

CAA PAPER 2001/9

**AIRCRAFT HARDENING RESEARCH  
PROGRAMME  
FINAL OVERVIEW REPORT**

**CIVIL AVIATION AUTHORITY, LONDON**

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FINAL OVERVIEW REPORT**

This paper has been compiled by staff of the Structures & Materials Department, Design and Production Standards Division of the Civil Aviation Authority Safety Regulation Group. The paper presents the results of research into means of mitigating the effects of explosions on civil transport aircraft, carried out under a CAA research contract by the Defense Evaluation and Research Agency, now QinetiQ.

AIRCRAFT HARDENING RESEARCH PROGRAMME  
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## **Executive Summary**

This report summarises research undertaken for the Civil Aviation Authority and the Department of Transport (now the Department of Transport, Local Government and the Regions), with support from the Department of Trade and Industry and the Federal Aviation Administration, to investigate means to mitigate the effects of explosions on civil transport aircraft.

It follows the loss of the Boeing 747 aircraft N739PA on flight Pan Am 103 in December 1988 and the response of the Civil Aviation Authority to the subsequent recommendations of the Air Accident Investigations Branch of the Department of Transport, Local Government & the Regions.

It has been demonstrated by trials, analysis and simulation that relatively simple steps can be taken to achieve much improved resistance of airframe structure and systems to explosions in flight.

The mitigation measures studied include extrinsic means such as the use of hardened baggage containers and protective liners for the fuselage skin or spacing materials for the cargo hold which ensure an increased stand-off between the device and the skin. Alternatively, or additionally, means to restrict baggage momentum or to distribute baggage itself have been illustrated. Aircraft systems may be similarly protected. Intrinsic measures to improve the structure itself include local reinforcement of skin and frames, improved attachment of fuselage stringers and selective placement of systems equipment.

The use of extrinsic and intrinsic measures, severally or in combination, may enable a range of existing and new aircraft to be effectively covered and minimise the safety risk.





# 1 INTRODUCTION

The loss of Boeing 747 N739PA on Flight Pan Am 103 in December 1988 caused the Civil Aviation Authority to undertake a programme of research to investigate means to mitigate the effects of such attacks on civil transport aircraft. It was based upon the final recommendation of the Report of the Department of Transport's Air Accident Investigation Branch that :-

"The airworthiness authorities and aircraft manufacturers undertake a systematic study to identify measures that might mitigate the effects of explosive devices and improve the tolerance of aircraft structures and systems to explosive damage."

The programme on aircraft explosions and hardening was funded jointly by the Civil Aviation Authority, the Department of Trade and Industry and the Department of Environment Transport and the Regions. Some specific funding was provided by the Federal Aviation Administration, in conjunction with the CAA, to undertake an additional full scale aircraft trial within the programme. Following a review of tenders, the Defence Evaluation Research Agency (DERA), now QinetiQ, was chosen to perform this research.

The research programme addressed three broad themes, namely:-

- The investigation of the vulnerability of fuselage structure to acts of sabotage by the detonation of improvised explosive devices, IEDs, in cargo hold baggage.
- The investigation of the vulnerability of the aircraft systems under similar threats and
- The potential to improve the resistance of both aircraft structure and systems to such acts of sabotage.

The programme concluded with the preparation of a detailed technical classified report. From this work a series of unclassified reports, an overview and supporting technical papers, were then drafted, addressing the constituent parts of the research, but de-sensitised for public dissemination.

This report is the overview which summarises the purpose for and the main findings of, the programme, without going into great detail on the technical issues involved. Technical issues are addressed in three supplementary technical reports, to be used in discussion with particular sections of the industry.

The programme has enabled the development of a comprehensive understanding of the threat to the structures and systems of civil transport aircraft. Conclusions have been derived by detailed computer modelling, by the use of an analytical vulnerability model and by validation through a comprehensive trial programme. Both models and tests enable the study of potential mitigation measures.

Comprehensive vulnerability models have been developed for the failure of the fuselage structure that reveal the criticality of the effects of transient explosive forces combined with service pressurisation on structural failure. Matching

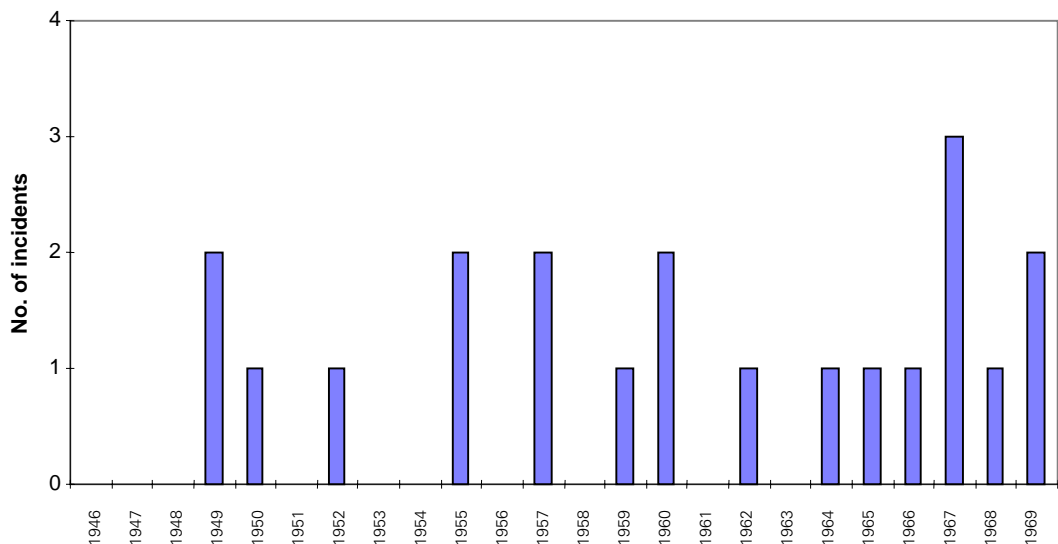
studies of the aircraft systems reveal the importance of penetration by fragments to the survival of systems.

It has been concluded that improvised explosive devices, IEDs, are capable of destroying a pressurised fuselage because of the combined effects of transient explosive forces and normal cabin pressurisation. Generally, aircraft systems are relatively resistant to explosive devices but selective improvements can be made. A key element of the work is the identification of possible methods for ameliorating the effects of on-board detonations.

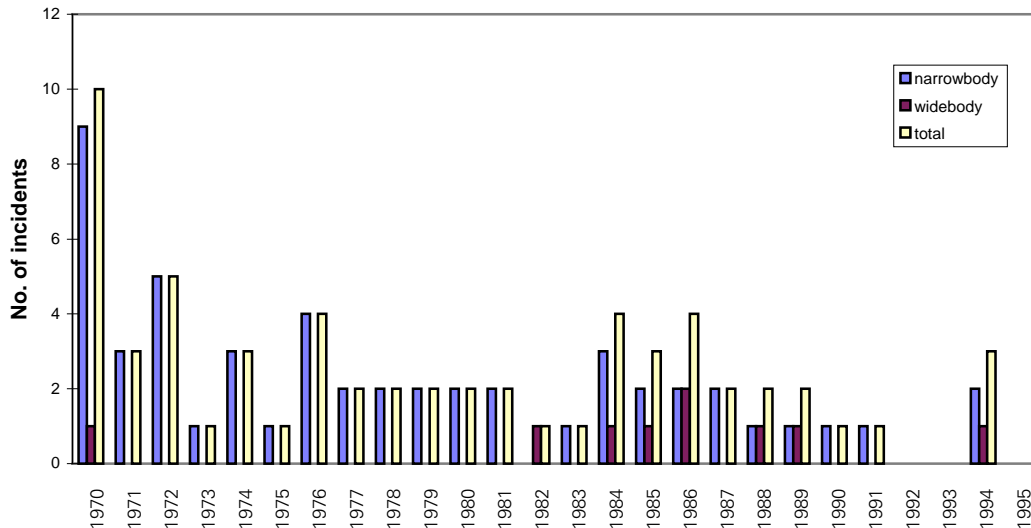
## 1.1 The problem

As indicated above, the main problem to be addressed is understanding the structural response of a fuselage structure to an internal explosion such as that which occurred and led to the loss of Pan Am 103 and the derivation of possible mitigating actions.

At the time of the 1988 accident it was believed that acts of terrorism or sabotage against civil aircraft posed a relatively minor threat. An early task within the programme was to research the history of aircraft attacks, both in specific terms and in terms of the general statistics of attack.



**Figure 1a Incidents due to the presence of IEDs on aircraft >5700kg max. weight. (For the period 1946-1969, narrow body only)**



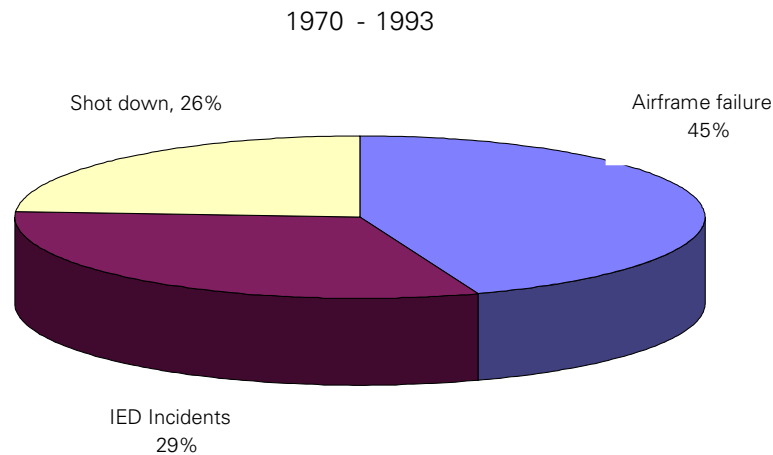
**Figure 1b Incidents due to the presence of IEDs on aircraft >5700kg max. weight. (For the period 1970- July 1995, now including wide body.)**

In analysing aircraft losses, two periods were considered, basically from the close of WW2 up to the introduction of wide bodied high altitude pressurised aircraft in 1970, and from 1970 to mid 1995. Studies to date have revealed that attacks against civil transport aircraft are a continuing [Figures 1a and 1b] and significant threat [Table 1].

**Table 1 IED attacks and consequent losses against civil aircraft between 1971 and 1995**

|                              | <b>In-flight attack</b> | <b>In-flight &amp; on- ground attacks</b> |
|------------------------------|-------------------------|---|
| IED attempts wide body       | 7                       | 9   |
| IED attempts narrow body     | 35                      | 52  |
| <b>Total attacks</b>         | <b>42</b>               | <b>61</b>                                 |
| Aircraft losses wide body    | 3                       | 5   |
| Aircraft losses narrow body  | 22                      | 35  |
| <b>Total aircraft losses</b> | <b>25</b>               | <b>40</b>                                 |

It has been found that in the incidents where loss of the fuselage structure has precipitated or threatened a catastrophic accident, the occurrence of fire in the aircraft hold has been the most frequent of threatening events. Once these fire-related events are removed from the statistics, it can be seen [Figure 2] that attack or sabotage is as significant as structural failure from normal in-service problems such as the degradation of fuselage structure by fatigue or corrosion.



**Figure 2 Comparison of IED incidents to non-sabotage airframe failures and incidents involving aircraft being shot/forced down**

An analysis of the loss of aircraft caused by sabotage and internal detonations, revealed a loss rate of approximately 1 per  $10^7$  flights, worldwide, averaged over the last 30 years. Although not directly comparable, it is of interest to note that the current rate of catastrophic failure for western built jets is approximately 4 per  $10^7$  flights.

## 2 PROGRAMME REQUIREMENTS

In order to develop methods that might be applied to mitigate the effects of acts of sabotage, the original requirement of the CAA programme, DERA needed to assess the vulnerability of both existing aircraft structures and aircraft systems to such acts. In the original contract, the stipulated scenario was a detonation of an IED in the cargo hold of commercial transport aircraft. An analysis of real acts of sabotage revealed that many also occur within the passenger cabin. However, the techniques evaluated in this research are generally applicable to the structure and systems of the whole aircraft and the threat to the passenger cabin has therefore been accommodated in the overall programme.

### 2.1 Programme Details

The subjects for research consisted of the 5 basic tasks listed below, with the resultant main deliverable shown in italics underneath

- **Task 1 – Basic explosive technology** work defining the physics of explosions as background for the other tasks.

*Classified report has been prepared that explains the theory used in this research.*

- **Task 2 – Prediction of effects on civil aircraft structures.** This covers the generation of a predictive mathematical model that accurately produces the loading produced by an explosive source. This addresses both the free air

and "within baggage" situations. Loads are then put onto a mathematical model of the fuselage structure, and the local and global response of the structure determined. Both the blast loading and structural response models have had been validated by test, including two full scale, fully pressurised aircraft fuselage tests on wide bodied European and American transport aircraft.

*This had demonstrated the predictive capabilities of the models.*

- **Task 3 – Vulnerability of aircraft to an explosion.** This is a study of the generic vulnerability of an aircraft. A generalised structural model was developed and used to retrospectively analyse previous incidents & trials.

*Model can be used to assess vulnerability of various combinations of structure and baggage.*

- **Task 4 – Aircraft Hardening.** Techniques covered are :-
  - hardened cargo containers and liners
  - hardened aircraft structure
  - system protection
  - increased stand-off distance of container to fuselage skin.

The concepts were developed and were incorporated on a full scale test trial of a fully pressurised wide bodied USA aircraft at Bruntingthorpe. This event was well covered by the media.

*Means of attenuating the blast effects and the causes of structural failure have been validated.*

- **Task 5 – Effects of explosions on aircraft systems.** Test and analysis of the effects of fragmentation and blast on actual a/c systems within a fuselage leading to the assessment of critical vulnerability

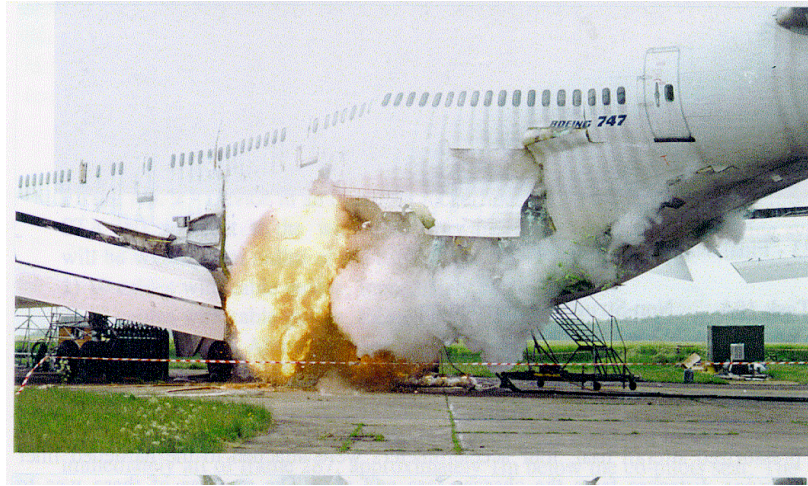
*Demonstration of the major influence of fragmentation as opposed to blast effects.*

### **3 DISCUSSION**

It is not possible to protect an aircraft from a very large internal explosion. However, cognisant of the effectiveness of detection equipment at airports, the maximum size of device likely to be a threat can be established. The explosive charges used on the test at Bruntingthorpe were of the order of this maximum size.

The test demonstrated that there are hardening techniques that can be effective without incurring prohibitive costs. However, when considering major modifications to current aircraft, or changing the design requirements for new types, it is essential to look very carefully at the possible effects which might detract from current safety features which have been in place for many years and found to be effective. It is therefore necessary for the regulatory authorities and Industry to work together to see how best to apply the lessons learned from the research. It remains clear that to prevent catastrophic failure, such as seen in the loss of Pan Am 103 over Lockerbie or the UTA DC-10 over the Tenere desert,

breaching of the fuselage by improvised explosive devices must be prevented. This research has demonstrated practical feasibility of prevention or “hardening” by 3 separate approaches of a hardened liner, a hardened container and a modified container.

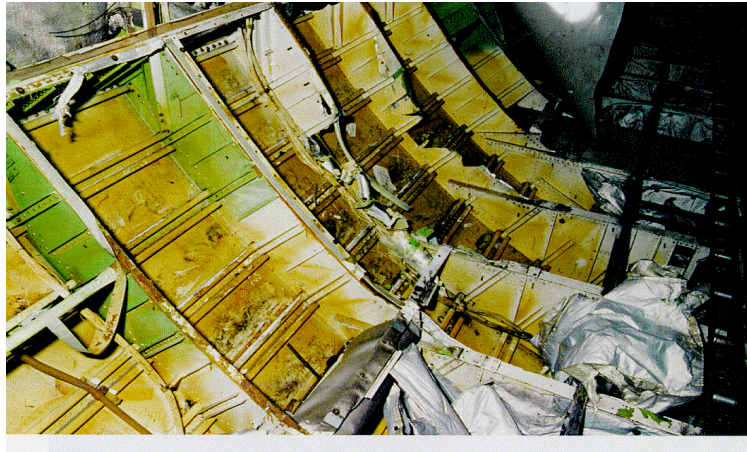


**Figure 3** Explosion at the non-hardened structure of the Bruntingthorpe article. 3 other locations on the aircraft which had been hardened, had similar size charges but had no significant structural damage



**Figure 4** A hardened liner in position prior to test. It is situated in the cargo bay, placed over the frames and extending over seven bays





**Figure 5 The structural damage under the liner after the test, showing crushed frames but no fuselage skin rupture. This damage would not have prevented safe flight and landing**

#### 4 RELATIVE EFFICIENCIES OF SELECTED HARDENING TECHNIQUES

The relative merits of the hardening schemes reviewed in this programme are indicated in Table 2. The relative cost of these schemes may be addressed in simple terms by considering the initial cost of adoption and the increase in operating costs from increased fuel burn or loss of payload. The comparison of systems can be made for any selected aircraft.

An approximate relative measure of performance can be derived by dividing the increase in resistance, in terms of increase in charge size, by the increased aircraft mass, or estimated payload loss. See table 2.

**Table 2 Relative performance of selected hardening techniques in a typical wide bodied aircraft**

| <b>Technique</b>               | <b>Mass Penalty Estimate tonne</b><br>(a) | <b>Relative Increase in Fuselage Resistance</b><br>(b) | <b>Performance index</b><br>(b) / (a) |
|--------------------------------|---|--|---------------------------------------|
| <b>Unprotected</b>             | n/a                                       | 1.0  | n/a                                   |
| <b>Retrofit</b>                |   |  |                                       |
| Hardened containers            | .90                                       | 1.7  | 1.9                                   |
| Hardened liners                | .46                                       | 4.2  | 9.1                                   |
| Enforced stand-off (air)       | Lost payload                              | 1.8  | ***                                   |
| Enforced stand-off ( foam)     | .39                                       | 2.3  | 5.9                                   |
| <b>New build</b>               |   |  |                                       |
| Increased skin thickness (4mm) | .57                                       | 3.0  | 5.3                                   |
| Increased frame strength       | .26                                       | variable   | variable                              |
| Anti-tear straps               | .32                                       | variable   | variable                              |
| Bonded stringers               | .031                                      | 2.3  | 74                                    |
| Local skin reinforcement       | .045                                      | 2.3  | 51                                    |

It is very clear that, for up to a doubling in resistance, the use of bonded stringers or local reinforcement of the skin under stringers is very effective provided that longitudinal skin joints are also protected. Beyond this charge size or for existing aircraft, the use of foam stand-off or hardened liners seem the best options being applicable to narrow and wide bodied aircraft respectively. Combinations of hardening schemes that might be attractive include the use of a liner material and foam stand-off for the critical case of narrow bodied aircraft that cannot take containers.

Hardened liners or the use of enforced stand-off and hardened containers may be the only realistic forms of defence applicable to in-service aircraft. The other hardening versions being applicable to new builds yet to be designed and certificated.

## **5 FINDINGS AND CONCLUSIONS**

### **5.1 The threat**

5.1.1 Acts of sabotage or terrorism pose a significant threat to civil airliners. These threats have taken the form of on-board explosive devices and attack from the ground. In those events in which catastrophic loss of the aircraft has occurred the major proportion occurred by failure of the fuselage.

### **5.2 Unit Load Devices & deployment of explosives**

5.2.1 ULDs or containers are supplied to a wide range of designs against a single specification. The ULD specification could be extended to include an explosive loading requirement.

5.2.2 Approximately 75% of the aircraft operating within European airspace cannot employ cargo containers. A solution based purely upon the use of hardened containers would thus not be comprehensive.

### **5.3 Structural issues**

5.3.1 A critical level of impulsive or explosive loading is required to produce deformation or failure and a physically based model for the onset of either failure or deformation has been derived and validated. The delivered impulse depends on the charge size and stand-off, whilst the Critical Impulse is determined by the fuselage construction.

5.3.2 Once breached by explosive forces the internal pressurisation of an aircraft at altitude, coupled with transient forces from the explosive, will drive a relatively small tear until it is of catastrophic length under the pressure alone. A similar tear in an unpressurised fuselage will stop growing once the explosive forces are spent.

### **5.4 Structural vulnerability and aircraft hardening**

5.4.1 The rise in pressure from an exploding device occurs so quickly that deliberate venting of the fuselage, when attacked, is impractical. For a charge of relatively small mass, placed randomly in baggage, critical loading times will range from



10 $\mu$ s for a device close to the skin, delivering forces through air, to 10ms for a device producing over-pressurisation of the structure from deep within baggage. Critical damage will occur during the first 1ms, too fast for venting. This is far faster than typical venting times of perhaps 2s.

- 5.4.2 The loading applied to fuselage structure by detonation of explosive devices represents a unique case that is not encompassed by current certification requirements.
- 5.4.3 A vulnerability model has been developed that predicts the probability of aircraft loss. This model correlates reasonably with the known rates of aircraft loss to acts of sabotage. The model can be applied without specific knowledge of the actual charge sizes or locations.
- 5.4.4 The vulnerability model has been sufficiently well validated to allow confidence in its use for the estimation of structural performance, for the estimation of critical charge sizes and as a means of quantifying the efficacy of hardening measures.
- 5.4.5 The vulnerability model has been a valuable tool for assessing the effect of critical structural issues such as stress concentrations in the fuselage skin, the potential value of intervening linings between the device and the skin and the effects of stand-off and baggage disposition.
- 5.4.6 For an aircraft to be hardened, any breaching of the fuselage skin must be prevented or the breaches must be contained at a sub-critical crack size under transient explosive loading. Achieving the latter is extremely difficult and so in practice breaching of the fuselage skin has to be regarded as unacceptable.
- 5.4.7 To withstand a realistic threat in a wide body aircraft, a liner capable of resisting breaching is likely to weigh 5 to 7kg/m<sup>2</sup>. However, this liner may not have to cover the whole of the hold floor and side walls.
- 5.4.8 Provided that a liner is not breached, it is equally important that it should not be accelerated into the fuselage skin, but rather the load should be transferred on to the frames as evenly as possible. Factors that affect deflection of the liner are its mass, the area over which the loads are transferred and the strength of its attachment to the aircraft structure.
- 5.4.9 If baggage is stored loose, then large items such as whole suitcases may be accelerated and cause critical structural damage. This can be prevented by the use of high performance netting as a restraint.
- 5.4.10 Modification to the fuselage structure to avoid stress concentrations has been shown to be highly effective in reducing structural vulnerability. For example, the use of adhesive bonding rather than mechanical fastening, or local thickening around stress concentrations, are very effective. These require only small increases in structural mass but give a large increase in overall ductility and hence resistance to explosive loading.
- 5.4.11 The critical impulse for skin failure is linearly dependent upon skin thickness e.g. doubling the skin thickness in a critical area will double the impulse level needed for breaching of the skin. The local thickening of the fuselage skin in critical areas

such as joints or stringer attachments may also provide an efficacious form of hardening.

- 5.4.12 Improvements in structural design (intrinsic means) could improve resistance to two or three times the charge size survivable by current aircraft. Other (extrinsic) means, such as hardened hold liners, would be needed to provide improvements up to five fold. The effects of combined hardening methods have not been fully researched, but the evidence presently available is that the combination of improved structure and a hardened liner could provide a fuselage with approaching a ten fold increase in resistance in terms of critical charge.

## 5.5 **Systems vulnerability**

- 5.5.1 Conventional mechanical control systems are vulnerable to fragment and blast damage. Carbon fibre control rods are less susceptible than conventional ones.
- 5.5.2 Fly-by-wire systems are virtually invulnerable to fragment damage as a result of having multiple elements, if the individual channels are physically separated. However, vulnerability is increased if the wires are bundled in the same loom. Fibre optic cables have a similar vulnerability.
- 5.5.3 The potential for fuel tank explosions resulting from fragment impacts is generally low. There is a potential for fire if fuel leaks from damaged fuel lines, which are vulnerable in certain positions on some aircraft.
- 5.5.4 Hydraulic systems are generally invulnerable with respect to actuators, as they are generally remote from the cargo hold. Hydraulic system redundancy also makes their vulnerability low. Hydraulic oil leakage can be a potential fire hazard.
- 5.5.5 The electromagnetic pulse, generated from a small IED within an aircraft does not pose a threat to the safety of the aircraft.

## 6 **FUTURE ACTIONS**

The dissemination of this research work presents a dichotomy that requires a balance to be struck between the sensitivity of the subject matter and the need to inform the industry. This Final Overview Report is intended to address the issue by providing sufficient information to initiate informed debate.

The CAA plans to initiate discussions on the findings of this research with the DTLR, UK operators and UK manufacturers in 2001. This will be followed by further dialogue with other authorities within JAA and the FAA.

This work and the outcome of the discussions with the industry will also have a significant bearing on the CAA's response to a forthcoming proposed Standard in ICAO Annex 8 Chapter 11 that will require aircraft designers to consider "additional design features which minimise the risk of catastrophic loss of the aeroplanes in the event of an explosive device".