DOT/FAA/CT-93/18

**FAA Technical Center**
Atlantic City International Airport
N.J. 08405

# Hardened Luggage Container Design Survey



Joseph Gatto

September 1993

Final Report



U.S. Department of Transportation
**Federal Aviation Administration**

## NOTICE

**Technical Report Documentation Page**

| 1. Report No. | 2. Government Accession No. | 3. Recipient's Catalog No. |
|---|---|---|
| DOT/FAA/CT-93/18 | | |

| | |
|---|---|
| 4. Title and Subtitle<br>HARDENED LUGGAGE CONTAINER DESIGN SURVEY | 5. Report Date<br>September 1993<br>6. Performing Organization Code<br>ACA-600 |
| 7. Author(s)<br>Joseph Gatto<br>Howard J. Fleisher (Galaxy Scientific Corporation) | 8. Performing Organization Report No. |
| 9. Performing Organization Name and Address<br>Federal Aviation Administration Technical Center<br>Aviation Security Research and Development Service<br>Atlantic City International Airport, NJ 08405 | 10. Work Unit No. (TRAIS)<br>11. Contract or Grant No.<br>DTFA03-92-C-00035 |
| 12. Sponsoring Agency Name and Address<br>U.S. Department of Transportation<br>Federal Aviation Administration<br>Assistant Administrator for Civil Aviation Security<br>Washington, DC 20590 | 13. Type of Report and Period Covered<br>Final Report<br>14. Sponsoring Agency Code<br>ACS-1 |

15. Supplementary Notes

Survey supported and report prepared by: Galaxy Scientific Corporation
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Pleasantville, NJ 08232-5562

16. Abstract

The Federal Aviation Administration (FAA) performed a detailed survey of blast containment and blast management hardened luggage container research. The survey addressed such issues as container construction methodologies employed, the status of the respective efforts, including prototype manufacturing and testing, and identification of relevant issues and concerns from a standardization/certification perspective. Companies contacted for this survey included hardened luggage container designers, current container manufacturers, and developers of advanced and/or composite materials that have application to hardened luggage containers.

| 17. Key Words | 18. Distribution Statement |
|---|---|
| Aircraft Hardening<br>Hardened Luggage Containers<br>Container Hardening<br>Blast Containment<br>Blast Management<br>Blast Mitigation | This document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161. |

| 19. Security Classif. (of this report) | 20. Security Classif. (of this page) | 21. No. of Pages | 22. Price |
|---|---|---|---|
| Unclassified | Unclassified | 41 | |

**Form DOT F1700.7** (8-72) Reproduction of completed page authorized

# PREFACE

This report was prepared by Galaxy Scientific Corporation under Contract No. DTFA03-92-C-00035 with the Federal Aviation Administration Technical Center (FAATC). The Program Manager at Galaxy Scientific Corporation was Mr. William Hassler, Jr. Mr. Howard Fleisher was the task leader, and Mr. Amit Patel provided support on the survey effort. Mr. Joseph Gatto of the FAATC was the Technical Task Manager during this project.

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| | |
|---|---|
| ADINA | Automatic Dynamic Incremental Nonlinear Analysis |
| ALCOA | Aluminum Company of America |
| AWACS | Airborne Warning and Control System |
| CAPI | Century Aero Products International |
| CFD | Computational Fluid Dynamics |
| CRT | California Research and Technology |
| EDS | Explosives Detection Systems |
| FAA | Federal Aviation Administration |
| FAATC | Federal Aviation Administration Technical Center |
| FRP | Fabric Reinforced Plastic |
| FY | Government Fiscal Year |
| GLCC | Great Lakes Composite Consortium |
| HDPE | High Density Polyethylene |
| HSAL | High Strength Aluminum |
| HSFG | High Strength Fiberglass |
| HULD | Hardened Unit Load Device |
| IATA | International Air Transport Association |
| MBB | Messerschmitt-Bolkow-Blohm |
| PL | Public Law |
| QSP | Quasi-Static Pressure |
| R,E,&D | Research, Engineering, and Development |
| SAE | Society of Automotive Engineers |
| SAGE | SAIC Adaptive Grid Eulerian |
| SAIC | Science Applications International Corporation |
| SLC | Structural Laminates Company |
| TNA | Thermal Neutron Activation |
| ULD | Unit Load Device |
| UTA | Union de Transports Aeriens |
| WISL | Woven Integrated Laminate Structure |

# EXECUTIVE SUMMARY

The Federal Aviation Administration (FAA) Aircraft Hardening Program has been developing a hardened luggage container since 1989. This container is designed to suppress the detonation products of explosive charge weights not currently detectable by Explosives Detection Systems (EDS), and includes factors such as weight, cost, and operability. To date, three container prototypes have been built and successfully tested, and two more prototypes are under development.

The Aircraft Hardening Program is working with several private companies conducting independent hardened luggage container research. Many of these blast containment and blast management techniques differ from those employed by the FAA, and may prove to be equally effective in enhancing aviation safety.

The FAA performed a detailed survey of blast containment and blast management hardened luggage container research. The survey addressed such issues as container construction methodologies employed, the status of the respective efforts, including prototype manufacturing and testing, and identification of relevant issues and concerns from a standardization/certification perspective. Companies contacted for this survey included hardened luggage container designers, current container manufacturers, and developers of advanced and/or composite materials that have application to hardened luggage containers.

## 1. INTRODUCTION.

December 21, 1988 marks the worst security-related disaster in U.S. civil aviation history. At approximately 7:03 that evening, Pan American Airways Flight 103, enroute from London to New York, was destroyed over Lockerbie, Scotland as a result of the detonation of an improvised explosive device onboard the aircraft. All 259 persons aboard the flight, as well as 11 residents of the town of Lockerbie, perished.

The bombing of Pan Am 103 was not an isolated incident. Within the past seven years, four other wide-body aircraft were lost to suspected terrorist bombings. On June 23, 1985, an Air India aircraft crashed into the sea as a result of an explosion in the forward cargo hold. All 329 persons onboard were killed. On November 29, 1987, Korean Air Flight 858 was destroyed in flight from an explosive device located in an overhead bin of the aircraft. All 115 persons on board were killed. On September 19, 1989, a Union de Transports Aeriens (UTA) flight was destroyed over the Sahara Desert from an explosion in the forward cargo hold of the aircraft. All 171 persons aboard were killed. Finally, on November 27, 1989, an Avianca flight was brought down by an explosive device located in the cabin area of the aircraft. All 107 persons aboard were killed. In all, almost 1000 people have perished in these acts of sabotage.

On August 4, 1989, Executive Order 12686 established the President's Commission on Aviation Security and Terrorism. The Commission began its work in November 1989 with the first in a series of public hearings. Through its six month investigation, the Commission reviewed security measures both in the U.S. and Europe. Government officials, security specialists, and airport and airline representatives were interviewed. Officials in the intelligence and counterterrorism communities were also consulted. In May 1990, after five public hearings and over two hundred fifty investigative interviews, the Commission presented its report to the President of the United States.

In this report, the Commission recommended that the Federal Aviation Administration (FAA) expand its security Research, Engineering, and Development (R,E,&D) program to accomplish the following:

a. The FAA should undertake a vigorous effort to marshal the necessary expertise to develop and test effective explosive detection systems.

b. The FAA should establish an expert panel of persons from the national laboratories, other government agencies, academia, and industry to oversee the design and development of this high priority initiative.

c. The FAA should undertake an intensive program of research and experimentation with the structure of aircraft to determine the kind and minimum weight of explosives which must be detected by any technology.

d. The FAA should conduct research to develop the means of minimizing airframe damage that may be caused by small amounts of explosives.

e. The FAA should avoid the undesirable reliance of any single commercial source of Thermal Neutron Activation (TNA) equipment by making every possible effort to encourage the development of additional sources.

f. The FAA must think ahead and anticipate how to counter the next generation of terrorist weapons before they are used to kill innocent people.

In November 1990, after review of the Presidential Commission's report, Congress enacted the Aviation Security Improvement Act of 1990, Public Law (PL) 101-604. PL 101-604 established an accelerated research, development, and implementation program designed to focus upon technological and procedural improvements for counteracting terrorist threats to civil aviation. PL 101-604 also required an intensive review of threats to civil aviation, particularly:

a. Explosive materials presenting the most significant threat,

b. Explosive configurations, explosive types, and minimum explosive weights which would cause catastrophic damage,

c. Explosive configurations, explosive types, and minimum explosive weights detected reliably by existing or near-term explosive detection technology,

d. Damage minimization methods against explosive materials which cannot be detected reliably by existing or near-term explosive detection technology,

e. Passenger screening, carry-on and checked baggage screening, and mail and cargo screening, and

f. Future technologies usable by terrorists and counteracting methodologies.

PL 101-604 also required the establishment of a scientific advisory panel as a subcommittee of the Research, Engineering, and Development Advisory Committee. This panel's purpose is to review, advise, and comment on the programs established above. This panel consists of individuals with scientific and technical expertise in developing and testing explosives detection systems, aircraft structures, explosive weapons effects, and other related disciplines.

Using the guidance provided by the Presidential Commission Report and the requirements mandated by PL 101-604, the FAA has structured a research and development program designed to meet the challenges presented by terrorism. As a first line of defense, various technologies are being investigated to deny the terrorist access to civil aviation facilities, including airport terminals, control centers, working ramp areas, and the aircraft.

In the event that a terrorist penetrates this first line of defense, a system of explosive detection devices and procedures are being developed which prevent further intrusion into the aviation facility. This is intended to deny final placement of the explosive either in the terminal area or onboard an aircraft.

Finally, if a device still evades detection, research efforts are underway to harden the aircraft structure and systems to the maximum extent feasible. Protecting the aircraft structure and flight critical subsystems through blast mitigation and damage management will increase the probability of passenger survival.

## 1.1 THE AIRCRAFT HARDENING PROGRAM.

The Aircraft Hardening program was initiated in 1990. The primary goals of the program are to identify the minimum explosive charge weight which will result in aircraft loss and to conduct research aimed at increasing commercial aircraft survivability in the event of an inflight explosion. To achieve these goals, the FAA has embarked on an intensive testing program coupled with computer modeling of onboard explosive detonations and their effects. The program has been divided into three separate project areas: blast characterization, container hardening, and aircraft vulnerability.

The blast characterization project is concerned with identifying the explosive effects parameters within the aircraft environment. For example, if the explosive device is assumed to be placed inside a piece of luggage in the cargo hold of the aircraft, then the initial shock wave may be attenuated by the contents of the luggage, air gaps, the luggage wall material, and the luggage container (if the aircraft uses them). Similarly, the quasi-static pressure (QSP) will be affected by the flammability of the contents of the luggage and the materials of the luggage itself, as well as the amount and availability of oxygen for the combustion phase of the explosion.

The container hardening project represents the near-term solution to the aircraft hardening problem. The goal of this project is to prove the feasibility of producing blast resistant aircraft luggage containers. Hardened containers built within the current International Air Transport Association (IATA) specifications can be introduced into the current fleet of aircraft immediately, thereby offering substantial protection to the flying public. The end-users of hardened containers are the airline industry, therefore, factors such as container tare weight, cost, durability, and other real world application considerations must be continually addressed to insure container feasibility.

The aircraft vulnerability project addresses the long-term solution to the aircraft hardening problem. The goal of this project is to identify the minimum explosive weight that will cause aircraft loss. Subsystems such as structures, flight controls, and aeromechanics are being evaluated to determine the vulnerability of the current fleet of aircraft. After the vulnerability analysis is complete, techniques for decreasing commercial aircraft vulnerability will be evaluated. The end-users of this information will be aircraft manufacturers. Incorporating the resulting data into future aircraft designs will produce aircraft better able to withstand an explosive detonation.

## 1.2 CONTAINER HARDENING PROJECT.

Modifying commercial aircraft to resist the detonation of undetectable quantities of explosives requires significant lead time, and, although technically possible, may prove to be economically unfeasible. As a near-term solution to this problem, the Aircraft Hardening Program is conducting an intensive research effort aimed at mitigating an explosion through hardening of the luggage containers used by commercial airlines in wide-body transport aircraft. The benefits of such a container, or Unit Load Device (ULD) are many. Development and incorporation of hardened containers may have a much smaller economic impact on commercial aircraft operations than would modifications to the aircraft fuselage itself. These new containers would provide immediate protection against explosives located in checked baggage. Developing a hardened luggage container is achievable with today's technology, and only requires the minimum two to three years development time for most aircraft systems.

The FAA effort was broken down into five distinct tasks. Determining the blast capacity of the current fleet of luggage containers was the first task. This was done both analytically, using state of the art computer programs, and experimentally, by performing explosive testing on currently employed luggage containers. The data from this effort not only justified the continuation of the project, but were used to improve the analytical models previously employed. The second task in the project involved a cursory analytical investigation of possible hardened luggage container designs. The most promising of these methods was then selected for proof-of-concept prototype development, which formed the third task of the project. This task is scheduled for completion at the end of Fiscal Year (FY)-93.

The remaining two tasks were initiated in FY-93, and are ongoing. The fourth project task involves an independent analysis and evaluation of composite/advanced materials that could be employed in luggage container designs. The assessment will consider factors such as practical and acceptable weight, manufacturing processes, operability, repair and maintenance capability, and their associated cost. Those materials that are discussed in sections three and five of this report, or which have been used in prototype design, will be the primary candidates for study under this activity.

The final task requires the development of design specifications for hardened luggage containers. Once the feasibility of such a design was demonstrated under the proof-of-concept prototype phase, development of the design specifications was started. The structural response of the containers tested thus far indicates that a quasi-static loading, with some dynamic effects influencing the response early in time, predominates. Thus, one possibility would be to have a static pressure loading specification. However, this specification alone will likely be insufficient to properly account for all the potential hardened luggage container designs.

The results of this effort will be applied toward the development of certification standards. The IATA, a Society of Automotive Engineers (SAE) subcommittee on luggage container specifications, will participate in the development of the standards and will monitor their implementation. Once the new standards are adopted, the FAA will be in a position to proceed with any requirements pertaining to container certification.

## 1.3 SCOPE OF THE EFFORT.

The FAA performed a survey of private industry's efforts involving hardened luggage container research. The survey provided information on the different methodologies employed by hardened container designers, and the status of the respective efforts, including prototype manufacturing and testing.

The companies surveyed included hardened luggage container designers, current container manufacturers, and manufacturers and developers of advanced materials. This report contains the results of that survey. The information contained herein is solely for the purposes of technology transfer; assessments of the various designs are not included. The FAA-funded container hardening effort, as described in section 1.2, is summarized in section two, including the objectives, results to date, and anticipated outcomes. In section three, the privately developed container designs are presented and discussed. IATA-type certification and standardization issues raised by hardened luggage container designers and current container manufacturers are presented in section four. Section five describes the different materials that have either been proposed for use or are presently being used by designers in hardened container prototypes. Finally, a summary of the survey results and recommendations pertaining to the future direction of the container hardening project are presented in section six. A brief description of the various computer codes used by hardened luggage container designers can be found in the glossary at the end of this report.

## 2. FAA-SPONSORED HARDENED LUGGAGE CONTAINER.

The initial objective of the FAA-sponsored container hardening effort was to prove the feasibility of producing blast resistant aircraft luggage containers. The hardened container ideally was to have the same weight, cost, operability, and maintainability as those containers which are currently used by the airlines. Increases in manufacturing cost were to be leveraged against an extended container lifetime. Following this proof-of-concept development, decisions for a detailed design were be made.

The project first required a determination of the blast resistance of the current fleet of containers, or ULDs. Once this resistance was established, design concepts that could improve container blast resistance were analytically investigated, using a Computational Fluid Dynamics (CFD) computer code to predict loading, and a finite element code to determine structural response. The most promising hardening technique was then adopted by the FAA to manufacture a new, hardened luggage container. Once the specific concept was found to be technically feasible, prototype manufacturing and testing were initiated.

Currently, the most common type of ULD used in commercial wide-body transports is the LD-3 container, shown in figure 2-1. LD-3s are designed and built for minimal weight in order to optimize carrier revenue. Their weights range from as light as 50 pounds for limited-use cardboard containers, to as heavy as 400 pounds for fiberglass containers, with an average LD-3 tare weight of about 225 pounds. These designs, while satisfying the requirements of the IATA, are wholly inadequate to contain explosions from charge weights that are currently detectable from both a technological and economic perspective.

Hardened containers built within the current IATA specifications for loading can be introduced into the current fleet of aircraft immediately upon development, thereby offering substantial protection to today's flying public. Since current luggage containers are replaced on an average of every two to five years, introduction of hardened containers into the market could be

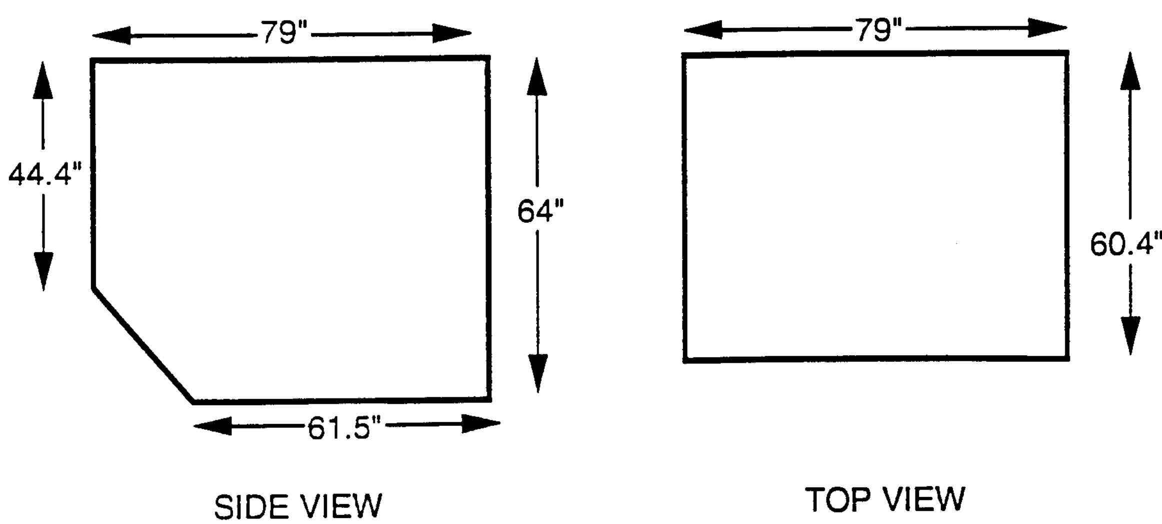


FIGURE 2-1 LD-3 UNIT LOAD DEVICE

accomplished through attrition over a period of time. The end-users of hardened containers are the airline industry, and therefore factors such as container weight, cost, durability, operability, and other real-world application considerations must be addressed continually to ensure container feasibility.

## 2.1 BLAST RESISTANCE OF THE CURRENT CONTAINER FLEET.

The ULD type which was studied in the container hardening project was of the LD-3 classification. This selection was made based upon the LD-3's prevalence as a container for luggage and cargo in commercial aircraft operations. Aluminum and fiberglass LD-3s are used almost exclusively by U.S. carriers on international flights involving Boeing 747, McDonnell Douglas DC-10, and Lockheed L-1011 aircraft. A typical arrangement in a wide-body aircraft cargo bay is shown in figure 2.1-1.

Discussions with manufacturers of ULDs indicated that the existing fleet is characterized by a variety of materials and fabrication details. This is due to the competitive response of manufacturers to the airlines' demand for a light and durable product, and their different requirements from order to order. Because of this diversity, the blast resistance of the current fleet had to be described by a range of explosive weights. The FAA previously had conducted a series of tests with aluminum LD-3s at very moderate charge weights. In these events, the explosive was placed within representative luggage packed inside the container. In each case, the container failed catastrophically. This testing formed the basis for the analytical and experimental study performed under this task.

The analytical procedure used for evaluating the LD-3 blast resistance consisted of two steps. First, the blast loading was estimated by computing the initially reflected shock wave and subsequent QSP. This was done with a combination of computational fluid dynamics and method of images calculations. JAYCOR performed this analysis with their EITACC and BWAVES

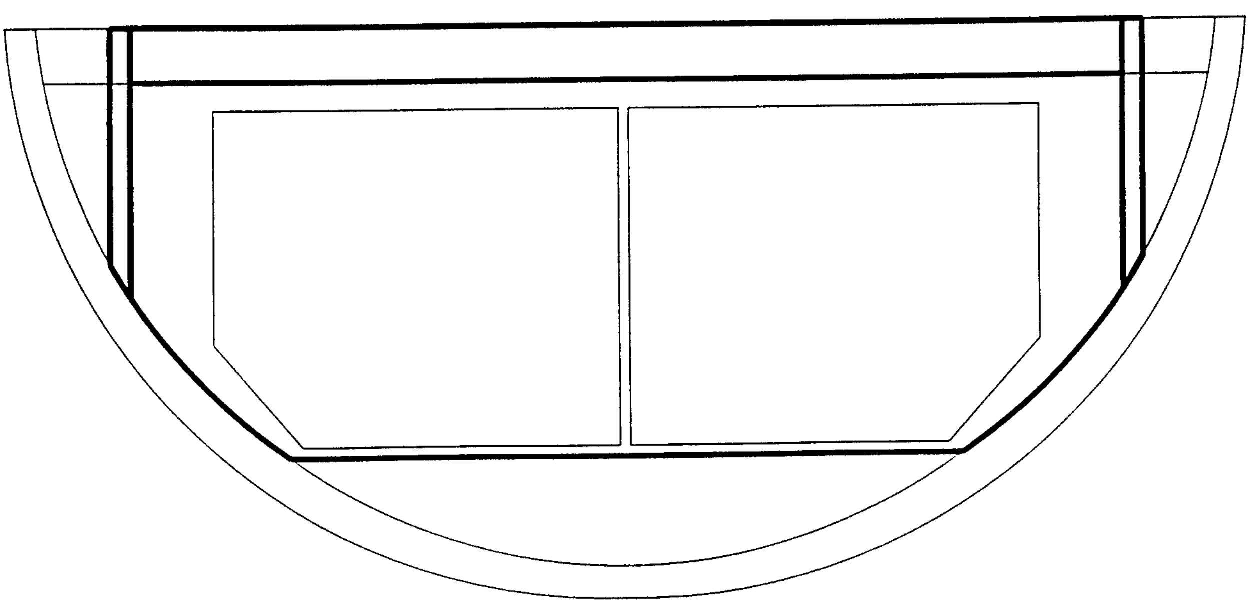

FIGURE 2.1-1 TYPICAL WIDE-BODY CARGO BAY ARRANGEMENT

programs, respectively. Next, the dynamic response of the container was approximated using the static deflection characteristics of the closest LD-3 panel in one-way membrane action. These characteristics were obtained via finite element analysis using the Automated Dynamic Incremental Nonlinear Analysis (ADINA) code. One and two-dimensional thin plates were modeled with iso-parametric beam and plate elements, respectively. The stress-strain relationship was described with an elastic, perfectly plastic model. The dynamic response of the container then was determined using an equivalent single-degree-of-freedom representation of the system. The equation of motion was calculated by applying transformation factors to the physical parameters to arrive at equivalent mass, resistance, and load terms that yielded the same deflection at the mid span of the plate. The resulting second order differential equation was then solved numerically using the Newmark-Beta method.

The analytical results were used to establish a test plan for the LD-3 containers. The testing was initiated at a relatively low charge weight, which was increased gradually until failure took place. The location of the explosive for all tests was at a distance of one foot normal to the center of the outboard sloping panel. The explosive was placed in a representative piece of luggage surrounded by other luggage inside the container. The region between the suitcase containing the explosive and the sloping panel was left vacant. This arrangement was chosen to provide a simple configuration to reduce uncertainty for loading predictions and quantitative measurements. Pressure and strain measurements were taken for each test, along with high speed video footage for post-test analysis of the explosive event. Figure 2.1-2 illustrates the test configuration, and table 2.1-1 presents the test matrix. The actual charge weights used in the tests cannot be presented in this unclassified report. Each letter in the charge weight column of the table represents a different explosive weight, with A the smallest size and F the largest.

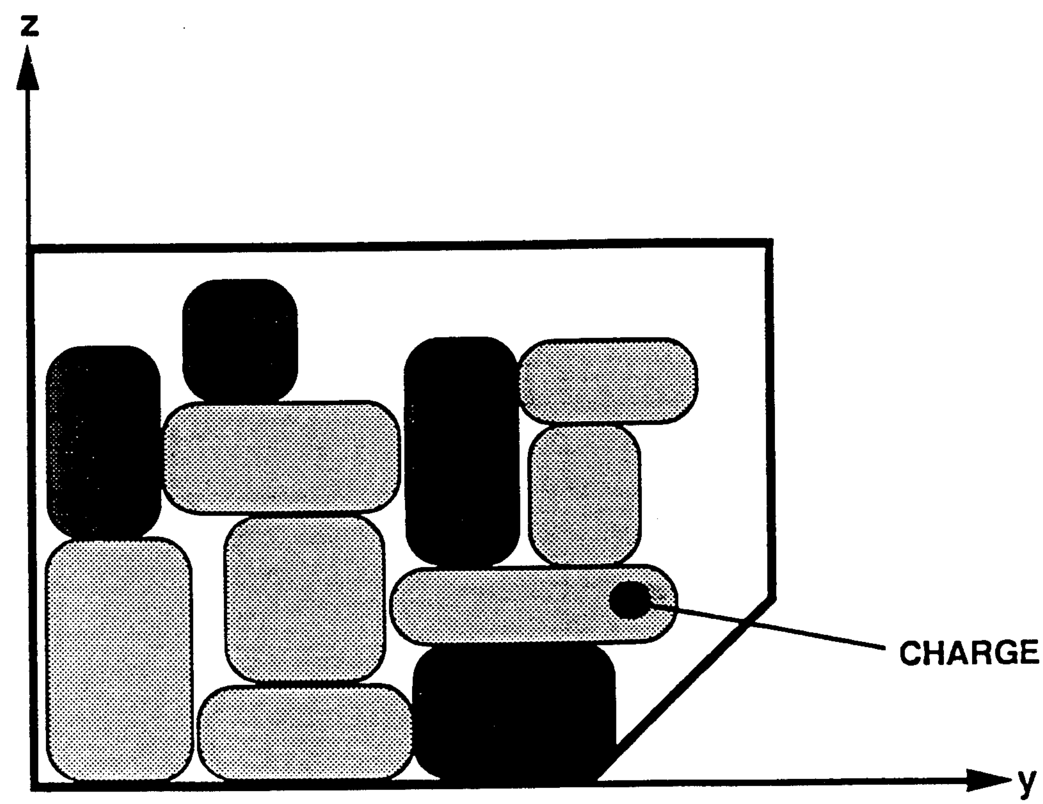


FIGURE 2.1-2 LD-3 TEST CONFIGURATION

TABLE 2.1-1 TEST MATRIX FOR ULD BLAST RESISTANCE

| Test | Container Type | Charge Weight | Failure? |
|---|---|---|---|
| 1 | Fiberglass | B | No |
| 2 | " | B | No |
| 3 | " | C | No |
| 4 | " | D | No |
| 5 | " | E | No |
| 6 | " | F | Initiated |
| 7 | Aluminum | A | No |
| 8 | " | C | No |
| 9 | " | D | Yes |

The testing revealed that the blast loading experienced by the LD-3 structure was dependent upon the strength of the luggage article that held the explosive charge, the location of the explosive in the luggage container, and the arrangement of the luggage surrounding the test article. In explosive tests on luggage prior to the LD-3 testing, it was observed that a heavy duty suitcase could suppress the blast loading of a small charge sufficiently to leave a negligible effect on the LD-3. Since blast loading is inversely proportional to the distance from the source of the explosion, the surfaces closer to the charge location (on the outboard side of the container in these tests) would be expected to experience higher loads. The data reaffirmed this. However, differences in the pressures measured on the outboard and inboard sides of the container could not be attributed to distance alone. Therefore, the magnitude of the blast loading on the LD-3 was also a function of the amount of protective luggage between the explosive and the LD-3 wall.

The tests were performed on both an aluminum and fiberglass LD-3 representative of those in service at the time. The results indicated that the containers had a minimal blast resistance capacity. The amounts of plastic explosive used were small and well below the detection capabilities of current devices. The experimental blast capacities were as much as 60 percent higher than those estimated analytically before the tests. This was attributed to the blast attenuating properties of the luggage and the conservative response model adopted in the computer analysis. Based on the new data, the analytical models were adjusted appropriately. The results of these tests served to justify the continuation of the container hardening effort.

## 2.2 INVESTIGATION OF POTENTIAL CONTAINER HARDENING TECHNIQUES.

Eight different methods to harden luggage containers were studied during this phase of the container hardening project. The primary criteria upon which the concepts were evaluated was tare weight versus charge weight contained. A computer model of an LD-3 container using the respective hardening technique being studied was first developed. The hardened LD-3 was strengthened to withstand a representative charge weight, up to a maximum value (i.e. a weight just under that which is assumed to be detectable by the technology of the near future). All calculations assumed the container was filled with luggage to 70 percent of its volume. Unless otherwise specified, all calculations were performed with the minimum IATA requirements for venting. The results summarized in the following section represent over 1000 iterative calculations.

The first method of enhancing the blast capacity of a container was to employ thicker structural members. This included thicker panels as well as a more substantial frame. Calculations were performed for aluminum, fiberglass, and polycarbonate LD-3s. Only marginal increases in blast capacity were noted by modifying existing containers in this manner, and the container tare weight was over six times that of an "average" LD-3, or approximately 1400 pounds. Furthermore, in aluminum containers, if the panel thicknesses become excessive, new manufacturing techniques would have to be employed.

The second technique studied considered controlled venting of the blast pressure in addition to the thickening of structural members. The venting served to relieve the blast loading in two ways. First, the reflected shocks were reduced since they were partially vented out of the container. Second, the QSP was minimized as the explosive gas escaped through the vent. For this hardening method, a 25 square foot vent area was assumed. The calculations showed that the container weights generally ranged from just 10 to 20 percent lower than those for the previous countermeasure. The conclusion was that the practical range of blast capacity achievable through thickening and venting existing LD-3s was limited.

Another hardening method examined provided an air gap between the luggage and thickened container walls. The air gap provided a larger standoff distance from the explosive and also allowed for a reduction in QSP build up due to the increase in free air volume within the container. The air gap could be achieved functionally by suspending the luggage with cargo netting within the container volume. The major drawback with this design was that in addition to the increased tare weight penalty incurred due to the thickened panels, the available volume for luggage was reduced because of the air gap. The calculations indicated that this method, like the two previous ones involving structural thickening, showed limited promise.

Instead of increasing the thickness of the container components, a fourth potential container hardening technique involved the addition of stiffeners to the LD-3 frame, thereby reducing the effective plate span lengths and increasing the load carrying capacity of the container. Existing plate thicknesses were assumed and kept constant for all calculations. Out of the three materials studied, this technique showed the greatest promise for fiberglass containers. However, the increase in tare weight, even for the fiberglass container, was excessive. The results for the first four hardening methods are shown graphically in figure 2.2-1.

The application of a honeycomb sandwich container construction was the fifth method investigated. This technique, which is employed commonly in aerospace construction, provided panels of high stiffness and light weight. Typical properties for an aluminum faced, aluminum honeycomb core system were selected. It was assumed also that plate failure would occur upon

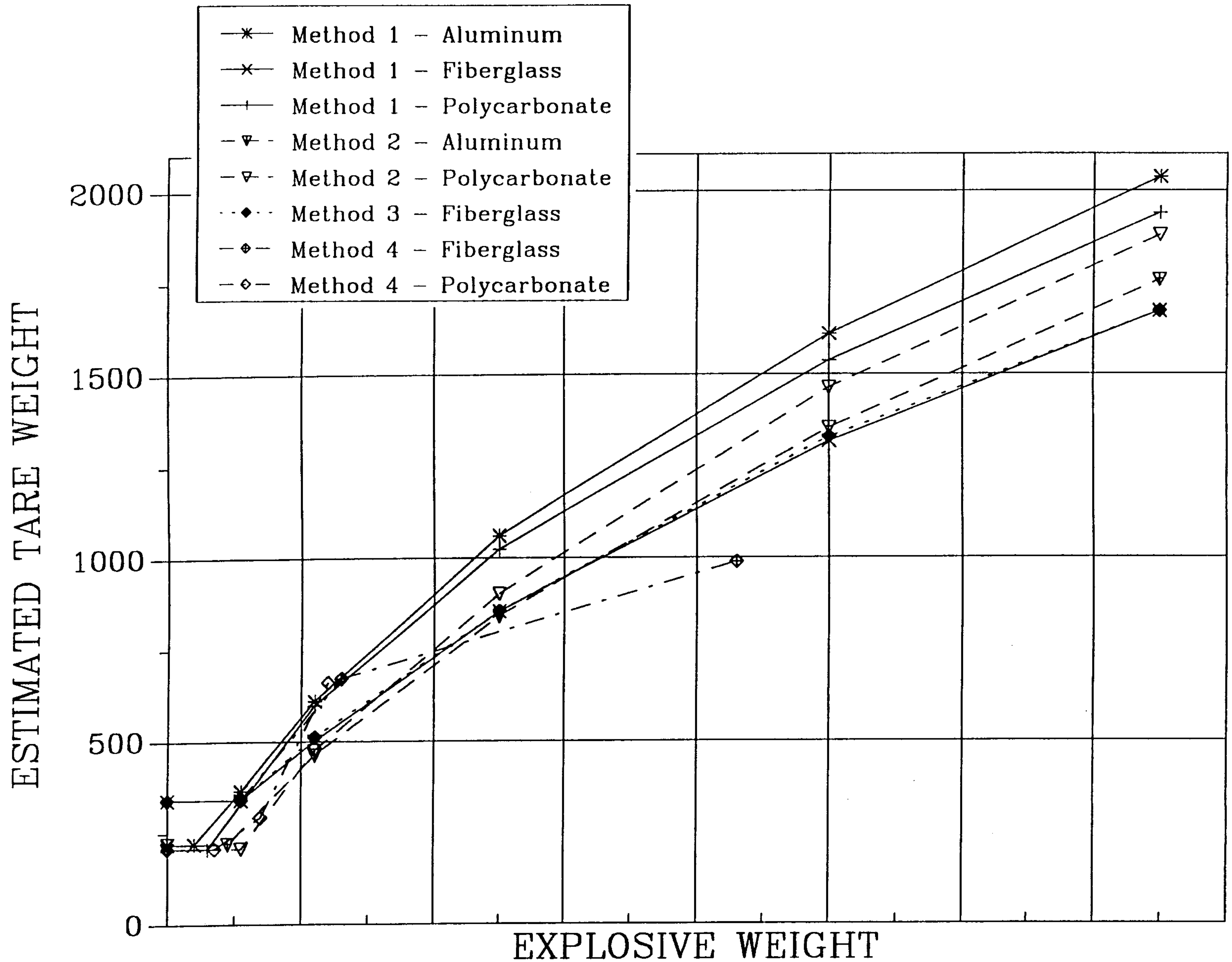


**FIGURE 2.2-1 SUMMARY OF HARDENING COUNTERMEASURES 1 - 4**

collapse of the honeycomb core. The results showed that this method was not as attractive for enhancing the blast capacity of LD-3s as the other measures previously considered.

The use of high-strength or highly ductile materials was the sixth method studied. Numerous materials ranging from carbon-graphite composites to low modulus high density polyethylenes were considered, but many of these were ruled out due to their excessive material cost or the difficult manufacturing techniques which would be required to develop such a container. Of those selected, high strength aluminum (HSAL), high strength fiberglass (HSFG), and high density polyethylene (HDPE) were chosen for detailed calculations. These techniques provided the best method for increasing the blast capacity of those studied thus far, as the increase in tare weight was reduced to just over four times the average, or about 1000 pounds. However, this option would require new manufacturing methods and could not be applied readily to upgrading existing containers.

Two applications of KEVLAR®[1] were investigated as part of the seventh container hardening method. KEVLAR is a material which exhibits a very high strength to weight ratio and offers high impact strength, chemical resistance, and relatively low flammability and off-gas emissions. It has been used in numerous applications ranging from soft body armor to military shelters. The first technique studied consisted of KEVLAR fabric sheets held in position by an aluminum frame. The second option was to construct a KEVLAR reinforced epoxy laminate for a unit body structure. This latter method produced the most economical results of any of those investigated. Implementation would allow for containment of relatively large explosive quantities at reasonable container tare weights. If KEVLAR containers are to be manufactured, special molds and fabrication methods will have to be developed. In addition to offering good resistance against blast pressure loading, a KEVLAR container would offer superior protection against fragment penetration, as exhibited in its application to personnel body armor.

The eighth and final technique considered for hardened luggage containers was the addition of a crushable foam liner. The method was based on the concept that as the foam liner crushes, it absorbs energy that would otherwise be directed against the container walls. Additionally, if venting were present, the load being applied to the container would be mitigated by the time the liner had fully crushed. A venting area of 25 square feet was assumed for the calculations, and a low density polyester urethane foam was selected. The thickness of the foam layer was varied from 4 to 12 inches. The results indicated that while a crushable foam liner may offer a limited increase in capacity at nearly comparable tare weights, there is a significant reduction in useable volume. The results from the last four hardening techniques are illustrated in figure 2.2-2.

Based upon the hardening techniques investigated in this study, the results indicated that an explosion could be mitigated best within a container constructed of either high strength, high ductility, or KEVLAR-like materials previously described. Utilizing this method, the container weight should fall under that of the heaviest containers (approximately 400 pounds) currently employed by the airlines.

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[1] KEVLAR is a registered trademark of the DuPont Company.

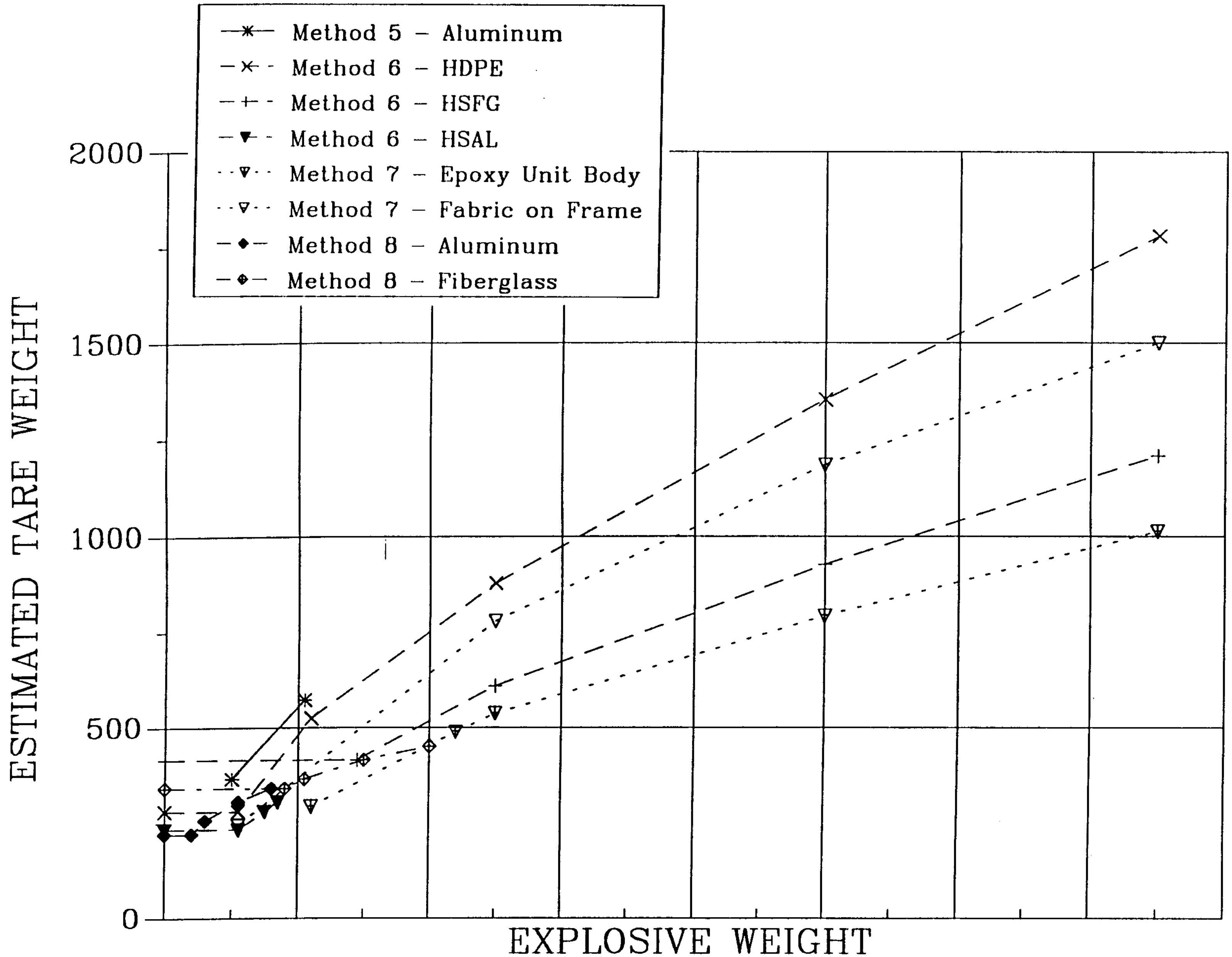


FIGURE 2.2-2 SUMMARY OF HARDENING COUNTERMEASURES 5 - 8

## 2.3 DEVELOPMENT OF A PROOF-OF-CONCEPT HARDENED CONTAINER PROTOTYPE.

The results of the study performed in the previous section led to the development of five hardened container prototypes of the LD-3 classification. These containers were manufactured using the light weight, high strength SPECTRA®[2] composite material, which has properties similar to KEVLAR, but a slightly higher strength to weight ratio. This material was also chosen for its fragment penetration resistance and fire retardant characteristics. The fiber selected for the production of the first two prototypes (designated Hardened Unit Load Device (HULD) 1 and HULD 2) was SPECTRA 900, woven into a style 913, 8 x 8 basket weave. The density of this fiber is 0.97 gm/cm$^3$. A thermosetting, fire retardant resin was used, with a cured resin density of 1.37 gm/cm$^3$. The containers weighed about 664 pounds each, and panel thicknesses varied from 0.27 inches around the sides and top panels, to 0.32 inches for the bottom panel.

An initial full scale test series was performed in January 1992 to demonstrate the feasibility of the hardening concept. In each test the containers were packed with representative luggage and a plastic explosive charge was placed in a piece of baggage, such that the center-of-gravity of the charge was approximately 11 to 12 inches from and perpendicular to the center of the sloping panel. The containers were instrumented with pressure and strain gages, and the events were recorded with both normal and high speed film. Although the preliminary results were good in terms of the blast containment properties of the hardened containers, the container door on the first test article failed before the maximum resistive capacity of the new design was determined. As a consequence, the detail through which the door of the container is restrained was redesigned. In addition, a steel door was constructed for one of the containers to determine the container capacity without regard for the door strength.

After refabrication of the doors, a second test series was performed in April 1992. A total of nine tests were performed in support of this effort (five of the tests were perforation shots performed on one of the LD-3 panels). In the first two tests of the container with the new composite door, the blast was successfully contained. In the third test at a considerably higher charge level, partial venting occurred as the capacity of the container-door connection was exceeded. The test of the container with the steel door, at an even higher charge weight, resulted in shock holing of the container. The charge weights used in this test series ranged from five to three hundred times higher than those withstood by current aluminum containers.

Analysis of the test data showed that the blast pressure loading appeared to be a slowly rising, gradually decaying phenomenon, whose magnitude was less than that for an empty container. This was consistent with related tests of blast propagation properties in luggage. The structural response of the panel to this loading exhibited single-degree-of-freedom, or membrane, behavior, and the blast capacity was determined by the details connecting the container and door to one another.

Using the data obtained from testing the first two containers, a third container (HULD 3) was developed. The fabrication technique chosen was a dry hand lay-up with a resin injection process, although a wet lay-up with a vacuum bag assist, wet lay-up by hand, and pre-pregnated

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[2] SPECTRA is a registered trademark of Allied-Signal, Incorporated.

material were also investigated. This container was constructed with SPECTRA 1000 material, which exhibited an improved strength-to-weight ratio when combined with the fabrication technique selected, as opposed to the SPECTRA 900 used previously. This allowed for a reduction in panel thicknesses to 0.25 inches, and a further weight savings was achieved by employing rounded corners in the design. These changes served to reduce the tare weight of the container to 392 pounds. This third container was transported from its production facility to the test site in a regular luggage container slot on a U.S. commercial airline. The container blast resistance was tested in November 1992, in the same manner as the previous two designs. This container was also found to be capable of withstanding an explosive charge size that may be detectable by Explosives Detection Systems (EDS) of the near future, and was seen to be slightly stronger than the previous two prototypes.

As a final step in the development of the FAA-funded container feasibility design, a detailed design study presently is being conducted for the purpose of constructing two additional LD-3 prototypes (HULD 4 and HULD 5). The development of HULD 4 focuses upon fabrication details and issues, and HULD 5 development addresses container operability concerns. These containers will exhibit an improvement in strength to weight ratio based upon the insight gained in the testing and fabrication processes performed thus far. This will further decrease the container tare weight, making it more attractive to the airline industry, while maintaining the container's blast resistant properties. Each of the two prototypes will be tested and the design subsequently will be reworked in order to optimize blast resistance, weight, and cost.

## 3. HARDENED LUGGAGE CONTAINER DESIGNS.

This section documents several hardened luggage container design concepts under development by private industry. The design techniques consist of both blast containment and blast management concepts, which are detailed below. The information contained herein was obtained via conference proceedings and presentations, phone conversations with the appropriate contacts within the respective companies, written surveys and questionnaires, and personal interviews. Since some of the technology required to successfully develop a hardened luggage container is in the developmental stages, the descriptions in this section are limited to data which is considered non-proprietary by each of the respective companies. Table 3-1 lists the companies contacted for this survey that are either developing a hardened luggage container, or currently manufacture containers. The design type column entry identifies the container design concept as a blast containment design (containment), a blast management design (management), or as a non-hardened design (standard). In cases where such information does not apply or is not available, the N/A nomenclature has been adopted.

TABLE 3-1 LUGGAGE CONTAINER DESIGNERS

| COMPANY | LOCATION | DESIGN TYPE |
|---|---|---|
| Air Cargo Equipment Corporation | Rancho Dominguez, CA | Standard |
| A.R.A.P. Grp., CRT Division, Titan Corp. | Princeton, NJ | Management |
| Century Aero Products International | Compton, CA | Containment |
| DuPont Company | Wilmington, DE | N/A |
| FMC Corporation | Santa Clara, CA | N/A |
| Grumman Corporation | Bethpage, NY | Containment |
| JAYCOR | Vicksburg, MS | Containment |
| MBB Deutsche Aerospace | Germany | Management |
| Nordisk Aviation | Los Angeles, CA | Standard |
| Northrop Corporation | Hawthorne, CA | N/A |
| Omega Engineering | Fort Worth, TX | Management |
| Royal Ordnance | England | Management |
| SATCO, Incorporated | El Segundo, CA | Standard |
| Science Applications International Corp. | San Diego, CA | Containment |
| SRI International | Menlo Park, CA | Management |
| Westinghouse Electric Company | Sunnyvale, CA | N/A |

## 3.1 BLAST CONTAINMENT CONCEPTS.

The following details those designs that have been classified as blast containment concepts. A blast containment design completely suppresses the effects of the explosion within the container. The container is considered an independent element within the cargo bay environment, and sufficient venting is allowed only to meet the minimum IATA venting requirements.

### 3.1.1 Honeycomb Aluminum Design.

Science Applications International Corporation (SAIC) is investigating a honeycomb aluminum design concept. The design consists of three layers of material, as shown in figure 3.1-1. The purpose of the inner layer is to provide good shock absorption properties, and a 5052 aluminum Hexcel honeycomb material was selected. The honeycomb construction reduces the high-peak transient spikes resulting from a bare charge explosion. The second layer of the container provides a high strength shell. A SPECTRA 900 fiber was chosen for this layer. This material was selected over other composites because of its superior strength to weight ratio. The outer layer of the container is composed of a basic aluminum alloy. This allows for a more controlled failure of the container if the SPECTRA layer fails. Furthermore, this layer protects the inner surface from damage that could be incurred during normal airline operations. The design also incorporates an independent panel concept, where a single panel could be removed and replaced if damaged. These would be fastened to the frame with screws or other attachments.

This design concept was verified using a one-dimensional hydrocode model via the SAIC Adaptive Grid Eulerian (SAGE) code. The preliminary study indicated that while the design did well in eliminating the shock loads, the quasi-static load generated by the combustion of the

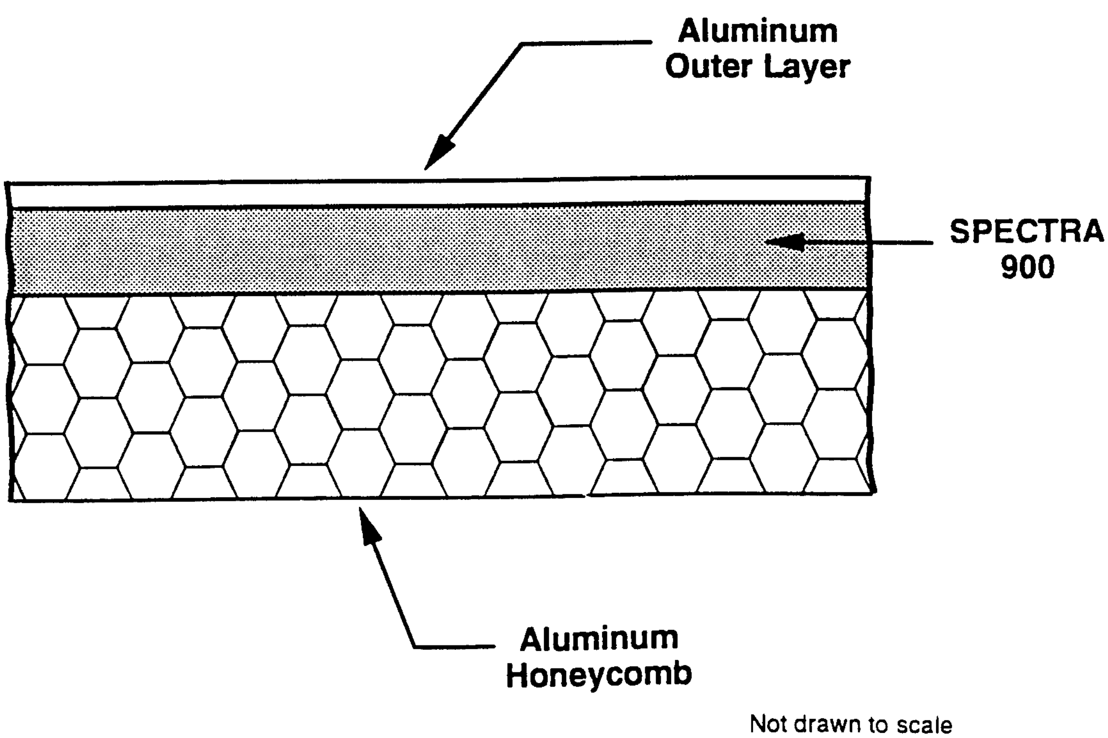


FIGURE 3.1-1 HONEYCOMB ALUMINUM PANEL

baggage contents was more troublesome, and could exceed the load due to the shocks. Some options considered in alleviating the QSP were pre-flight evacuation of the container, replacement of the air (i.e. oxygen) in the container with nitrogen, or providing an active fire suppression system within the container. Each of these potential solutions has its own unique set of operational issues.

The SAIC effort has not advanced beyond this stage due to funding limitations. Ideally, the next step would be to perform three-dimensional computational analysis. SAIC has proposed to use two simulation models, INBLAST for load generation and DYNA3D to measure container response. This would be followed with scaled testing, and, finally, full scale tests of the design for verification. SAIC estimates that with $100,000 in some combination of funds, two prototypes could be built within six to nine months.

3.1.2 Integrally Hardened Luggage Container.

Grumman Corporation is investigating an integrally hardened luggage container which incorporates three essential principles: energy (shock) absorption, controlled pressure reduction, and fragment containment. The design goals are accomplished via several layers of different materials, each performing a separate function, as presented in figure 3.1-2. The centermost layer would be a KEVLAR blanket, sandwiched and supported on both sides by a layer of foam. The

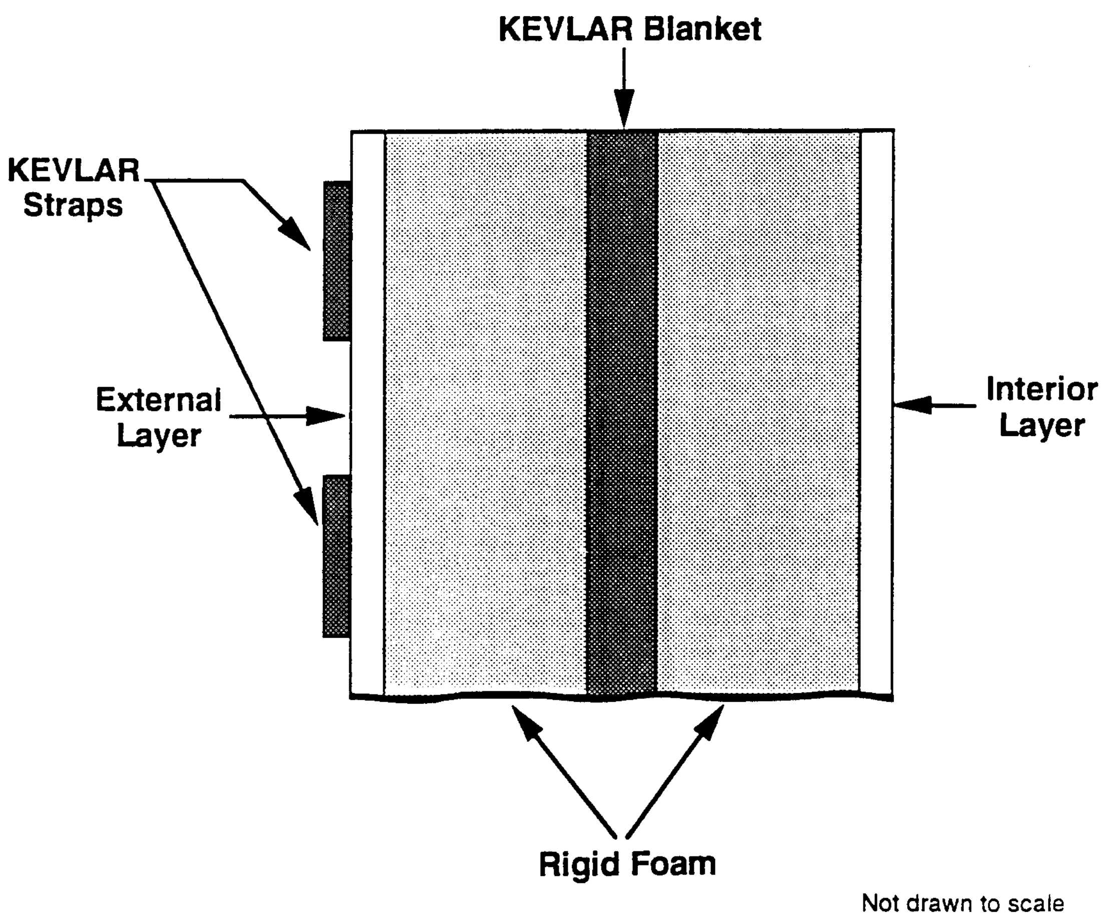


FIGURE 3.1-2 INTEGRALLY HARDENED CONTAINER PANEL

innermost and outermost layers would be composed of either aluminum or fiberglass, which are employed in standard containers.

The interior and exterior materials protect the internal layers from becoming damaged by the luggage and other minor operational impacts. The outer layer further serves as a base for the KEVLAR straps surrounding the container. The foam layer would contain a rigid urethane or phenolic foam. The foam provides shock attenuation, absorbing energy as it crushes, and supports the KEVLAR blanket. It is also fire retardant. The KEVLAR blanket prevents fragments from progressing through the container. The blanket is a sandwich of KEVLAR felt between two layers of KEVLAR fabric which are stitched together. These blankets have been previously subjected to ballistic tests. Finally, the exterior container walls are constrained and joined by KEVLAR straps. When the interior pressure of the container reaches a certain level, the container edges will distort and open between the straps, thus allowing for a controlled pressure reduction.

This design has been proposed for new container development as well as for modification to existing containers. The projected weight for a modified container is 600 pounds, and about 400 pounds for a new container. These hardened containers would carry a reduced payload as well, with a nine percent reduction for the modified version, and a three percent reduction in the new container.

### 3.1.3 Hardened Container with Interlocking Joint.

Century Aero Products, International (CAPI), is the only current container manufacturer that plans to design and develop their own hardened luggage container. Their primary product construction uses a tough, polycarbonate panel (composed of lexan) clamped to an aluminum extrusion framework. This design handles the day-to-day loading and unloading of luggage well, and thus container repair is infrequent, yet easily accomplished when necessary. This is attributed to their patented interlocking joint, which allows for damaged panels to be removed within five to six minutes.

Their pursuit of a hardened container design began with testing the blast capacity of their current lexan containers. The results indicated that a much higher charge weight could be contained than was previously determined under the FAA testing (see section 2.1), although still below the present threat level. This was attributed to the joint design, which allows for spherical expansion of the structure in a blast, thereby increasing its tolerance to the pressures generated. Because of these findings, the CAPI design essentially allows an additional layer of composite material to be added to the current panels. The work is still in the developmental stages, and no test prototypes have been built as yet. CAPI has the facilities and equipment necessary to produce hardened containers on site.

## 3.2 BLAST MANAGEMENT CONCEPTS.

The following details those designs that have been classified as blast management concepts. A blast management design considers the container as part of a system with the aircraft cargo bay. Thus, one type of blast management design may allow a controlled amount of the explosive products to mix with the cargo bay air, thereby reducing the loads (and damage potential) to any one component; a second blast management container may in fact be designed to fail, but in so doing the container structure would absorb most of the blast energy, making the residual blast effects upon the cargo bay negligible.

### 3.2.1 Hardened Luggage Container with Fire and Explosion Suppression Blanket.

The hardened luggage container design at SRI International (formerly Stanford Research Institute) has been underway since late 1991. In May 1993 SRI was issued a Notice of Allowance for the patent of their hardened container design. SRI presently is in the process of teaming with a container manufacturer for commercial purposes.

The SRI design takes advantage of the entire cargo bay of the aircraft. The container sides (which are adjacent to other containers) are designed to fail under the blast pressures generated by the explosive event. This allows the high pressure gases to flow out of the initial container and into other containers along the same row. Furthermore, the design slowly vents the explosive products into the cargo bay, increasing the pressure in this area at a reduced rate, and thereby extending the duration over which the pressure impulse acts upon the aircraft fuselage.

The SRI hardened luggage container has the same shape and exterior dimensions as a standard container. It is wrapped with a flow through mitigation blanket woven from S-Glass or other strong materials, and lined with a fire resistant foam and perforated aluminum alloy sheet. The exact arrangement and size distribution of the holes on the aluminum liner and mitigation blanket were optimized based on the strength of the materials used to construct the container. Container repairability has been emphasized throughout the design process.

Scaled testing was performed to help develop an understanding of blast phenomenology. The test series involved several experiments with ¼-scale test articles. Each test specimen was based on a full scale container with a volume of 158 $ft^3$, and a length of five to six feet per side. The test results showed that while the mitigation blanket deformed as designed, it remained essentially intact while containing the debris and fragments produced by the explosion.

SRI is adapting existing containers with their design, as well as developing new containers. The new containers have been tested at a reduced scale with a variety of materials. The design is not material dependent, although the tensile strength of the material is the most important parameter. A weight-cost tradeoff decision will be left to the customer (i.e. the airlines), with a fiberglass container being the cheapest to manufacture but the heaviest in tare weight, and a SPECTRA container being the lightest in tare weight but the most expensive to produce. The containers have been developed to IATA specifications, and weigh less than 400 pounds.

Based upon these results, SRI presently is acquiring full size test articles. Testing is planned during summer 1993, and the containers will be tested with and without luggage. SRI has indicated that in order to generate realistic test data and conditions, it is necessary to account for both the blast resistance and the effects of the rigid body motion of the container upon the aircraft. This requires appropriate consideration of the aircraft cargo hold structure.

3.2.2 Hybrid Material Container Design.

Royal Ordnance is designing a hardened container that employs hybrid materials. Royal Ordnance's background in materials characterization testing and explosives research led them away from the use of monolithic materials. Their testing also revealed that the properties of items located behind the charge is important as well in determining the blast loading upon the structure. Royal Ordnance has also tested their design on a simulated cargo bay floor.

The container panels consist of standard materials, and aluminum is heavily employed. The panels are flat sheet, jointed at the corners, and are composed of several different materials. The exact amount and configuration of each material used in the panel construction depends upon the blast pressures (i.e. explosive energy) the design is intended to mitigate. Certain portions of the container are designed to fail early to alleviate the QSP. This failure is referred to as "graceful degradation" by the Royal Ordnance designers, and they identified the joints as the weak point of the container.

The current design is based upon a smaller threat (i.e. charge size) than the FAA is designing towards. This container weighs about 275 pounds including a forkliftable base (the base weighs about 35 pounds). The cost of this container is £1,450 (about $2,100 on August 1, 1993). If the design strength were increased to withstand the FAA's threat level, it was estimated that the container would weigh an additional 50 pounds.

Emphasis also was placed on repairability, for although it is difficult to repair a damaged panel, one can be removed easily and completely replaced. The container parts (i.e. panels and joints) can be manufactured locally, or centrally at one major location and assembled at different sites. The container design fits into the current airline industry structure, and should perform the same as current containers since they are constructed of materials used in today's container fleet.

3.2.3 Overboard Venting Design.

Work on this design concept began in 1990 as a joint venture between QSI and Omega Engineering. A patent was awarded to Omega Engineering in March 1993 (U.S. patent No. 5,195,701), the details of which are summarized below. The design mitigates blast effects by venting them through the aircraft fuselage to the aircraft exterior. Fragmentation damage is reduced through the use of composite material construction. There are two distinct designs which serve the purposes outlined above.

In the first design, shown in figure 3.2-1, the location of the door is moved to the outboard side of the container. This allows for placement of an upper door and lower door. Each of these doors is secured to the container by hinges located on the top and bottom panels of the container, respectively. The upper door swings upward and the lower door swings downward to provide access to the container interior. Each of these doors has a blade circumscribed around its periphery. The blade can be constructed of any material that is harder than the material of the aircraft structure, such as steel or titanium. Finally, the doors may be secured to one another via a latch, which is designed to fail at a pre-determined internal pressure or stress level, allowing the doors to be propelled outward.

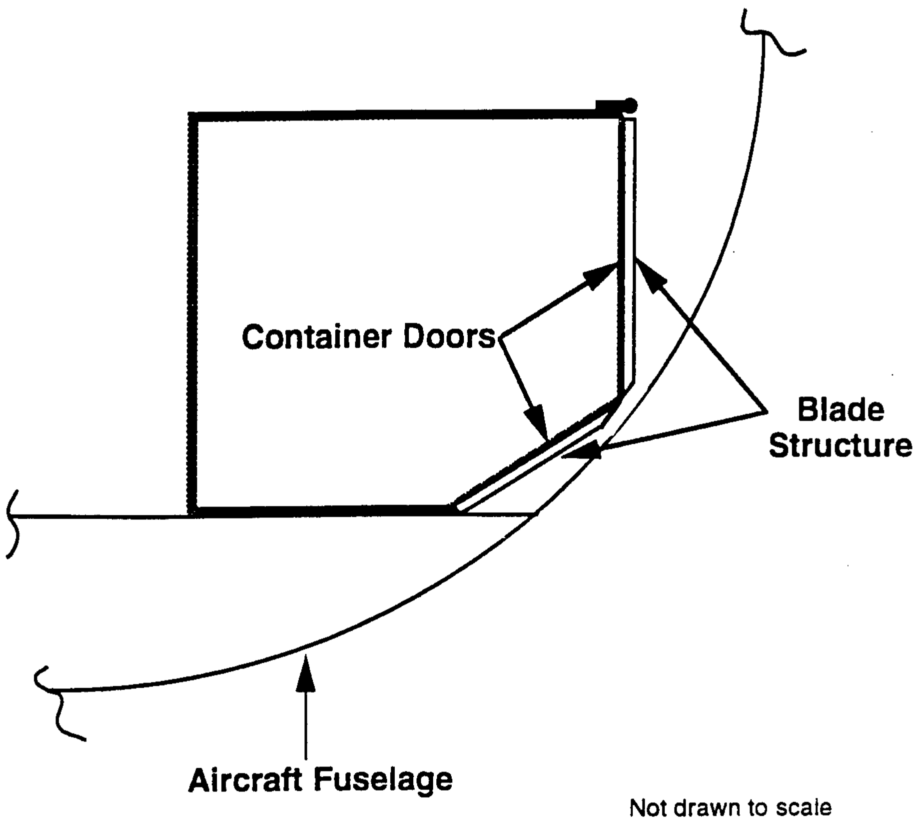


FIGURE 3.2-1 CONTAINER WITH BLADED DOORS

In the event of an explosion, the container sides will expand due to the blast pressures, causing the latch to fail and the doors to subsequently open. The force of the explosion will cause the door hinges to come loose, allowing the doors to be propelled outward, and the blades to slice through the aircraft structure, breaching the fuselage. This hole enables the high pressure explosive products to vent overboard, thereby relieving the blast loading and minimizing the damage on the remainder of the aircraft structure.

The second design would be employed on aircraft that have flight control systems running along the fuselage area where the first design would cut. This concept employs a series of ballistic penetrators located in the interior of the container, as illustrated in figure 3.2-2. The penetrators may be oriented in any direction, so that the fuselage will be breached in a location devoid of crucial flight control systems. A strong flexible hose, ideally made of KEVLAR, is attached at one end to the penetrator, and at the other end to the top surface of the penetrator compartment. Several penetrators, located side by side, may be placed within this segment of the container volume. This container functionally would have only one door, located on the upper outboard panel. A rectangular sleeve would be lowered over the container top and sides to reinforce the structure after the luggage has been loaded and the door secured. This sleeve would be composed of composite material.

In an explosive event, the high pressure gas will rupture the top of the penetrator compartment and travel through each hose, causing them to expand. The gas will then act upon the penetrator surfaces, causing the penetrators to move with great velocity along the compartment guide, which is shown downward in figure 3.2-2. The penetrators subsequently would rupture the container bottom and pierce the aircraft fuselage. Once this hole has been created, the high pressure gas from the explosion will vent overboard, thereby limiting the damage to the aircraft structure.

The first test of the former container concept was performed in December 1990, on a ¼-scale model. Since that time, there have been eight subsequent tests on both ¼ and ½-scale models. A full scale test was planned for late summer 1993. All testing thus far has been performed with empty containers, and has focused on the first design (no tests have been performed on the ballistic penetrator design). However, scaled testing on the latter design is planned for late 1993.

The full scale model was estimated to weigh 188 pounds, with a cost of about $2000 per container. The container is composed of 95 percent E-Glass (conventional glass fiber) and 5% aramid fibers formed in an epoxy resin. The container is manufactured in a one piece wrapped manner, using basic tooling and mechanization. This choice of materials and manufacturing processes are believed to increase the container durability and life cycle.

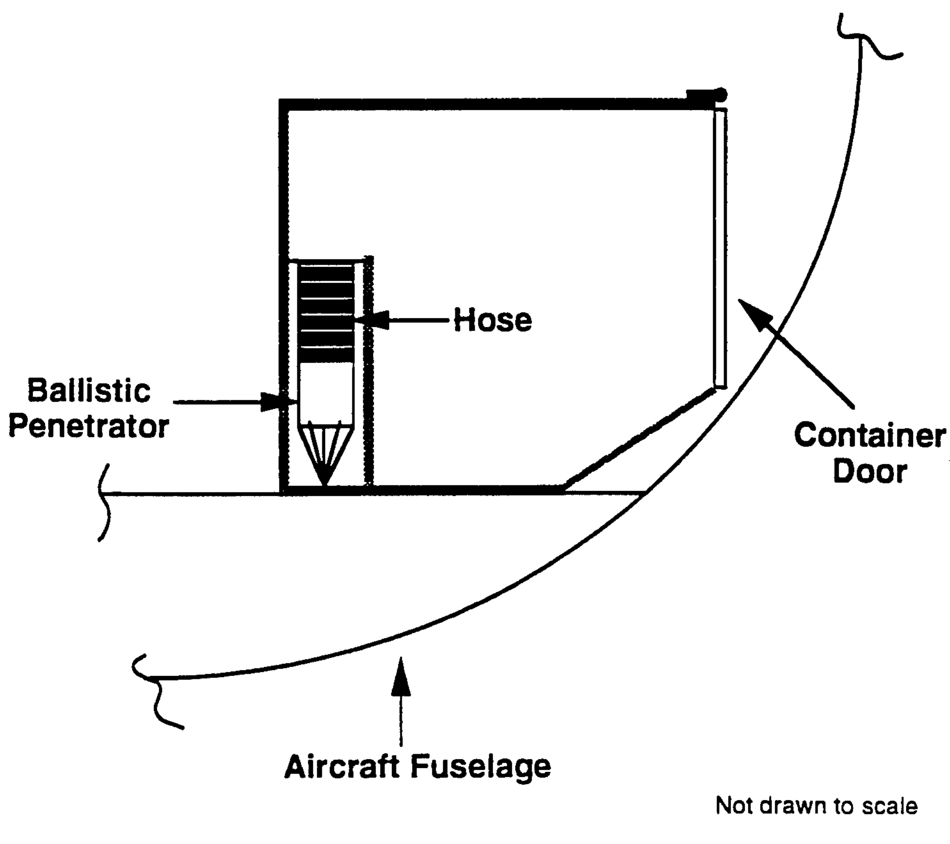


FIGURE 3.2-2 CONTAINER WITH BALLISTIC PENETRATOR

3.2.4 Woven Integrated Structural Laminate.

Past research by the A.R.A.P. Group of California Research and Technology (CRT) has included the development of methods for evaluating new armor materials, and designing weight efficient containment structures to confine the energy absorbing ceramic elements of metal matrix ceramic armors. This experience led to the development of Woven Integrated Structure Laminate (WISL) Fabric Reinforced Plastic (FRP) matrix armor.

WISL's distinguishing properties (patented by CRT under U.S. Patent No. 4,923,728) arise from its structural matrix of FRP composite incorporating elements of energy absorbing material, such as light weight foam. The matrix construction allows for a continuous structure by employing reinforcing fabric interwoven with the energy absorbing elements. Because of these properties, WISL can be used to construct a lightweight container with a unit body structure (i.e. no supporting frame is necessary). Furthermore, the WISL container would have rounded corners, thereby increasing its blast resistance and decreasing its tare weight. Finally, the WISL structure could be repaired with standard FRP patching methods.

This type of container construction would mitigate a blast in several ways. First, the WISL provides high strength, and its large section modulus results in a much smaller deflection for a given pressure loading as compared to fiberglass and aluminum. Also, the use of a low density foam would allow for energy absorption by crushing under the blast loading. The use of segmented elements within the structure allows for controlled venting of the high pressure explosive products at predetermined locations. Finally, the WISL container offers considerable fragmentation resistance.

Under internal research and development funds, CRT conducted a series of static and dynamic pressure loading tests on WISL, aluminum, and fiberglass panels for the purpose of material performance characterization and comparison. The static tests were conducted with aluminum and fiberglass panels typical of current LD-3 containers, and the WISL panel was constructed to represent an equivalently weighted container. The dynamic tests were performed for aluminum and WISL panels only.

The aluminum panel used for the static tests was composed of 2024-T3 alloy and had a thickness of 0.635 millimeters (mm). The fiberglass panel consisted of three plies of E-Glass in a polyester resin. This panel was approximately 2.54 mm in width. The WISL panel contained an E-Glass fabric-reinforced polyester resin matrix with closed cell PVC foam. This panel was 14 mm thick, and while heavier than the aluminum and fiberglass panels, a container composed of six such panels would weigh only about 300 pounds. This is because much of the weight in aluminum and fiberglass containers is due to the supporting frame, while monocoque construction can be used in a WISL container, thereby enabling the full weight to be distributed only in the panels.

In the first series of tests, each panel was subjected to a set pressure level and its deflection measured. The WISL panel, as expected, deflected very little in comparison to the others. In the second series of tests, each panel was loaded to a maximum pressure value. Although none of the panels ruptured, each had permanent deflections due to plastic deformations. Again, the WISL panel had a significantly smaller permanent displacement.

The WISL panel used in the dynamic testing was lighter than the statically tested specimen, and a container composed of six of these panels would have weighed approximately 200 pounds. The aluminum panel ruptured at a relatively low pressure level, while the WISL panel withstood almost three times this value with only a small amount of permanent deformation.

3.2.5 Other Designs.

Deutsche Aerospace (formerly MBB) began a hardened container design effort in early 1992, when four ⅓ scale hardened containers were built and tested to demonstrate feasibility. These tests were conducted from February to June 1992. The test articles were constructed of a monolithic material consisting of glass and KEVLAR. These containers were quickly fabricated in response to public pressure, and therefore a detailed design study was not performed prior to the tests. Furthermore, the container design did not incorporate a door. However, they did contain the blast, and pressure-time histories were recorded.

In October 1992, a standard aluminum LD-3, filled with luggage, was tested. The results were catastrophic, and fire was evident as well. Since this, test, the Deutsche Aerospace effort has been beset with many delays. The company plans on teaming with Aerospaciale, thus making the research effort a joint venture. A feasibility study was started recently. A full scale steel container with one open end was constructed to provide a framework for materials testing. One panel composed of any material can be bolted onto the structure. The panel's performance may then be characterized by detonating explosives in the container and measuring its response. All future work is dependent upon the results of this study.

The Deutsche Aerospace design remains vague at this point in the development phase. Essentially, the container would suppress a blast up to a certain amount, and then would be designed to vent excess gas pressures generated from a larger explosion. Several concepts are under consideration to provide this function to the container. However, one of the designers stated that the venting would occur both into the cargo bay and through holing the fuselage.

Westinghouse Electric Company was contacted and expressed interest in the survey, however at the time of the this report no information on their design had been provided. The DuPont Company also was contacted, and while they are developing their own hardened container design, they were unable to provide information for this survey.

## 4. IATA-TYPE CERTIFICATION AND STANDARDIZATION ISSUES.

During the course of this survey, several designers raised questions about the certification process, and how the standard for a hardened luggage container might be stated. The following details those concerns, and issues related to IATA-type certification and standardization of hardened luggage containers.

JAYCOR has been funded by the FAA to develop preliminary design specifications. These are operationally based; that is, they are material and design independent. The design specification is similar to present IATA-type ULD requirements for various loads, and is essentially a static pressure load criteria. Determining the magnitude of this pressure would be based on a specific threat level (i.e. charge size) and an appropriate accounting of dynamic effects. However, there are several considerations that must be addressed before adopting this type of approach.

The most prominent issue is the appropriateness of applying such a standard to blast management designs. Since these designs will mitigate the blast by venting the high pressure gases to some extent, or may fail at selected locations, it seems unlikely that such a container would perform as well as a blast containment design under the suggested loading condition. SAIC suggested that basing hardened container certification only on static loading conditions may lead to overly optimistic estimates of design strength. They proposed developing a classified dynamic standard for loading instead. Grumman Corporation expressed concern about reducing the complicated loading mechanisms associated with an explosion to a simple load (pressure) condition. They also raised the issue of if and how the loads induced by fragments would be considered in the certification process.

If actual explosive testing is deemed necessary for proper certification, issues such as charge location and luggage placement within the container must be addressed. Also, fire suppression may have to be considered as part of the certification process. Finally, environmental considerations related to disposal or recyclability of out-of-service hardened containers composed of non-conventional materials (e.g. composites) will need to be addressed in the future.

## 5. ADVANCED MATERIALS FOR HARDENED LUGGAGE CONTAINERS.

In this section, the various materials mentioned by hardened luggage container designers are described. This includes materials or structures with unique applications, such as honeycomb sandwich construction, composite fibers such as KEVLAR, S-2 Glass®[3], and SPECTRA, and hybrid materials such as ARALL®[4] (aramid reinforced aluminum) and Glare®[5] (glass reinforced aluminum. Table 5-1 lists those companies contacted during this survey that produce, or are planning to produce, such materials for commercial use. In addition to the companies listed in the table, FMC Corporation and Northrop Corporation provided insight on many issues related to composite materials applications.

TABLE 5-1 ADVANCED/COMPOSITE MATERIAL MANUFACTURERS

| COMPANY | LOCATION |
|---|---|
| Allied-Signal, Incorporated | Morristown, New Jersey |
| The Dow Chemical Company | Midland, Michigan |
| DuPont Company | Wilmington, Delaware |
| Owens-Corning Fiberglass Corp. | Wayne, Pennsylvania |
| Structural Laminates Company | New Kensington, Pennsylvania |

Although selecting an appropriate material is an important step in the design process, it is only one aspect of the material selection procedure. Differences exist in the processing method of the material (e.g. autoclave, vacuum bag oven cure, etc.), the fabric properties (e.g. twill, plain weave), and its finish (e.g. polyester compatible, epoxy compatible). Each factor influences the behavior and manufacturability of the material, and must be considered during the selection process.

### 5.1 HONEYCOMB SANDWICH CONSTRUCTION.

Honeycomb type structures are prevalent in aerospace applications because they provide a good strength to weight ratio. The basic concept behind the sandwich construction is that a very small increase in a real density or relative weight in the form of a honeycomb core will significantly improve bending strength and stiffness. Honeycomb sandwich structures are available in a wide variety of materials and sizes. Much of the information contained in this subsection was obtained from the Hexcel Corporation, producers of a wide variety of honeycomb materials and configurations.

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[3] S-2 Glass is a registered trademark of Owens-Corning Fiberglass Corporation.

[4] ARALL is a registered trademark of Structural Laminates Company.

[5] Glare is a registered trademark of Structural Laminates Company.

Honeycomb is manufactured in two ways; an expansion process, or a corrugation process. Most types follow the expansion process, but higher density products often are manufactured with a corrugation process. Depending on the intended purpose, the shape of the honeycomb cells will vary. The basic cell structure is a hexagon. A hexagonal cell can be overexpanded in the vertical direction, which allows for easier forming in the horizontal direction. The cell also can be altered to provide improved forming strength (i.e. the strength of the honeycomb is retained after forming), and enhanced compression properties. Other configurations may be fabricated in response to specific needs, if required. Hexcel produces honeycomb in materials such as aluminum (5052, 5056, and 2024 alloys), glass fabric reinforced, and aramid fiber reinforced materials. A typical honeycomb sandwich construction is shown if figure 5.1-1.

The overall design requirement for a honeycomb structure is that it must have enough flexural and shear rigidity to prevent excessive deflections under normal loading conditions. In order to accomplish this, the honeycomb facing material must be thick enough to withstand the tensile, compressive, and shear stresses, and the core must have sufficient strength to withstand the shear and compressive stresses induced by the loads. The core must also be thick enough and have a large enough shear modulus to prevent buckling and crinkling of the sandwich under lateral loads. This latter need often exceeds other considerations in the actual design of sandwich structures.

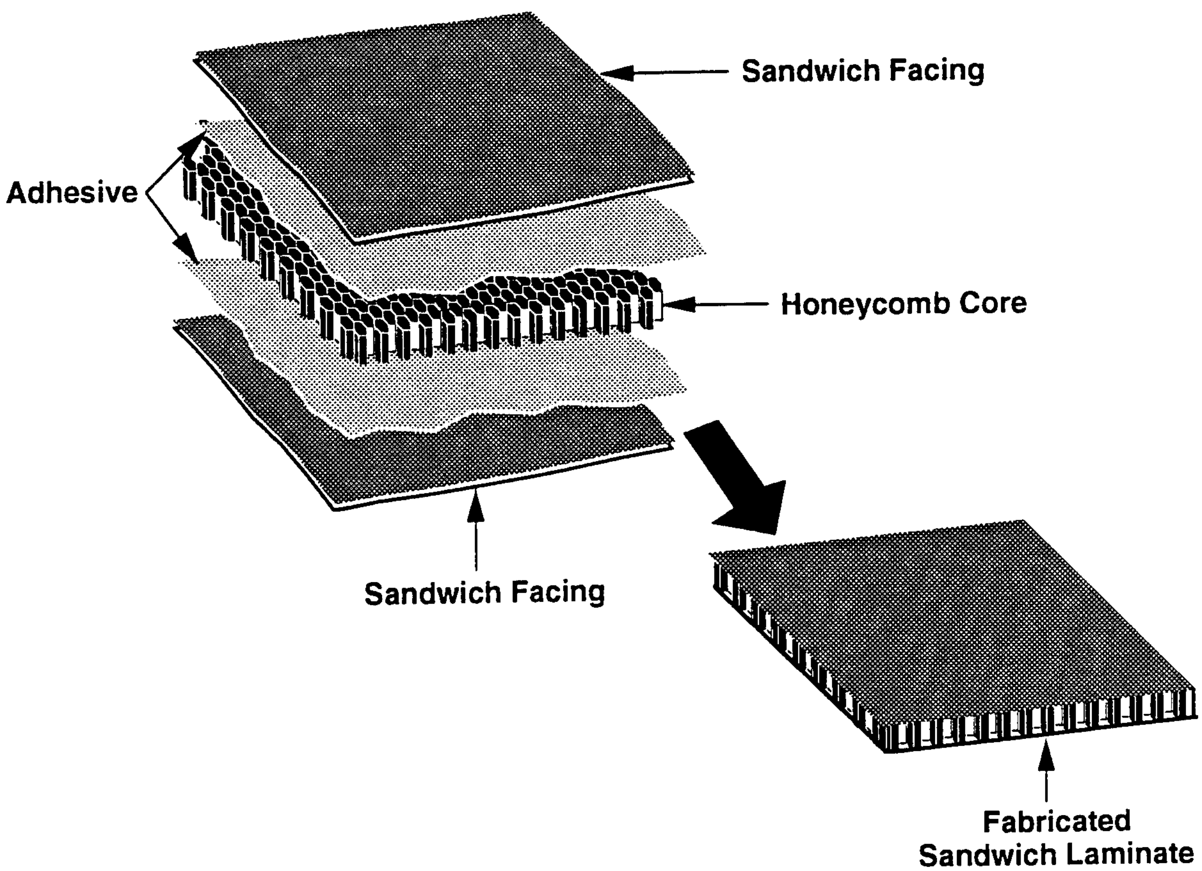


FIGURE 5.1-1 TYPICAL HONEYCOMB SANDWICH CONSTRUCTION

One of the advantageous properties of honeycomb sandwich structure is its crush strength, which translates into energy absorption capacity. After the honeycomb exceeds its ultimate compressive strength, it will continue to deform plastically and crush at essentially a constant stress level. Thus, for a given honeycomb core material and density, the energy absorption capacity is predictable, making it ideal for such applications.

## 5.2 COMPOSITE FIBERS.

KEVLAR is an organic fiber in the aromatic polyamide family produced by the DuPont Company. Three forms of KEVLAR aramid fiber have been commercially available since 1972. These are designated KEVLAR 49, KEVLAR 29, and KEVLAR. KEVLAR 49 has a high tensile strength and high tensile modulus, and is designed for use as reinforcement in plastic matrix materials. KEVLAR 29 has the same strength as KEVLAR 49, but only two-thirds the tensile modulus. This form is suited for a variety of applications including ballistic-resistant garments and structures. KEVLAR has properties similar to KEVLAR 29 and is intended for rubber reinforcement uses. KEVLAR is five times as strong as steel on a pound for pound basis.

KEVLAR 49 has been used in a variety of aerospace applications, and can be found in Boeing 767, McDonnell Douglas DC-9-80, and Airbus A-310 aircraft. Its specific tensile strength (tensile strength divided by fiber density) is greater than that of any other commercially available fiber for plastic reinforcement. Epoxy resin systems provide the composite with the physical properties required for aircraft and aerospace applications. Typical fiber volume of filament wound composites is 60-65 percent. Epoxy resin composites reinforced with KEVLAR 49 exhibit excellent impact, fatigue, corrosion, fire, and crack resistance, as well as allowing for manufacturing cost efficiency.

S-2 Glass is a high strength fiber used for composite reinforcement in aerospace, defense, and demanding commercial applications. As a reinforcement, S-2 Glass has been used extensively in various uni-directional and woven fabric forms. For example, Boeing and McDonnell Douglas use S-2 Glass fiber composite cargo liners in commercial aircraft. The liners consist of S-2 Glass fiber impregnated with polyester and phenolic resin pressed into a laminate. Considering the concerns for blast protection and flammability of the hardened luggage container, phenolic and epoxy resin systems are likely to be valued for favorable results.

S-2 Glass fiber offers enhanced strength and stiffness properties, as well as excellent impact, temperature, and fatigue resistance. The fiber provides 85 percent greater strength and twice the impact resistance compared with conventional glass fiber (E-Glass) in resin impregnated strands. It is also 25 percent stiffer than E-Glass, making it ideal for aircraft floor applications (skin panels and liners). S-2 Glass possesses excellent temperature resistant properties and retains greater fiber tensile strength in high temperature environments than aramid and carbon composites. Furthermore, S-2 Glass offers inherent low flammability and smoke generation when combined with appropriate resin matrices.

There is presently a significant and proven body of repair technology applicable to hardened luggage containers produced with S-2 Glass reinforcements. Repair approaches already exist for various applications, such as in the radome of the Airborne Warning and Control System (AWACS) aircraft and commercial aircraft cargo liners. A hardened luggage container design using S-2 Glass fibers can be developed at commercially competitive costs when compared with aramid and carbon composites, using commercially acceptable production processes. Additionally, because of its relative low cost and unique properties, S-2 Glass reinforcement is often considered for inclusion in hybrid reinforced composite systems.

SPECTRA is a light weight, high strength composite material produced by Allied-Signal, Incorporated. It provides an excellent strength to weight ratio, fragment penetration resistance, and fire retardant properties. The material's impact energy absorption capacity is approximately 20 times greater than for glass and aramid fiber reinforced materials.

The Dow Chemical Company is currently developing a high performance fiber called PBO. This fiber will be appropriate for use as a ballistic and fire resistant reinforcing fiber or fabric system for hardened luggage containers. Conventional composite processing and repair systems can be employed. Because PBO fiber is still under development and not commercially available, no technical information of a non-proprietary nature may be included in this report.

## 5.3 HYBRID MATERIALS.

In comparison to typical aluminum alloys, fiber-metal laminates offer significant weight savings and potential manufacturing cost reduction in aerospace applications. In addition, fiber-metal laminates inhibit many of the typical drawbacks associated with composites. The laminate consists of fiber-impregnated adhesive sandwiched between thin, high strength aluminum alloy sheets. Two types of laminates have been developed by Structural Laminates Company (SLC), an affiliate of the Aluminum Company of America (ALCOA) and Akzo America, Incorporated.

ARALL and Glare laminates are a relatively new family of fibrous-metal materials that feature high strength, low weight, and high resistance to fracture. The laminate is a bonded arrangement of thin aluminum alloy sheets interspersed with plies of epoxy-adhesive that have been impregnated with aramid (used in ARALL) or glass (used in Glare) fibers. ARALL and Glare laminates display significant improvements over monolithic high strength aluminum, and possess other characteristics that make them competitive with advanced composites. These properties include an 8 to 20 percent reduction in density over aluminum, a 60 percent increase in strength compared to 7075 and 2024 aluminum alloys at comparable stiffnesses, resistance of the outer metal layer to damage normally detrimental to a fiber-resin system (i.e. moisture, thermal attacks, and impacts), and vibration damping ability superior to aluminum. Furthermore, ARALL and Glare can be fabricated, handled, and attached by the same processes as monolithic metals. The properties of the ARALL and Glare laminates can be modified in several ways, such as varying the fiber-resin system, aluminum alloy and/or sheet thickness, ply arrangement, and amount of post-cure mechanical stretch.

ARALL and Glare laminates can be used in structures requiring resistance to impacts, and offer a significant weight savings when compared to current materials. ARALL has been applied to the cargo door of the C-17, developed by Douglas Aircraft Company, and its properties are ideally suited to handle circumferential stresses associated with pressurization inside an aircraft. The Boeing Company recently baselined the 777 bulk cargo floor in Glare, which is the first Glare application on a commercial transport aircraft. SLC is presently in the qualification process with a number of other airframe manufacturers.

## 6. SUMMARY AND RECOMMENDATIONS.

A survey of private industry was conducted to determine the status of their various hardened luggage container design efforts. Of those companies surveyed, ten have viable designs at some point in the development process. Three of these are blast containment concepts, five are blast management concepts, and two (the Westinghouse Electric Company and DuPont Company designs) are of unknown type. The survey data also provided information on the designers' concerns related to certification and standardization of hardened luggage containers, and the types of advanced/composite materials currently used, or proposed for use, in hardened luggage container designs.

Of the eight hardened container designs that have been detailed, three (SRI International, Royal Ordnance, and Omega Engineering designs) have reached the prototype development and testing stages, and a fourth (Century Aero Products, International (CAPI)) will enter this phase shortly. Of the remaining four designs, and based on discussions with the respective designers, two (Science Applications International Corporation (SAIC) and the A.R.A.P. Group of California Research and Technology (CRT)) appear unlikely to advance further without funding from the Federal Aviation Administration (FAA). Deutsche Aerospace recently has received the backing of the German Government to proceed with their container development. Grumman Corporation has discussed their design with the Great Lakes Composite Consortium (GLCC), and a prototype may be developed and tested if the GLCC obtains funding from the FAA.

The International Air Transport Association (IATA)-type certification and standardization issues raised by the hardened container designers also must be considered and addressed. One possible means of accounting for both types of designs would be to consider the pressure in the cargo bay as well as in the container. It may be feasible to develop two different certification tests, the first as described in section four of this report, and the second involving a maximum allowable pressure in a simulated aircraft cargo hold. This latter test would provide a means of measuring the blast resistance of those containers employing blast management concepts. This test also would be operationally based. Only one of these certification tests would have to be passed by a potential hardened luggage container.

The next logical step from the perspective of the container hardening project would involve an independent assessment of the various designs and/or materials described in the body of this report. If enough funding is available, the FAA could provide assistance to those designers with viable hardened luggage container concepts. This assistance should be limited to testing support, where a well developed test plan exists, since such data would be useful in the aircraft vulnerability project of the Aircraft Hardening Program.

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## GLOSSARY.

The following describes the various computer codes mentioned by container designers during the course of the survey.

ADINA: Automatic Dynamic Incremental Nonlinear Analysis is a computer program that calculates structural response by employing finite element calculations.

BWAVES: A computer program developed by JAYCOR to model the shock waves resulting from an explosion. The solution algorithm employs the Method of Images (MOI).

DYNA3D: A computer program developed by Lawrence Livermore National Laboratory that determines structural response via finite element calculations.

EITACC: A computer program developed by JAYCOR to model the highly nonlinear phenomena of shock propagation, reflection, and shock-shock interaction. The computation fluid dynamics (CFD) program solves the full time-dependent Navier-Stokes equations by finite difference.

INBLAST: A computer program developed by the Naval Surface Warfare Center to model the shock loads and quasi-static pressures generated by the detonation and combustion of an explosive in a closed or partially vented structure.

SAGE: The SAIC Adaptive Grid Eulerian is a computer program developed by Science Applications International Corporation that simulates the detonation and resultant shock waves of an explosive. The program solves the CFD equations.