM (1958-2007)" are based on data contained in Reference 3. The curve annotated as "FAA Forecast" is based on data contained in Reference 4. The differences in the RTM values from the three data sets are discussed in Section 4.1.

The best estimate of the number of Revenue Ton Miles is indicated by the curve annotated as "Best Estimate of RTM" in Figure 3. It may be seen that this curve approximates to the "FAA Forecast."

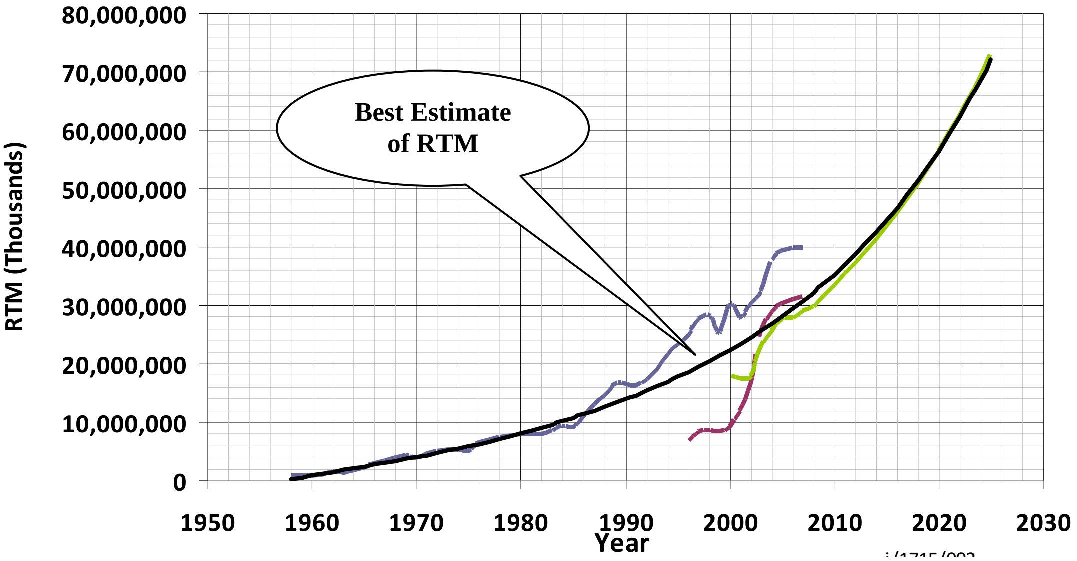

Figure 3. Assessment of the Number of Revenue Ton Miles per Annum for the US Fleet—Best Estimate

This best estimate of the likely number of Revenue Ton Miles per annum is reproduced in Figure 4. The shaded area under the curve represents the assessed accumulated number of Revenue Ton Miles for the US fleet over the period 1967 to 2007 inclusive.

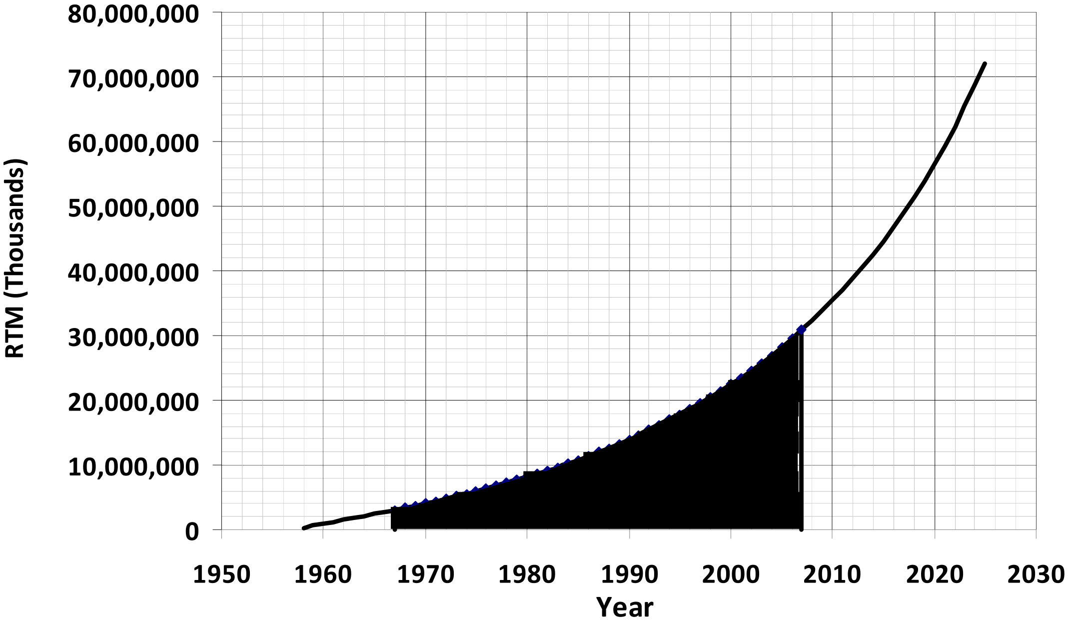

Figure 4. Assessment of the Cumulative Number of Revenue Ton Miles for the US Fleet Over the Period 1967 to 2007

Based on the data illustrated in Figure 4 it is assessed that the Revenue Ton Miles accumulated by the US cargo fleet is as shown in Table 2.

Table 2. Assessed Revenue Ton Miles for the US Fleet

1967 to 2007 inclusive	2007
545,200,000,000	31,354,400,000

The χ^2 distribution may be used to derive the confidence level in any given accident rate based on the number of accidents experienced over a given time period. The χ^2 distribution used in the model is based on the four identified cargo fire accidents over the period 1967 to 2007 and the cumulative Revenue Ton Miles (545,200,000,000). The distribution is illustrated in Figure 5.

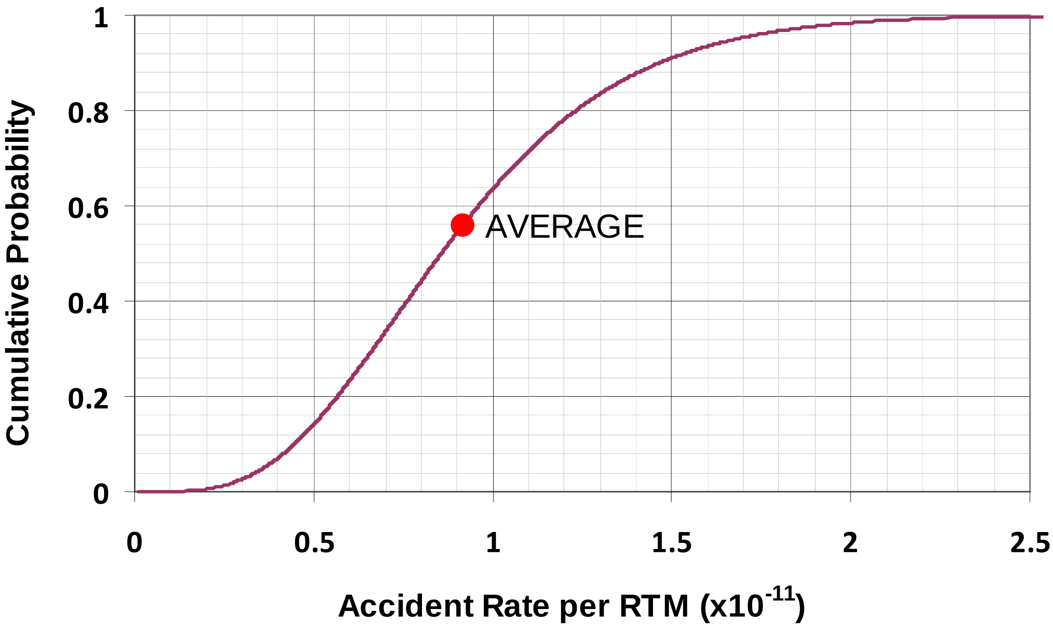

Figure 5. Accident Rate per Revenue Ton Mile

It should be noted that the average value shown in Figure 5 is the average of the χ^2 distribution, which is somewhat higher than the simple average derived by dividing the number of accidents, by the accumulated Revenue Ton Miles. This issue is discussed in Section 4.1.

2.1.1.3 Function of Step 1.

At each iteration of the model, a random number is generated between zero and one. This random number determines the value on the vertical axis of the distribution shown in Figure 5. The accident rate appropriate to this value is taken by the model as the accident rate at that iteration of the model for all aircraft weight categories.

2.1.2 Aircraft Usage.

2.1.2.1 Data.

The proportion of Revenue Ton Miles, associated with each cargo airplane weight category, was derived from data obtained from Reference 3 and is illustrated in Figure 6 with the absolute values shown in Table 3.

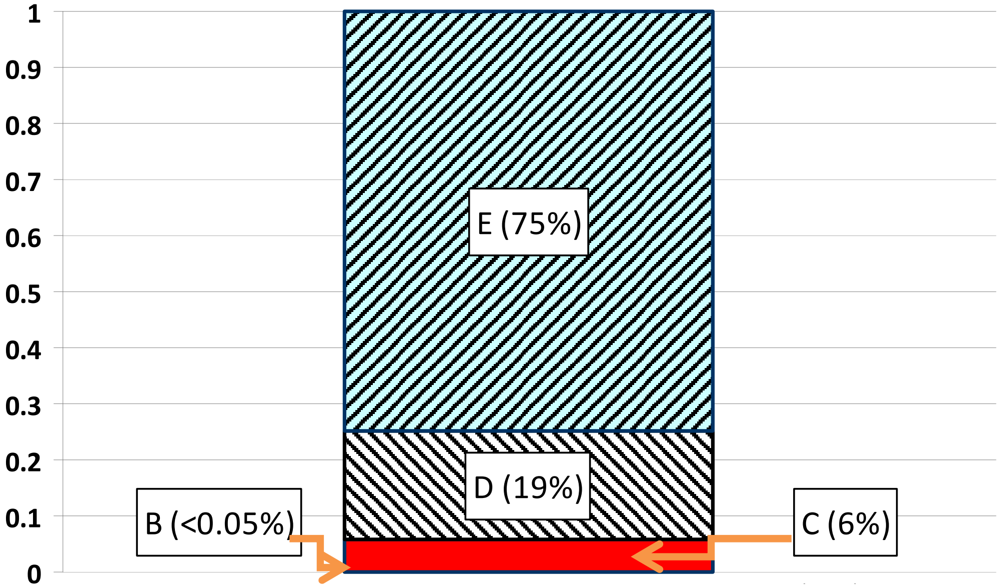

Figure 6. Weight Category Distribution (based on 2007 Revenue Ton Miles)

Table 3. Revenue Ton Miles (2007) by Aircraft Weight Categories

WEIGHT CATEGORY	**REVENUE TON MILES (2007)**
B	**13,500,000**
C	**1,764,300,000**
D	**6,107,900,000**
E	**23,468,700,000**

2.1.2.2 Function of Step 2.

Step 2 simply allocates to the model, the assessed number of Revenue Ton Miles in 2007, as shown in Table 3, appropriate to the selected aircraft weight category.

2.1.3 Aircraft Characteristics.

2.1.3.1 Data.

The aircraft characteristics required by the model are:

- Number of Crew aboard
- Aircraft Value
- Cargo Value

All of which are dependent on aircraft weight category.

2.1.3.1.1 Number of Crew.

An assessment of the distribution of the number of crew[3], for each aircraft weight category, was based on data for cargo aircraft contained in Reference 1. Only US registered cargo airplanes, type-certificated to FAR Part 25 and operating under FAR Part 121, were selected from the database. The extracted data were assumed to follow Weibull distributions, which are shown in Figure 7.

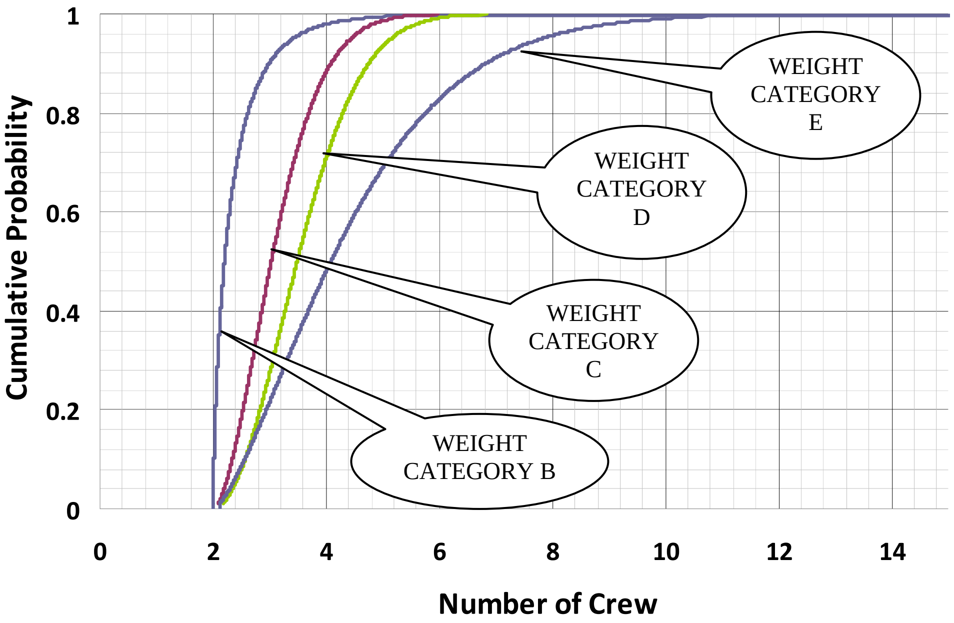

Figure 7. Distribution of Number of Crew

2.1.3.1.2 Aircraft Value.

An assessment of the distributions of aircraft values was based on data contained in Reference 5. Only average values for weight category C, D, and E cargo aircraft were available from this data source. Passenger aircraft average values were used for weight category B aircraft. There were

---

[3] The number of crew includes all personnel on-board – some of which may not be designated crewmembers.

no data regarding the variance on these average aircraft values. It was therefore assumed that the variance of the cargo aircraft distribution values was similar to the variance of passenger aircraft values, which were also derived from Reference 5. The derived cargo aircraft value distributions, which were assumed to approximate to a Normal Distribution, are shown in Figure 8.

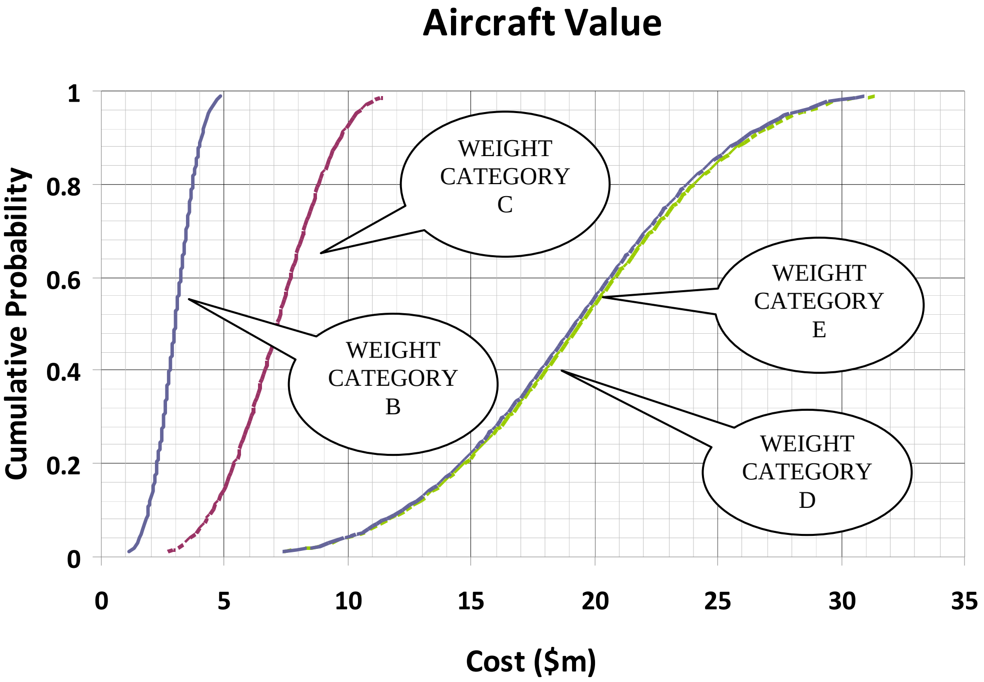

Figure 8. Assessed Distribution of Aircraft Value by Weight Category

2.1.3.1.3 Cargo Value.

Based on Reference 3 the average cargo value was taken as $97,900[4] per ton. The average number of tons of cargo carried per flight in 2007 was assessed for each aircraft weight category based on data contained in Reference 3. Based on these data the average cargo value per flight could be assessed for each aircraft weight category as shown in Table 4.

Table 4. Average Cargo Value per Flight

WEIGHT CATEGORY	AVERAGE CARGO VALUE PER FLIGHT($ MILLIONS 2007)
B	0.14
C	1.1
D	2.6
E	4.1

---

[4] US$ at year 2007 levels

2.1.3.2 Function of Step 3.

2.1.3.2.1 Number of Crew.

At each iteration of the model, and separately for each weight category, a random number is generated between zero and one. This random number determines the Crew Number appropriate to the aircraft weight category based on the distributions shown in Figure 7.

2.1.3.2.2 Aircraft Value.

At each iteration of the model, and separately for each weight category, a random number is generated between zero and one. This random number determines the Aircraft Value appropriate to the aircraft weight category based on the distributions shown in Figure 8.

2.1.3.2.3 Cargo Value.

At each iteration of the model, and separately for each weight category, the Cargo Value appropriate to the aircraft weight category is selected based on the values shown in Table 4.

2.1.4 Accident Characteristics.

This step of the model determines whether the accident is Controllable or Uncontrollable and whether it results in collateral damage to personnel on the ground, ground installations, aircraft, vehicles, etc.

Cargo fire accidents are categorized into CONTROLLED and UNCONTROLLED accidents. CONTROLLED accidents are those where following the fire the flight crew had some degree of control of the aircraft onto the ground. UNCONTROLLED accidents are those where following the fire, the flight crew lost control in flight and the aircraft impacted with the ground. In instances where control was lost on final approach and the aircraft came to a stop within the airport perimeter the accident is considered CONTROLLED.

A distinction between these two categories is required since UNCONTROLLED accidents are more likely to incur collateral damage and to result in more severe consequences to the aircraft and occupants than CONTROLLED accidents.

2.1.4.1 Data.

2.1.4.1.1 Controlled v Uncontrolled.

The cargo fire accidents to the US fleet over the period 1967 to 2007 inclusive, as described in Section 2.1.1.1.1, are all considered CONTROLLED accidents.

Although there were only four accidents, all of which were CONTROLLED, there is still a probability that an UNCONTROLLED accident could occur. To account for this, the proportion of accidents that are likely to be CONTROLLED (or UNCONTROLLED) may be assessed, from the division of accidents shown in Table 5, for any particular confidence level, by using the

Binomial Distribution. The small sample size results in a probability distribution with a large variance. However, this has been assessed as being preferential to using data for passenger carrying aircraft which may be subject to different circumstances and hence incorrectly bias the study.

Table 5. Division of Accidents to US Cargo Airplanes Over the Period 1967 to 2007—Controlled v Uncontrolled

CONTROLLED	UNCONTROLLED
4	0

Using the binomial distribution, Figure 9 shows the cumulative probability distribution for the probability of an accident being CONTROLLED.

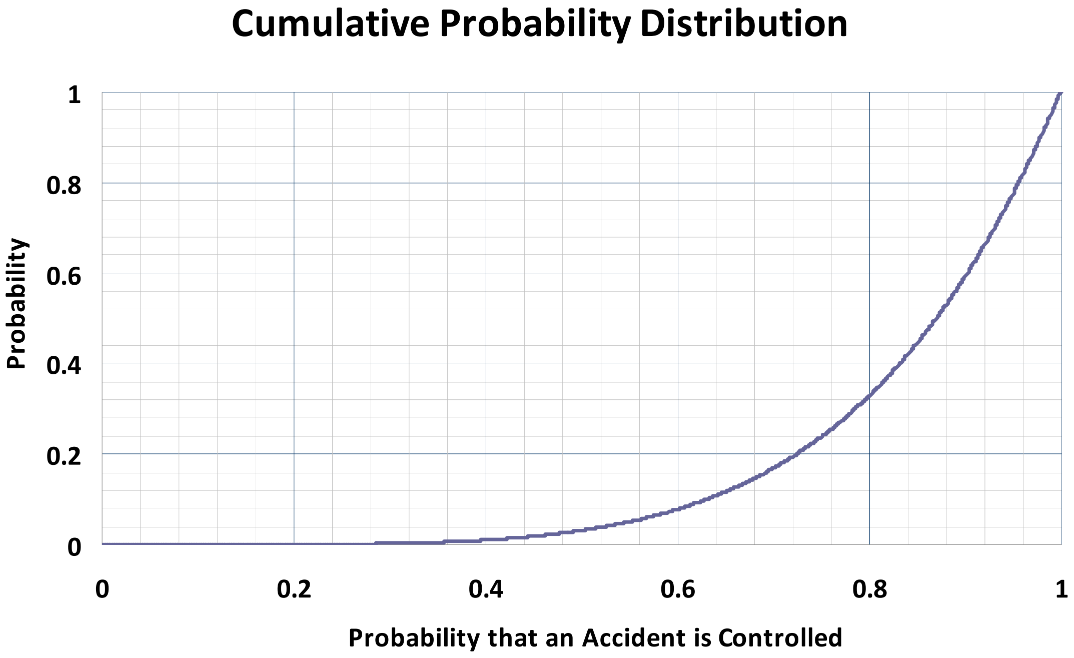

Figure 9. Cumulative Probability Distribution for the Probability That an Accident is CONTROLLED

The model randomly selects on the vertical axis of the distribution shown in Figure 9 and derives a probability that the accident is CONTROLLED.

This is illustrated by the example shown in Figure 10. In this example iteration of the model, a random number generates a value of 0.4. This value equates to a probability that the accident is controlled of 0.82. The model then selects a second random number. If its value is less than 0.82 the accident is deemed CONTROLLED. If it is greater than 0.82 the accident is deemed to be UNCONTROLLED at this iteration of the model.

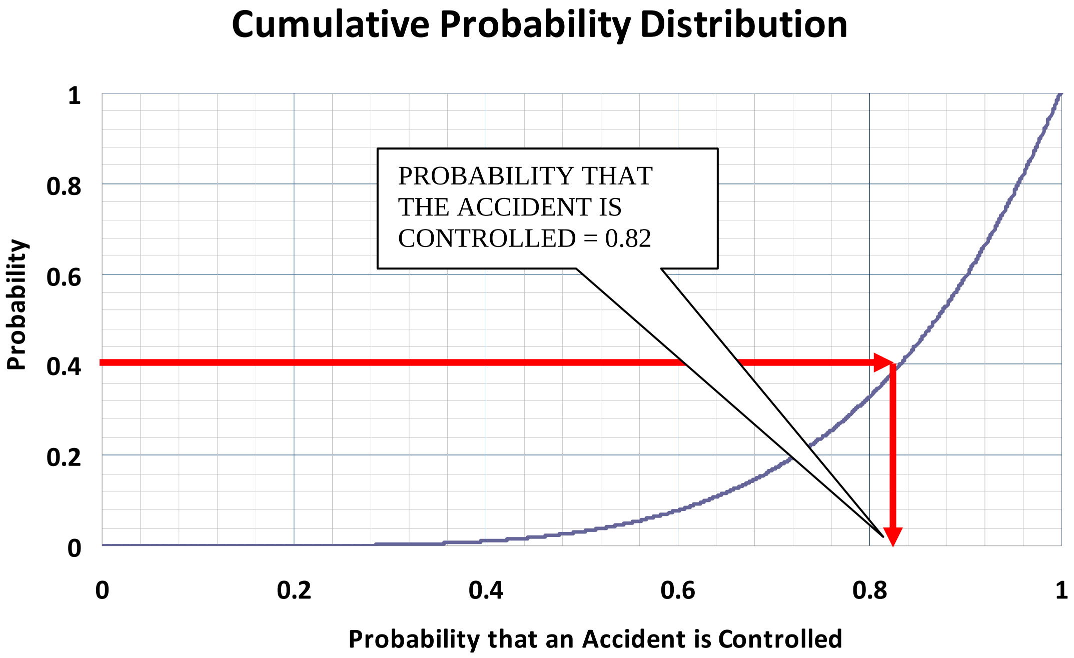

Figure 10. Example Determination of the Probability of an Accident Being CONTROLLED

2.1.4.1.2 Probability of the Accident Resulting in Collateral Ground Damage.

The probability of the accident resulting in collateral damage is expected to be different for CONTROLLED and UNCONTROLLED accidents. The CSRTG Accident Database (Reference 1) was searched for accidents to passenger carrying aircraft and cargo carrying aircraft that were assessed to be similar in terms of their in-flight event and impact sequence to what might be expected from an in-flight cargo fire. One hundred and seventy-eight accidents to passenger and cargo carrying aircraft were identified and divided into those that were assessed as CONTROLLED and those that were UNCONTROLLED.

A determination was made for each accident as to whether there was collateral damage to buildings, aircraft, or persons on the ground. This resulted in the following division of accidents shown in Table 6.

Table 6. Division of Accidents Collateral or No Collateral Damage

	CONTROLLED	**UNCONTROLLED**	**TOTAL**
COLLATERAL DAMAGE	**1**	**9**	**10**
NO COLLATERAL DAMAGE	**71**	**97**	**168**
TOTAL	**72**	**106**	**178**

Based on these data, it might be expected that typically there is a 1 in 72 chance of a controlled accident resulting in collateral damage i.e. a probability of approximately 0.014. Similarly, for an uncontrolled accident the probability of sustaining collateral damage might be expected to be 9 in 106 or approximately 0.085. However, the Monte Carlo model uses an assessment of the likely variation in these probabilities based on the Binomial Distribution using a similar process to that described in Section 2.1.4.1.1 for the determination of an accident being CONTROLLED or UNCONTROLLED.

2.1.4.2 Function of Step 4.

At each iteration of the model, and separately for each weight category, two random numbers are generated between zero and one. These random numbers determine whether the accident is CONTROLLABLE or UNCONTROLLABLE, based on the distribution shown in Figure 9, as described in Section 2.1.4.1.1.

The model then determines whether the accident results in collateral damage. This determination is made by randomly selecting on Binomial distributions of the probability of there being collateral damage derived from the data shown in Table 6, as described in Section 2.1.4.1.2.

2.1.5 Primary Damage Cost.

This step of the model assesses the costs incurred resulting from injuries sustained by the crew (Fatal & Serious) and the degree of damage sustained to the aircraft and cargo. The extent of this primary damage is dependent on whether the accident is CONTROLLED or UNCONTROLLED and whether it involves ground collateral damage or not.

2.1.5.1 Data.

The 178 accidents discussed in Section 2.1.4.1.2, that had an accident sequence similar to what might be expected from an in-flight cargo fire, were placed into four datasets:

1. **CONTROLLED** with No Collateral Damage

2. **CONTROLLED** with Collateral Damage
3. **UNCONTROLLED** with No Collateral Damage
4. **UNCONTROLLED** with Collateral Damage

In each data set, the accidents were ranked in order of severity in terms of the damage sustained by the aircraft, the proportion of injuries (Fatal and Serious) sustained by the crew, the cost of collateral damage and the damage sustained by the cargo.

Table 7 illustrates the nature of the data used to determine primary damage.

Table 7. Illustration of the Data Used to Determine Primary Damage

UNCONTROLLED WITH NO COLLATERAL DAMAGE – EXAMPLE ONLY – NOT REAL DATA					
Accident Number	**Proportion of Crew**			**Aircraft Damage**	**Assessed Proportion of Cargo Damage**
	Fatal Injuries	**Serious Injuries**	**Minor/No Injuries**		
1	**1**	**0**	**0**	**DESTROYED**	**1**
2	**0.8**	**0.2**	**0**	**DESTROYED**	**1**
3	**0.6**	**0.3**	**0.1**	**DESTROYED**	**1**
4	**0.5**	**0.5**	**0**	**SUBSTANTIAL**	**1**
…	**…**	**…**	**…**	**…**	**…**
…	**…**	**…**	**…**	**…**	**…**
98	**0**	**0**	**1.0**	**MINOR**	**.5**

2.1.5.1.1 Crew Injuries.

The costs incurred resulting from crew injuries is calculated from the product of:

- The proportion of the crew sustaining Fatal, Serious and Minor/No injuries
- The number of crew on-board
- The monetary value associated with the injuries

The proportion of the crew sustaining Fatal, Serious and Minor/No injuries is determined by randomly selecting on the appropriate accident dataset allocated by the model as illustrated in the example dataset contained in Table 7. The number of crew on-board is determined from Step 3. The monetary value associated with the predicted injuries to crewmembers is as shown in Table 8, which is based on data obtained from the FAA (Reference 6). Serious injuries are assigned a monetary value of 2.76 million US$. This is the average value for injuries classified as Severe (MAIS 4) and Critical (MAIS 5) based on Reference 6.

Table 8. Monetary Value of Injuries

INJURY SEVERITY	MONETARY VALUE MILLIONS OF DOLLARS (2007)
FATAL	**5.8**
SERIOUS	**2.76**

By way of example the crew injury costs for accident number 4 in Table 7 appropriate to a cargo aircraft with four crewmembers would be:

0.5 x 4 x 5.8 + 0.5 x 4 x 2.76 million US$

=11.6 + 5.52 million US$

= 17.12 million US$

2.1.5.1.2 Aircraft Damage.

Once again, the appropriate accident dataset, allocated by the model, is used to determine whether the aircraft was Destroyed, sustained Substantial, Minor, or No damage.

The aircraft value derived in Step 3 is multiplied by the proportions shown in Table 9, appropriate to the aircraft damage in order to obtain an absolute value of the damage sustained by the aircraft.

Table 9. Proportion of Aircraft Value Damaged in the Accident

AIRCRAFT DAMAGE	REPAIR COST AS A PROPORTION OF AIRCRAFT VALUE
DESTROYED	**1**
SUBSTANTIAL	**0.8**
MINOR	**0.2**

By way of example the aircraft damage costs for accident number 4 in Table 7 appropriate to a cargo aircraft valued at 12 million US$ would be:

0.8 x 12 million US$

=9.6 million US$

2.1.5.1.3 Cargo Damage.

Cargo damage is assessed in a similar manner to aircraft damage. The cargo value appropriate to the aircraft weight category (see Table 4) is simply multiplied by the assessed proportion of cargo damage, determined from the appropriate accident dataset, to obtain a monetary value.

By way of example the cargo damage costs for accident number 98 in Table 7 appropriate to a cargo aircraft in weight category C would be:

0.5 x 1.1 million US$

=0.55 million US$

2.1.5.2 Function of Step 5.

Step 4 of the model determines whether the accident under consideration is classified as CONTROLLABLE or UNCONTROLLABLE and whether it results in collateral damage or not. This determines the accident dataset to be used as described in Section 2.1.5.1.

At Step 5, the model selects a random number between zero and one for each iteration of the model, and for each weight category. The greater the random number the more severe the accident chosen by the model, from the appropriate dataset, and hence the greater the injuries to the crew and the damage to the aircraft and cargo.

2.1.6 Collateral Damage Cost.

2.1.6.1 Data.

It is assumed that the values of collateral damage that may be caused by a cargo aircraft are similar to those resulting from an accident to a passenger aircraft. From the accidents to passenger and cargo carrying aircraft that were assessed to be similar in terms of their in-flight event and impact sequence to what might be expected from an in-flight cargo fire an assessment was made of the value of the collateral damage. The total monetary value for each accident was determined based on the data contained in Table 10. These values were based on those contained in Reference 6 and advice from the FAA Office of Aviation Policy and Plans.

Table 10. Monetary Value Used in the Assessment of Collateral Damage

DAMAGE	MONETARY VALUE MILLIONS OF DOLLARS (2007)
FATAL INJURY	5.8
SERIOUS INJURY	2.76
LARGE BUILDINGS	5
SMALL BUILDINGS	0.3

The assessed collateral damage values for each accident were arranged in increasing level of monetary value and plotted as a cumulative Weibull Distribution, as shown in Figure 11.

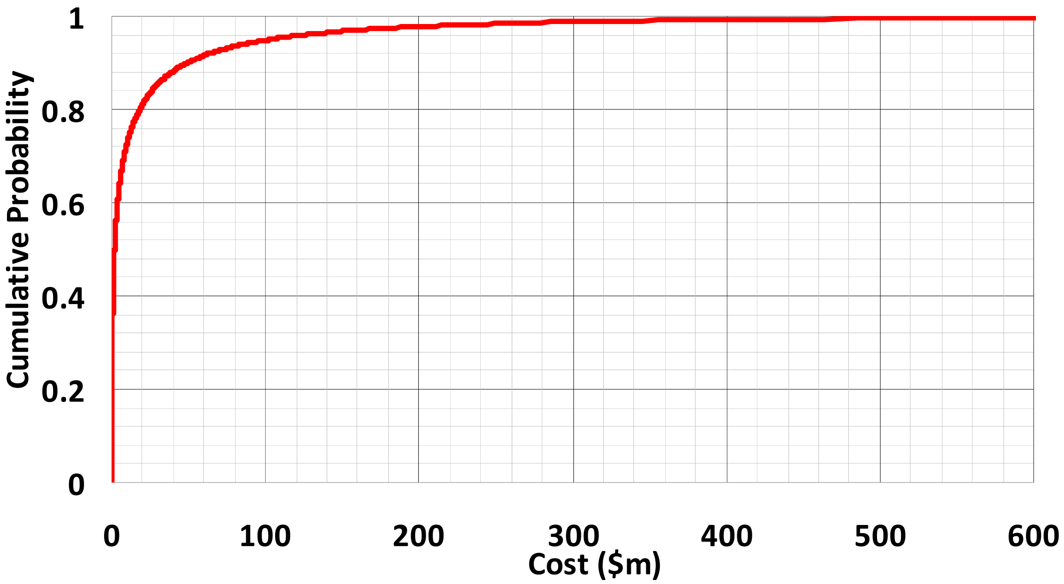

Figure 11. Probability Distribution of the Monetary Value of Collateral Damage

2.1.6.2 Function of Step 6.

At Step 6, a random number is selected between zero and one for each iteration of the model, and for each weight category. This number is used to select on the probability distributions of monetary values of collateral damage shown in Figure 11. For accidents deemed not to result in collateral damage, as determined by Step 4, the model simply returns a zero value for collateral damage.

2.1.7 Total Damage Cost.

Step 7 of the model simply sums the monetary values for Primary Damage derived in Step 5 and the Collateral Damage derived in Step 6 for each weight category.

2.1.8 Predicted Benefit.

Step 8 of the model simply multiplies:

- The Accident Rate derived from Step 1
- The Aircraft Usage derived from Step 2
- The Total Damage Cost per accident derived from Step 7

The resultant value is derived for each iteration of the model to determine the predicted benefit appropriate to 2007 for each weight category. The total benefit appropriate to 2007 is then obtained by summing the benefits for each weight category. The model is run 32,000 times to determine an average predicted benefit for the US fleet and the confidence interval for the prediction.

2.2 PREDICTED BENEFIT PER YEAR.

2.2.1 Benefit—Entire US Fleet.

The predicted average benefit for the entire US Fleet appropriate to 2007 is assessed to be approximately:

$ 7.4 Million

The confidence associated with any given level of benefit is shown in Figure 12. There is a 63% confidence that the average benefit of $7.4 Million will not be exceeded. The confidence range varies from a 5-percentile of $ 2.0 Million to a 95-percentile of $ 16.9 Million as illustrated in Figure 12.

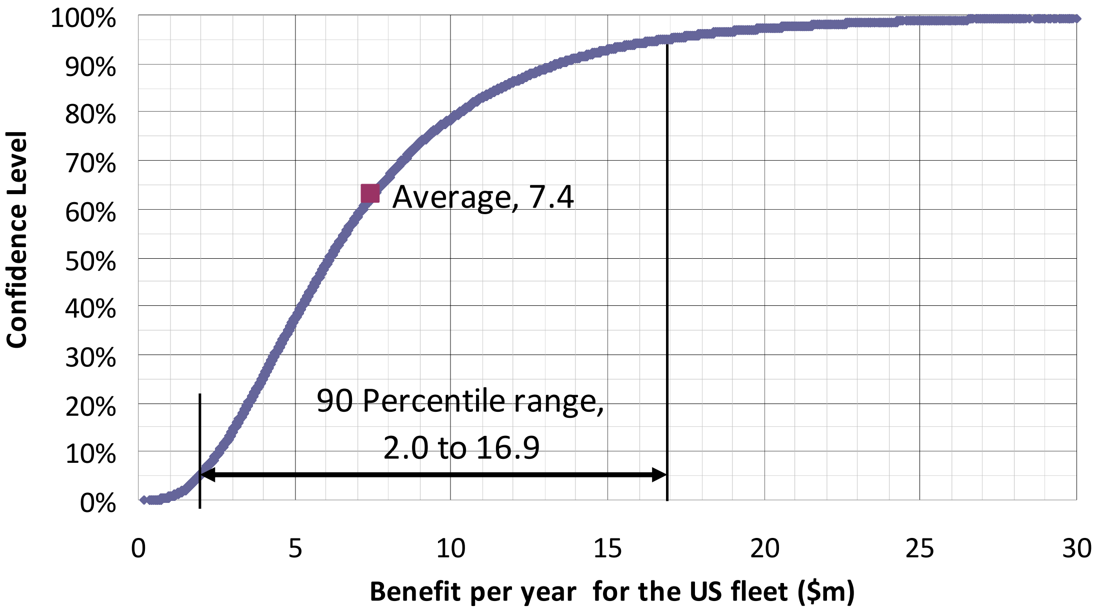

Figure 12. Distribution of Assessed Benefit per Year for US Fleet

The assessed benefit may be divided amongst the following contributory elements as shown in Figure 13:

- Aircraft Damage
- Crew Injuries (Fatal and Serious)
- Cargo Damage
- Collateral Damage

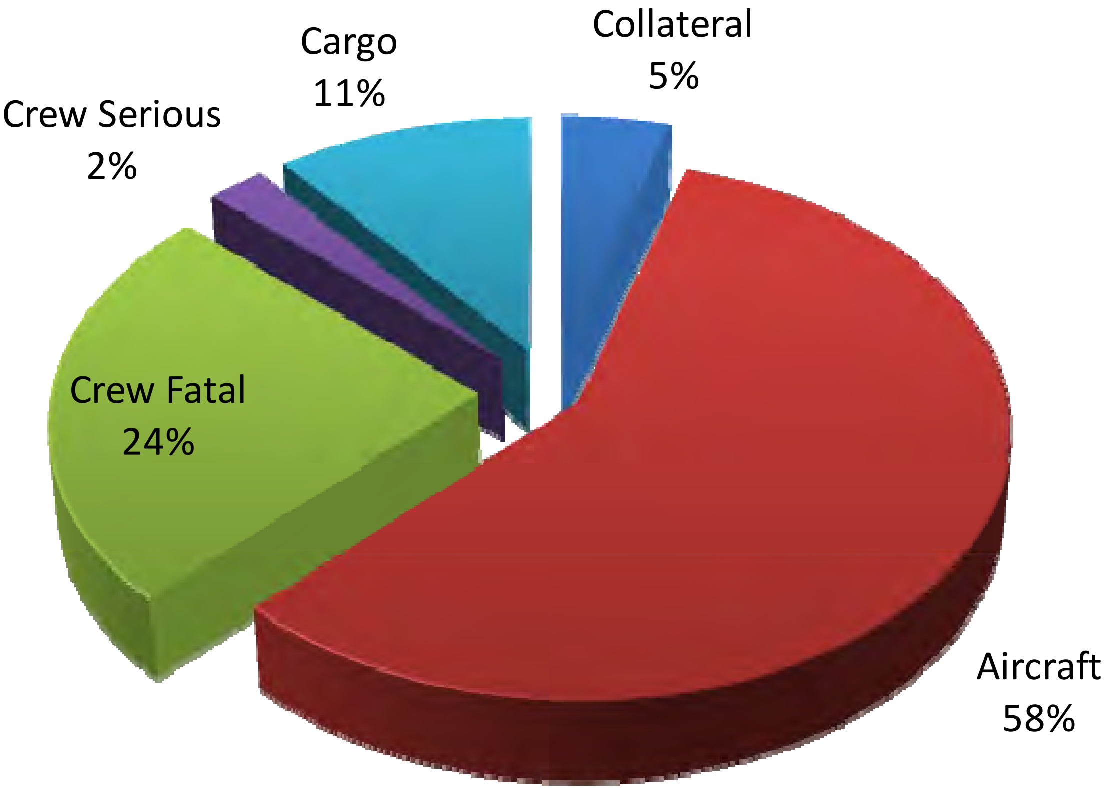

Figure 13. Breakdown of Benefit

2.2.2 Benefit - US Fleet by Weight Category.

The predicted average benefit for the entire US Fleet appropriate to 2007, by aircraft weight category, is as shown in Table 11.

Table 11. Average Predicted Total Benefit for US Fleet per Year—by Weight Category

WEIGHT CATEGORY	BENEFIT
B	NEGLIGIBLE
C	$200,000
D	$1,400,000
E	$5,800,000

It is assessed that the number of aircraft in the US cargo fleet by weight category is as shown in Table 12.

Table 12. Assessed Number of Cargo Aircraft in the US Fleet—by Weight Category

WEIGHT CATEGORY	NUMBER
B	78
C	313
D	339
E	293

Based on the data contained in Table 11 and Table 12 the predicted benefit per aircraft per year by aircraft weight category may be determined as illustrated in Table 13.

Table 13. Predicted Benefit per Aircraft per Year—by Weight Category

WEIGHT CATEGORY	BENEFIT
B	NEGLIGIBLE
C	$640
D	$4,100
E	$19,900

3. COST ANALYSIS.

Following the fatal accident to a South African Airways Boeing 747 combi in November 1987, the FAA tasked an Aviation Rulemaking Advisory Committee (ARAC) to develop a proposal for future class B cargo compartments. (The current Cargo Compartment Classifications of 14 CFR 25.857 are contained in Appendix 1 of this report for reference.)

Recommendations made by the ARAC have led both the FAA and the European Aviation Safety Agency (EASA) to consider the introduction of a new Class F Cargo Compartment. EASA have recently issued a Notice of Proposed Amendment to introduce *"…standards for newly classified Class F cargo compartments by adding CS 25.857(f) (1), (2), and (3)"* (Reference 7).

The ARAC Report (Reference 8) contains the following statement with respect to Class F Cargo Compartments:

> *"The proposed Class F cargo compartment requirements allow for a wide range of cargo fire protection strategies. Methods of meeting Class F requirements could include, in part: (1) use of special cargo containers, (2) installation of a water misting system, (3) installation of a built-in suppression system that uses Halon or another suppressant agent, and (4) installation of a suppression system that relies on a distribution system to direct the contents of hand-held fire*

> *extinguishers to certain areas of the cargo compartment. After evaluating several options, a fire protection system incorporating a built-in fire suppression system was selected for this analysis. This system would use Halon 1301, and would incorporate other features including a fire detection system and a partial liner that meets part 25, Appendix F, Part III. The FAA believes that this type of system would likely be selected by U.S. operators because it would provide maximum flexibility for cargo loading with minimal logistical impact. The primary difference between the cargo compartment used in this cost analysis, and a Class C compartment, would be that all parts of the liner in the proposed Class F compartment would not necessarily meet part 25, Appendix F, Part III."*

The cost analysis carried out in this study, is based on the replacement of the existing Class E cargo compartments on cargo aircraft with the new Class F cargo compartment. The primary option considered, is that subjected to the cost analysis defined in the ARAC document i.e. one that uses "… *Halon 1301, and would incorporate other features including a fire detection system and a partial liner that meets part 25, Appendix F, Part III."*

It is recognized that Halon is being phased out due to its ozone depleting characteristics, and hence systems of this type are not feasible for future fire suppression systems. However, Halon systems are likely to be replaced by other fire suppression systems of a similar weight and cost. Hence, a Halon fire suppression system has been used as a baseline for assessing cost.

The cost assessment is an average value per aircraft in each weight category expressed in 2007 US Dollars. These costs are considered to be to a rough order of magnitude since accurate costs can only be derived by carrying out a full engineering appraisal of each aircraft type. The detailed method of assessing cost is explained in Section 3.1.

Based on the predicted benefit, a determination of the cost of a fire suppression system that is likely to be cost beneficial has also been assessed, as explained in Section 3.2.

3.1 CURRENT HALON SYSTEMS.

Halon systems work by flooding the cargo compartment with Halon gas. The concentration of Halon in the local atmosphere interferes with the burning reaction and suppresses the flame. Halon is stored in pressurized containers and distributed via a series of pipes and fire suppression nozzles. Existing fire or smoke detection systems already on-board cargo aircraft could be retained as part of any Halon fire suppression system and hence do not feature in the assessment of cost. The cost elements considered in this assessment are

- Cost of Suppression System Development
- Cost of Liner Development
- Cost of Suppression System Installation
- Cost of Liner Installation
- Operating Cost – increased fuel burn
- System Maintenance Cost

3.1.1.1 Cost of Suppression System Development.

The ARAC document (Reference 8) assessed that the cost of developing a fire suppression system for an aircraft of the size of a Boeing 737 or a Boeing 727 (both weight category C) would be $585,000. It is optimistically assumed that this is the cost associated with two aircraft types and that one aircraft type would be half this value. Therefore, the associated cost for one aircraft type would be $292,500 at 1999 price levels. Assuming an annual inflation rate of 2.0% this amounts to $342,710 at 2007 levels.

It is assumed that the development costs of weight category B, D and E aircraft will differ from the weight category C aircraft assessed in Reference 8. The development costs of weight category B aircraft are likely to be less than weight category C aircraft and weight category D and E cargo aircraft are likely to have higher costs. It is arbitrarily assumed that the costs will be a function of aircraft weight and therefore the weight category C development costs in Reference 8 need to be factored accordingly. These factors are shown in Table 14.

Table 14. Aircraft Weighting Factors

AIRCRAFT WEIGHT CATEGORY	FACTOR
B	**0.32**
C	**1.00**
D	**1.86**
E	**2.86**

The cost would need to be divided over all aircraft of the same type in the US fleet.

By way of example, for all aircraft types in weight category B, assessed to be 78 aircraft of 6 different types in the US fleet, the cost to develop a suppression system per aircraft would be:

= ($342,710 x 0.32) x (6 / 78) = $8,436 per aircraft

Similar calculations were carried out for each cargo aircraft type in the US fleet. The average values for all aircraft in each of the weight categories are shown in Table 15.

Table 15. Assessed Average Suppression System Development Costs per Aircraft

AIRCRAFT WEIGHT CATEGORY	AVERAGE SUPPRESSION SYSTEM DEVELOPMENT COSTS PER AIRCRAFT
B	**$8,436**[5]
C	**$4,380**
D	**$7,521**
E	**$10,036**

3.1.1.2 Cost of Liner Development.

A similar approach was adopted for the assessment of liner development costs as was used for the suppression system development cost, using Reference 8 as the cost data source. The development cost associated with the liner is expected to include incremental costs for design and approval of this application. The cost of developing cargo compartment liners for a Boeing 737 or a Boeing 727 was assessed as $994,214 at 1999 levels. It is optimistically assumed that this is the cost associated with two aircraft types and that one aircraft type would be half this value. Therefore, the associated cost for one aircraft type would be $497,107 at 1999 price levels. Assuming an annual inflation rate of 2.0% this amounts to $582,440 at 2007 levels. Once again, It is assumed that this liner development cost may be corrected using the factors shown in Table 14 to accommodate aircraft weight.

By way of example, for all aircraft types in weight category B, assessed to be 78 aircraft of 6 different types in the US fleet, the cost to develop a liner per aircraft would be:

= ($582,440 x 0.32) x (6 / 78) = $14,337 per aircraft

Similar calculations were carried out for each cargo aircraft type in the US fleet. The average values for all aircraft in each of the weight categories are shown in Table 16.

---

[5] The comparatively high cost of weight category B aircraft is due to the relatively small number of cargo airplanes of this size in the US fleet – assessed to be 78 in 2007.

Table 16. Assessed Average Liner Development Costs per Aircraft

AIRCRAFT WEIGHT CATEGORY	AVERAGE LINER DEVELOPMENT COSTS PER AIRCRAFT
B	$14,337[6]
C	$7,443
D	$12,783
E	$17,056

3.1.1.3 Cost of Suppression System Installation.

Reference 8 suggests a cost of suppression system installation of $282,000 per aircraft at 1999 levels.

However, these costs were derived for combi aircraft of the size of a Boeing 737 or a Boeing 727 and the installation costs of a suppression system associated with a cargo aircraft will be significantly greater. The cargo compartments on these aircraft are to a rough order of magnitude approximately 2.5 as large on a cargo aircraft as on a combi. Therefore, the installation costs contained in Reference 8 were multiplied by 2.5 to assess the costs appropriate to a cargo aircraft. Furthermore, the installation costs of weight category B, D and E aircraft will differ from the weight category C aircraft assessed in Reference 8. The installation costs of weight category B aircraft will be less than weight category C and weight category D and E greater. It is arbitrarily assumed that the costs will be a function of aircraft weight and hence the factors shown in Table 14 were used to accommodate aircraft size.

The derived installation costs per aircraft were escalated to 2007 prices using an annual inflation rate of 2.0%. The resultant cost for each weight category of aircraft is shown in Table 17.

Table 17. Assessed Average Suppression System Installation Costs per Aircraft

AIRCRAFT WEIGHT CATEGORY	AVERAGE SUPPRESSION SYSTEM INSTALLATION COSTS PER AIRCRAFT
B	$264,326
C	$826,020
D	$1,536,397
E	$2,362,417

---

[6] The comparatively high cost of weight category B aircraft is due to the relatively small number of cargo airplanes of this size in the US fleet – assessed to be 78 in 2007.

3.1.1.4 Cost of Liner Installation.

The same methodology was employed for the derivation of liner installation costs as was used for the suppression system installation costs. Once again, the appropriate base data contained in Reference 8 and the factors contained in Table 14 were used.

The resultant cost for each weight category of aircraft is shown in Table 18.

Table 18. Assessed Average Liner Installation Costs per Aircraft

AIRCRAFT WEIGHT CATEGORY	AVERAGE LINER INSTALLATION COSTS PER AIRCRAFT
B	**$494,071**
C	**$1,543,972**
D	**$2,871,787**
E	**$4,415,759**

3.1.1.5 Operating Cost—Increased Fuel Burn.

Reference 8 assessed that the annual cost per aircraft of the fuel burn, associated with the weight increment resulting from the incorporation of the suppression system and the cargo compartment liners, was $8,794. This cost assessment was based on a fuel cost of $1 per US gallon and was appropriate to weight category C combi aircraft (Boeing 727 and Boeing 737). For a weight category C cargo aircraft, this assessment needs to be multiplied by a factor of 2.5 to accommodate the larger cargo compartment of a cargo aircraft. Account should also be taken of the increase in fuel cost since the ARAC assessment was made based on $1 per US gallon. For this analysis, a fuel cost of $2.102 per US gallon was used (see Reference 9). Therefore, the increased operating cost associated with the extra fuel burn is given by:

$$\$8,794 \times 2.5 \times 2.102$$

$$= \$46,212 \text{ per aircraft per year}$$

To accommodate the differences in size of the cargo compartment of weight category B, D and E cargo aircraft from weight category C aircraft the factors given in Table 14 are used. This leads to an assessed average annual increase in operating costs per aircraft, due to increased fuel burn for each weight category of aircraft, as shown in Table 19.

Table 19. Operating Cost—Increased Fuel Burn

AIRCRAFT WEIGHT CATEGORY	AVERAGE ANNUAL INCREASE IN OPERATING COSTS PER AIRCRAFT DUE TO INCREASED FUEL BURN
B	$14,788
C	$46,212
D	$85,955
E	$132,168

3.1.1.6 System Maintenance Cost.

The maintenance cost assessment of $2,269 per aircraft per annum suggested in Reference 8 was used as a basis for the assessment. Escalating this cost from 1999 values to 2007 at an average annual inflation rate of 2.0% yields a annual cost per combi aircraft of $2,658. It is assumed that this cost will not increase for a cargo aircraft but will increase with aircraft size; hence, once again the factors contained in Table 14 were used to obtain the values shown in Table 20.

Table 20. Maintenance Cost

AIRCRAFT WEIGHT CATEGORY	AVERAGE ANNUAL MAINTENANCE COST PER AIRCRAFT
B	$851
C	$2,658
D	$4,945
E	$7,603

3.1.1.7 Total Cost per Aircraft.

The total costs per aircraft by each of the weight categories are summarized in Table 21.

Table 21. Total Costs per Aircraft by Weight Category

	Non-Recurring Costs					Annual Operating Costs		
Weight Category	**System Development**	**Liner Development**	**System Installation**	**Liner Installation**	**TOTAL**	**Fuel**	**Maintenance**	**TOTAL**
B	**$8,436**	**$14,337**	**$264,326**	**$494,071**	**$781,170**	**$14,788**	**$851**	**$15,639**
C	**$4,380**	**$7,443**	**$826,020**	**$1,543,972**	**$2,381,815**	**$46,212**	**$2,658**	**$48,871**
D	**$7,521**	**$12,783**	**$1,536,397**	**$2,871,787**	**$4,428,489**	**$85,955**	**$4,945**	**$90,900**
E	**$10,036**	**$17,056**	**$2,362,417**	**$4,415,759**	**$6,805,267**	**$132,168**	**$7,603**	**$139,771**

3.2 COST BENEFICIAL SYSTEMS.

Section 2 and Section 3 described the benefits and costs that are likely to accrue from the installation of a Halon (or a suitable alternative) fire suppression system together with the required cargo compartment liners.

In order to compare the assessed benefit and cost values, the non-recurring costs must be converted to an annual value. There are several ways in which this might be done however most involve amortizing the cost over a period of time. The annual cost incurred reduces as the time considered is increased. Capital employed to install a fire suppression system will result in a loss of income from investment. This may be considered as the minimum annual cost associated with the non-recurring costs. Assuming a 4.5% income from capital investment the minimum annual cost of fitting a fire suppression system would be 4.5% of the non-recurring cost.

For each Weight category of aircraft, Table 22 summarizes:

1. The average benefit per aircraft per year (see Table 13)
2. The minimum non-recurring cost per aircraft per year based on the loss of income from investment—4.5% of the total non-recurring cost (see Table 21)
3. The operating cost per aircraft per year (see Table 21)
4. The total cost per aircraft per year – the sum of 2 and 3 above
5. The cost benefit ratio – the ratio of 4 and 1 above

Table 22. Cost Benefit Ratio—Halon System

Weight Category	Average Benefit per Aircraft per Year	Minimum Non-Recurring Cost per Aircraft per Year	Operating Cost per Aircraft per Year	Total Cost per Aircraft per Year	Cost Benefit Ratio
B	**NEGLIGIBLE**	**$35,153**	**$15,639**	**$50,791**	**N/A**
C	**$640**	**$107,182**	**$48,871**	**$156,053**	**244**
D	**$4,100**	**$199,282**	**$90,900**	**$290,182**	**71**
E	**$19,900**	**$306,237**	**$139,771**	**$446,008**	**22**

It may be seen that the cost benefit ratios are high for all weight category aircraft. Weight categories E and D have the lowest cost benefit ratios. The 95-percentile model prediction of benefit for weight category E aircraft was approximately $49,000 and for weight category D aircraft approximately $9,800 These values of benefit result in cost benefit ratios in the order of 9 and 30 respectively. It is therefore evident that a Halon type system is unlikely to be cost beneficial for cargo aircraft of any weight category.

However, other options might be considered that could be cost beneficial. The ARAC document (Reference 8) and the EASA NPA (Reference 7) suggest alternate means for fire control or suppression in cargo compartments and some of these might be shown to be both practical and cost beneficial.

Figure 14 shows the likely division of the costs, for all weight category aircraft in the US freighter fleet, for a Halon type system.

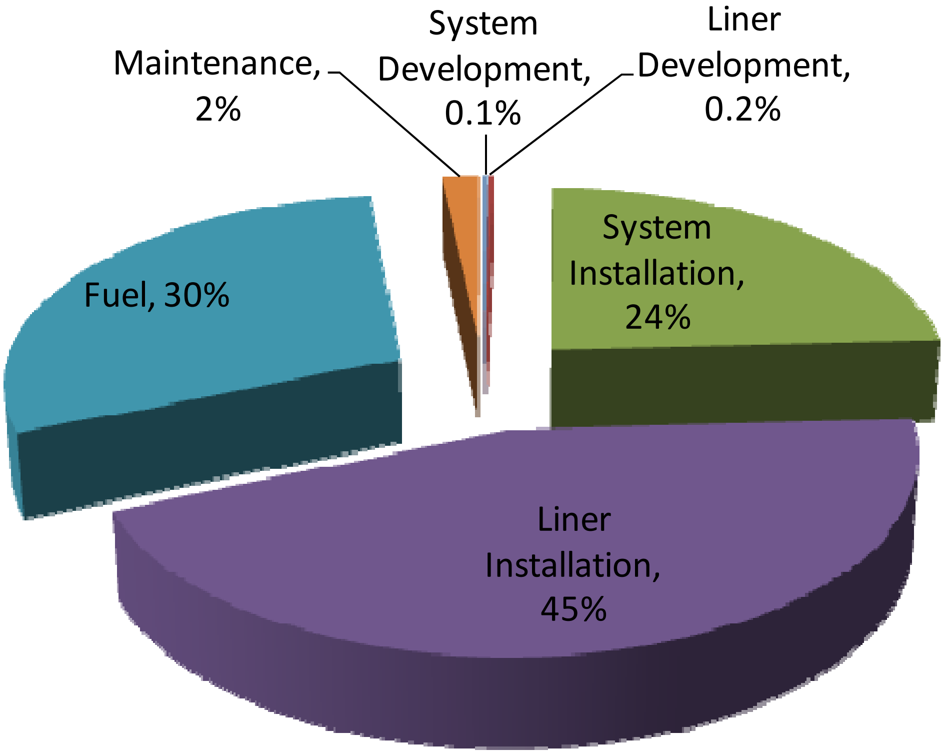

Figure 14. Annual Cost Breakdown

It may be seen from Figure 14, that the cost of the system is largely dependent on the installation cost (for a Halon type system the liner and suppression system) and the cost incurred from additional fuel burn resulting from the weight increase. On this basis, for a system to be cost beneficial the following equation must be satisfied:

$$\mathbf{B} = \mathbf{f} + \mathbf{i} \qquad \text{Equation 1}$$

Where:

$\mathbf{B}$ is the benefit per year at which the suppression system becomes cost beneficial
$\mathbf{f}$ is the increased fuel cost per year and
$\mathbf{i}$ is the installation cost per year

However, the increased fuel cost per year may be expressed as:

$$\mathbf{f} = \mathbf{w} \times \mathbf{g} \times \mathbf{h} \times \mathbf{c} \qquad \text{Equation 2}$$

Where:

$\mathbf{w}$ is the total suppression system weight (lb)
$\mathbf{g}$ is the incremental fuel burn per pound per aircraft flight hour (gallons/lb hour)
$\mathbf{h}$ is the aircraft flight hours per year (flight hours)
$\mathbf{c}$ is the fuel cost per gallon ($/gallon)

The minimum installation cost per year, $\mathbf{i_m}$, is equal to:

$$\mathbf{i_m} = \mathbf{I} \times \mathbf{r} \qquad \text{Equation 3}$$

Where:

$\mathbf{I}$ is the total suppression system installation cost ($) and
$\mathbf{r}$ is the loss of income from capital investment (%/year)

Substituting equations 2 and 3 into equation 1 yields:

$$\mathbf{B} = (\mathbf{w} \times \mathbf{g} \times \mathbf{h} \times \mathbf{c}) + (\mathbf{I} \times \mathbf{r}) \qquad \text{Equation 4}$$

Rearranging Equation 4 yields:

$$\mathbf{w} = [\mathbf{B} - (\mathbf{I} \times \mathbf{r})] \div (\mathbf{g} \times \mathbf{h} \times \mathbf{c}) \qquad \text{Equation 5}$$

Equation 5 may be used to evaluate the relationship between weight and cost of installation of a complete fire suppression system that might be considered cost beneficial, as defined by the threshold benefit B. The threshold benefit for each aircraft weight category corresponds to the average predicted benefit per year shown in Table 22.

The values of $\mathbf{g}$, $\mathbf{c}$ and $\mathbf{r}$ were assumed as follows:

$\mathbf{g}$ = 0.0049 gallons/lb per flight hour (based on data contained in Reference 5)
$\mathbf{c}$ = US$ 2.102 per gallon (based on data contained in Reference 9)
$\mathbf{r}$ = 4.5% per year

The assessed aircraft flight hours per year, **h**, based on data contained in Reference 3, is as shown in Table 23.

Table 23. Average Flight Hours - h

AIRCRAFT WEIGHT CATEGORY	AVERAGE FLIGHT HOURS PER YEAR US CARGO FLEET IN 2007
B	**506**
C	**1122**
D	**1444**
E	**2857**

A "cost-benefit" chart showing the total system weight against installation cost per aircraft, for a cost beneficial system, is shown in Figure 15 for a weight category E aircraft.

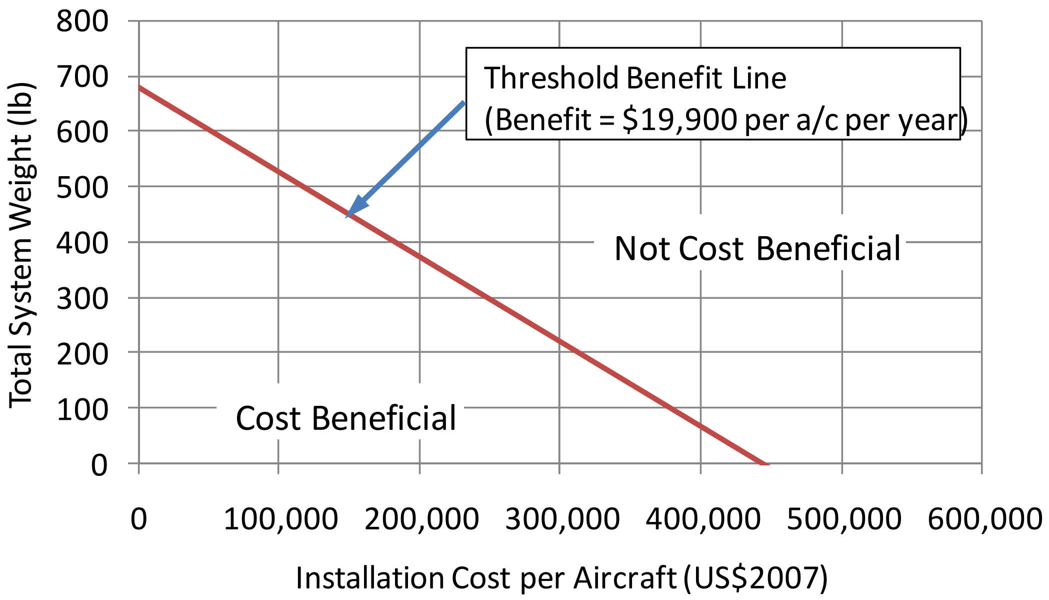

Figure 15. Relationship Between Total System Weight and Installation Cost for a Cost Beneficial System Fitted to a Weight Category E Aircraft

As the chart suggests, any combination of the total suppression system weight and cost of installation that falls above the threshold line is considered not cost beneficial, and below that is considered cost beneficial.

A similar chart is shown in Figure 16 for weight category D and Figure 17 for weight category C aircraft, for their respective threshold benefits.

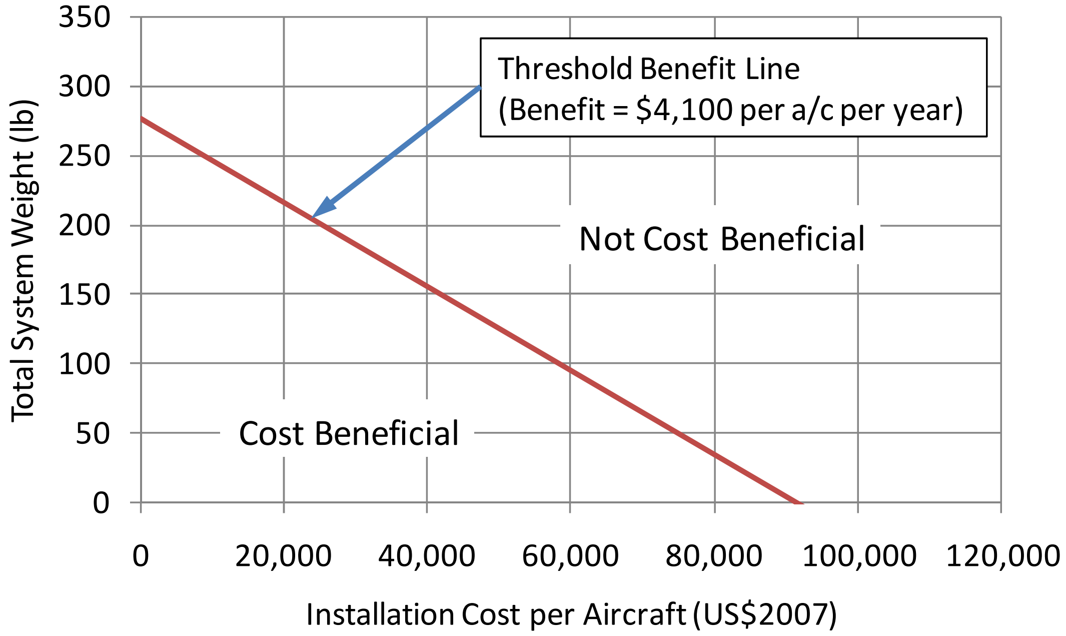

Figure 16. Relationship Between Total System Weight and Installation Cost for a Cost Beneficial System Fitted to a Weight Category D Aircraft

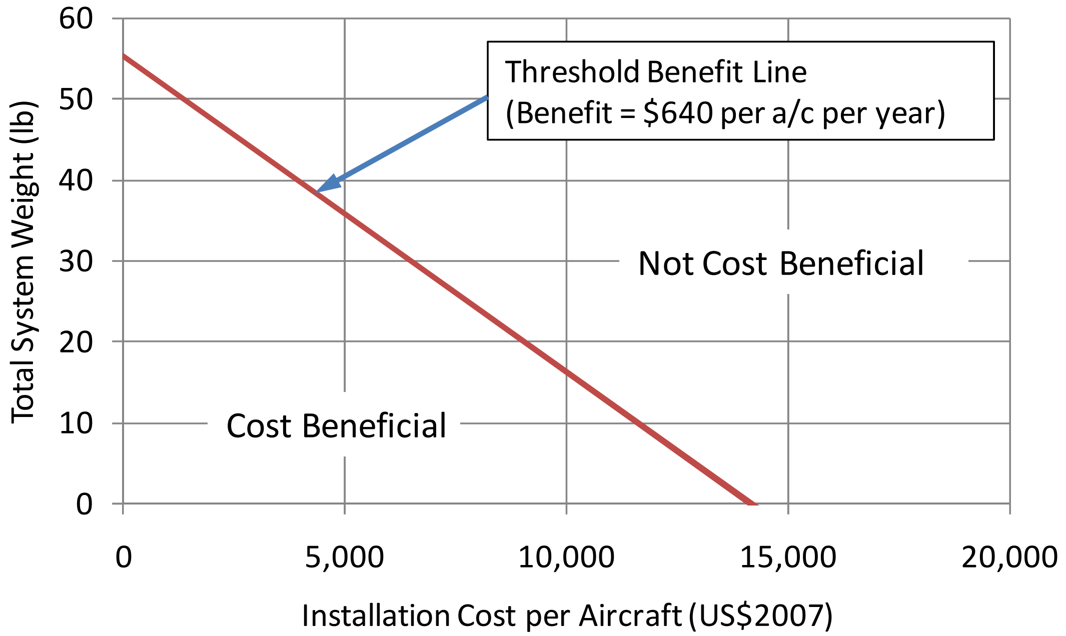

Figure 17. Relationship Between Total System Weight and Installation Cost for a Cost Beneficial System Fitted to a Weight Category C Aircraft

4. DISCUSSION & CONCLUSIONS.

4.1 ACCIDENT RATE & AIRCRAFT USAGE.

RTM is a significant factor in the prediction of benefit. While there is a large variation in RTM from the three data sources, the best estimate prediction correlates well with the available data prior to 1985 and the FAA prediction after 2004. The discrepancies that exist in the data are considered likely to result from the inclusion of data on aircraft that are not within the scope of this study (RTM estimated higher than the best estimate prediction) and incomplete reporting (RTM estimated lower than the best estimate prediction).

However, it is unknown whether any errors in these data are likely to increase or decrease the prediction of benefit since it is unknown whether the RTM values are likely to be higher or lower than the best estimate prediction.

The assumption that the cargo fire accident rate is related to Revenue Ton Miles is considered reasonable. It may be seen from Figure 18 that based on this assumption the accident rate does not appear to vary significantly from the 1980s to the present day. The average value over the period 1967 to 2007 is shown as the "Simple Average Rate" in Figure 18. The "Moving Average Rate" is simply the total number of accidents experienced at any given time divided by the Revenue Ton Miles accumulated up to that time.

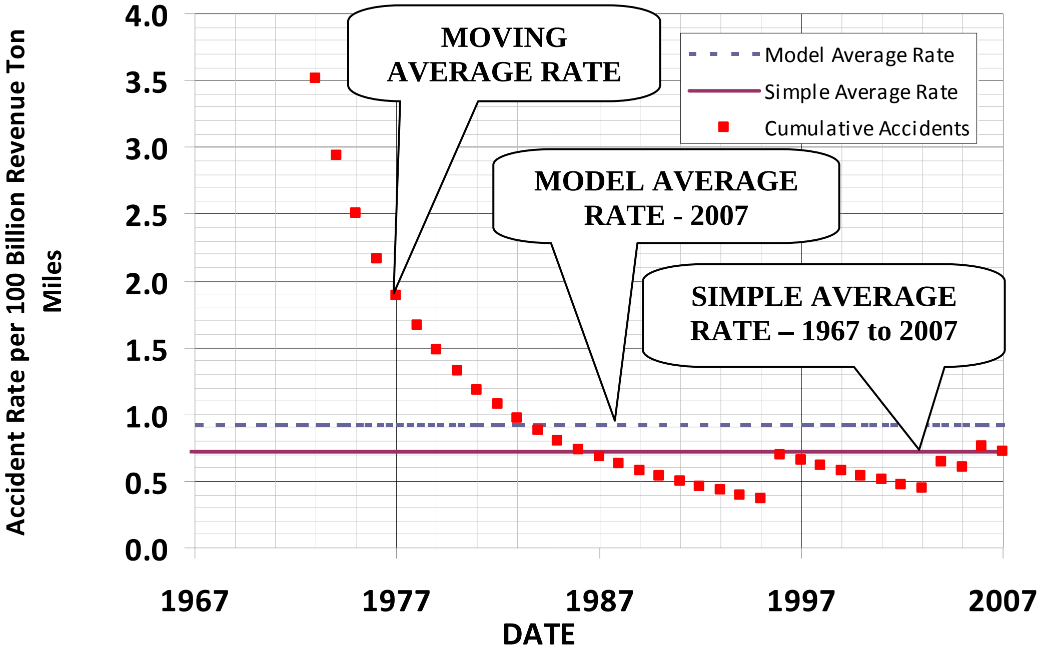

Figure 18. Variation in Cargo Fire Accident Rate per Revenue Ton Mile Over the Period 1967 to 2007

Since it is likely that stricter controls on the carriage of cargo have resulted in a reduction in the risk of an in-flight fire it might be expected that the 2007 accident rate would be less than the average experienced over the period 1967 to 2007. Therefore, use of this “Simple Average Rate” might be considered to result in too high a prediction of benefit.

The prediction of benefit derived from the model is based on accident rates generated by the χ^2 distribution. This again is likely to result in an over estimate of the benefit since the average accident rate from this distribution is 25% higher than the “Simple Average Rate.”

Conclusion 1 - It is considered that the assumptions made in relation to cargo fire accident rate provide a reasonable estimate of the intrinsic rate of the current US fleet. Any errors that might exist in the RTM data will have a reasonably significant effect on the prediction of benefit. However, since the value of any errors is unknown, it cannot be determined whether they would increase or decrease the prediction of benefit. However, the use of the χ^2 distribution is to some extent conservative and is likely to give an overestimate of the benefit.

4.2 CONTROLLED V UNCONTROLLED ACCIDENTS.

All four of the cargo fire accidents to US registered aircraft identified in this study were deemed CONTROLLABLE. Only two other possible cargo fire accidents were identified worldwide – no official information is available regarding either. The first of these accidents occurred in Brazil in 1992 to a Boeing 737 aircraft and is thought to have been caused by the crew becoming distracted by intermittent activation of the cargo compartment warning system, rather than it being an actual cargo fire. However, it would appear that it was an UNCONTROLLABLE accident. The second accident occurred in Nigeria in 1994 to a Boeing 707 aircraft. This is thought to have been caused by a cargo bay fire and may also have been UNCONTROLLABLE.

In summary, it is likely that there have been five accidents worldwide (including the four to US registered aircraft) and possibly one was UNCONTROLLABLE. Based on the probability distribution described in Section 2.1.4.1.1, the model prediction is that approximately one in five accidents is likely to be UNCONTROLLABLE. This would seem to be reasonable when compared with the in-service occurrences.

Conclusion 2 - The assumptions made in the study, regarding the likely proportion of UNCONTROLLABLE accidents are considered reasonable when compared with the limited in-service data.

4.3 COLLATERAL DAMAGE.

Based on the probability distributions described in Section 2.1.4.1 the model suggests that approximately one in twenty-five cargo fire accidents are likely to result in collateral damage. This is difficult to substantiate by in-service data on cargo fire accidents since there are so few occurrences and none resulted in collateral damage. As described in Section 2.1.4.1.2, 178 accidents to passenger carrying aircraft were studied that were similar to a cargo fire accident in terms of their in-flight event and accident sequence. Of these, ten resulted in collateral damage – or approximately one in eighteen. This does not seem to be incompatible with the one in twenty five probability utilized in the model.

The assumption that accidents to passenger aircraft chosen are adequately representative of in-flight cargo fire accidents in terms of the magnitude of the collateral damage that might be incurred would seem reasonable. However, it is also assumed that the magnitude of collateral damage does not vary significantly with aircraft weight category. One might expect that larger aircraft would result in greater collateral damage. However, the collateral damage cost constitutes only 5% of the total benefit and sensitivity analyses suggested that even if the collateral damage costs were doubled it would only change the predicted benefit by less than 10%. On this basis, it is considered that the assumption that collateral damage does not vary with aircraft weight category does not significantly alter the conclusions of the analysis.

It is interesting to note that the distribution of the collateral costs used in the model suggests that one in twenty accidents, involving collateral damage, result in ground damage of more than US$ 100,000,000 and one in a hundred accidents more than US$ 340,000,000. However, this distribution was based on a small dataset so cannot be considered as definitive.

Conclusion 3 - Collateral damage costs do not appear to contribute significantly to the prediction of benefit.

4.4 CREW INJURIES.

In the absence of any more accurate data, the distribution of the number of crew on-board US registered cargo aircraft was assumed largely unchanged over the period 1967 to date. Based on this assumption data was extracted from the CSRTG Accident Database, Reference 1, to determine the likely distribution of the number of crew for each of the four weight category aircraft. The data used were assumed to follow Weibull distributions. The basis for using this distribution is that it accommodates data that is truncated at the lower end – i.e. it reflects that the crew complement cannot be less than two.

There are limited data available to validate the likely number of crew fatalities predicted by the model per accident. From the four cargo fire accidents to US registered aircraft identified in this study there were three fatalities. This amounts to 0.75 fatalities per accident. The average value predicted by the model was determined to be approximately 0.9, which correlates well. The model also predicts an average of 0.2 serious injuries per accident compared to the current total for the US fleet of cargo aircraft of zero.

The monetary value per accident associated with the crew injuries derived from the model are:

$$0.9 \times 5.8 + 0.2 \times 2.76 \text{ million US\$}$$

$$= 5.8 \text{ million US\$ (approx.)}$$

This may be compared to the costs actually incurred in fatal cargo fire accidents to the US fleet[7] of:

$$0.75 \times 5.8 + 0 \times 2.76 \text{ million US\$}$$

$$= 4.4 \text{ million US\$ (approx.)}$$

Hence, the model prediction and the in-service experience correlate reasonably well.

If the accident to the Boeing 707 in Nigeria in 1994 were taken into consideration, the crew injury costs would increase significantly since this accident involved three fatalities and two serious injuries. However, it is considered reasonable to restrict the cost benefit analysis to US registered aircraft; widening the scope would mean many of the other variables used in this analysis would also change and these may be inappropriate to the US fleet.

Conclusion 4 - Crew injuries (fatal and serious combined) are a significant factor in the prediction of benefit. It is considered that the predictions of crew injuries derived in this study correlate well with the in-service experience.

4.5 AIRCRAFT DAMAGE.

Aircraft value is a significant factor in the prediction of benefit. In the absence of data for all of the aircraft values for the US fleet in 2007 it is assumed that the average aircraft values contained in Reference 5 are reasonably accurate. If this is the case, the model average predictions of benefit will also be reasonably accurate. The most questionable issue is therefore the assumptions made with regard to the variance of these values, which will affect the likely range of the prediction of benefit. It is unknown whether any errors in these data are likely to increase or decrease the prediction of benefit.

In the absence of data regarding aircraft repair costs, pessimistic assumptions were made as to the costs incurred. If the aircraft was Destroyed, the cost is simply the value of the aircraft. It was assumed that Substantial damage resulted in a cost equivalent to 80% of the aircraft value and for Minor damage 20% of the aircraft value. For the accidents predicted by the model, the average aircraft damage amounts to approximately 85% of the aircraft value. This is considered a reasonable assessment of the likely cost.

Conclusion 5 - Aircraft value is the largest contributor to the prediction of benefit.

Conclusion 6 - Whilst the accuracy of the aircraft values data cannot be confirmed, pessimistic assumptions regarding the likely damage costs will tend to increase the assessed benefit.

---

[7] See list of accidents to US cargo fleet in Section 2.1.1.1.1

4.6 CARGO DAMAGE.

The only data source currently available regarding cargo value is that contained in Reference 3. It may be seen from the cost breakdown shown in Figure 13 that cargo value contributes approximately 11% of the benefit. The data in the model results in an average of 97% of the cargo being destroyed in cargo fire accidents.

4.7 ASSESSMENT OF COST & BENEFIT.

The cost benefit ratio for a weight category E aircraft was assessed to be approximately 22 and even based on the 95-percentile assessment of benefit still as high as approximately 9. For weight category D aircraft the cost benefit ratio was assessed to be approximately 71 and based on the 95-percentile assessment of benefit approximately 30. For weight category B aircraft, the cost benefit ratio is even higher.

On this basis it is concluded that Halon fire suppression systems, or alternatives that may be developed for below floor cargo compartments, are not likely to be cost beneficial.

The assessments of both cost and benefit necessitated estimates to be made of some of the values used in the calculations. Although confirmed data, were it available, would change both the cost estimates and the predictions of benefit, it is considered unlikely that these would affect the conclusions of this study.

Conclusion 7 - It is concluded that Halon fire suppression systems, or alternatives that are likely to be developed for below floor cargo compartments, are unlikely to be cost beneficial for the main deck cargo compartments of cargo aircraft of any weight category.

However, alternate fire protection systems may prove to be cost beneficial, particularly on larger cargo aircraft. Possible alternate systems were suggested as part of the proposed regulatory activity relating to the main cargo compartments of combi aircraft (see References 7 and 8).

Conclusion 8 - Fire suppression systems of the kind currently being considered for the cargo compartments of combi aircraft, may prove to be cost beneficial, particularly on larger cargo aircraft.

5. SUMMARY OF CONCLUSIONS.

Conclusion 1 - It is considered that the assumptions made in relation to cargo fire accident rate provide a reasonable estimate of the intrinsic rate of the current US fleet. Any errors that might exist in the RTM data will have a reasonably significant effect on the prediction of benefit. However, since the value of any errors is unknown, it cannot be determined whether they would increase or decrease the prediction of benefit. However, the use of the χ^2distribution is to some extent conservative and is likely to give an overestimate of the benefit.................................37

Conclusion 2 - The assumptions made in the study, regarding the likely proportion of UNCONTROLLABLE accidents are considered reasonable when compared with the limited in-service data…………………………………………………………………………….………...37

Conclusion 3 - Collateral damage costs do not appear to contribute significantly to the prediction of benefit………………………………………………………………………………………38

Conclusion 4 - Crew injuries (fatal and serious combined) are a significant factor in the prediction of benefit. It is considered that the predictions of crew injuries derived in this study correlate well with the in-service experience………………………………………………….....39

Conclusion 5 - Aircraft value is the largest contributor to the prediction of benefit…………….39

Conclusion 6 - Whilst the accuracy of the aircraft values data cannot be confirmed, pessimistic assumptions regarding the likely damage costs will tend to increase the assessed benefit……...40

Conclusion 7 - It is concluded that Halon fire suppression systems, or alternatives that are likely to be developed for below floor cargo compartments, are unlikely to be cost beneficial for the main deck cargo compartments of cargo aircraft of any weight category……………...………..40

Conclusion 8 - Fire suppression systems of the kind currently being considered for the cargo compartments of combi aircraft, may prove to be cost beneficial, particularly on larger cargo aircraft………………………………………………………………………………………40

6. REFERENCES.

1. RGW Cherry & Associates Limited, February (2008) *The Cabin Safety Research Technical Group Accident Database, Version 31*, Prepared for Transport Canada, the Federal Aviation Administration and the UK Civil Aviation Authority. United Kingdom: Author
2. The National Transportation Safety Board Accident Database, http://www.ntsb.gov/
3. The US Department of Transportation, Research & Innovative Technology Administration, Bureau of Transportation Statistics, http://www.bts.gov
4. Federal Aviation Administration, (2008) FAA Aerospace Forecast 2008 – 2025. United States: Federal Aviation Administration.
5. GRA, Incorporated, (2007) Economic Values for FAA Investment and Regulatory Decisions, A Guide, United States: Author

6. Federal Aviation Administration. (2008) Revised Departmental Guidance: Treatment of the Value of Preventing Fatalities and Injuries in Preparing Economic Analyses United States: Federal Aviation Administration http://www.faa.gov/regulations_policies /policy_guidance/benefit_cost

7. EASA, (2008) Notice Of Proposed Amendment (NPA) No 2008-10, Class B/F Cargo Compartments, Germany: Author

8. Federal Aviation Administration – Regulations and Policies, Aviation Rulemaking Advisory Committee, Cargo Standards Harmonization Working Group, Task 1 – Main Deck Class B Cargo Compartments, United States: Author

9. Air Transport Association*, Annual Crude Oil and Jet Fuel Prices,* United States: Author http://www.airlines.org/economics/energy/Annual+Crude+Oil+and+Jet+Fuel+Prices.htm

APPENDIX 1—14 CFR 25.857 CARGO COMPARTMENT CLASSIFICATION

(a) *Class A.* A Class A cargo or baggage compartment is one in which—

(1) The presence of a fire would be easily discovered by a crewmember while at his station; and

(2) Each part of the compartment is easily accessible in flight.

(b) *Class B.* A Class B cargo or baggage compartment is one in which—

(1) There is sufficient access in flight to enable a crewmember to effectively reach any part of the compartment with the contents of a hand fire extinguisher;

(2) When the access provisions are being used, no hazardous quantity of smoke, flames, or extinguishing agent, will enter any compartment occupied by the crew or passengers;

(3) There is a separate approved smoke detector or fire detector system to give warning at the pilot or flight engineer station.

(c) *Class C.* A Class C cargo or baggage compartment is one not meeting the requirements for either a Class A or B compartment but in which—

(1) There is a separate approved smoke detector or fire detector system to give warning at the pilot or flight engineer station;

(2) There is an approved built-in fire extinguishing or suppression system controllable from the cockpit.

(3) There are means to exclude hazardous quantities of smoke, flames, or extinguishing agent, from any compartment occupied by the crew or passengers;

(4) There are means to control ventilation and drafts within the compartment so that the extinguishing agent used can control any fire that may start within the compartment.

(d) [Reserved]

(e) *Class E.* A Class E cargo compartment is one on airplanes used only for the carriage of cargo and in which—

(1) [Reserved]

(2) There is a separate approved smoke or fire detector system to give warning at the pilot or flight engineer station;

(3) There are means to shut off the ventilating airflow to, or within, the compartment, and the controls for these means are accessible to the flight crew in the crew compartment;

(4) There are means to exclude hazardous quantities of smoke, flames, or noxious gases, from the flight crew compartment; and

(5) The required crew emergency exits are accessible under any cargo loading condition.