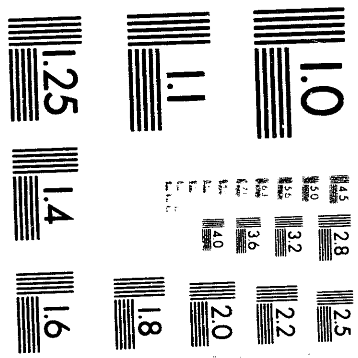
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CHARACTERIZATION OF EXPLOSIVE DEVICES IN LUGGAGE: INITIAL RESULTS OF THE ART-IIC TEST SERIES*

M. A. Akerman and M. D. Kass
Oak Ridge National Laboratory
P. O. Box 2009
Oak Ridge, TN 37831-8088
(615) 574-4687
and
B. T. Clough
USAF Wright Laboratory
Wright-Patterson AFB, OH 45429-6553
(513) 255-2831

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Characteristics and damage associated with exploded luggage aboard aircraft are presented in this paper. Plastic-sided suitcases filled with typical travel possessions were exploded inside the fuselage of decomissioned B-52 aircraft. Multilayered shield panels, mounted to one side of the fuselage. served to protect the aircraft body and flight system components from both the blast wave and exploded fragments. The resulting damage produced by the explosions was characterized and the absorbing characteristics of the shielding were evaluated. In addition, the energy of the luggage fragments was estimated.

INTRODUCTION

Oak Ridge National Laboratory (ORNL) in cooperation with the USAF Wright Laboratory and the FAA performed a series of tests characterizing the damage caused by bare charges and charges contained inside suitcases (caged charges) located inside stationary aircraft.[1] During the test series, the effectiveness of a multilayered shield panel designed to protect both flight system components and aircraft skin against flying debris was evaluated. Current aircraft liners consist of woven fiberglass epoxy which has an areal density of 0.2 g/cm^2. The areal density is a measure of mass per unit area and is determined by dividing the bulk density by the thickness. The goal of the shield development is to develop a liner which would replace the existing one while offering improvements to blast and fragment shielding. A series of earlier tests concluded that the major threat to flight system components was not air blast, but rather the damage caused by the exploded fragments.[1] Following each test in ART-IIC, the damage to the plane caused by the resulting explosion was assessed and the exploded fragments were collected and analysed. The kinetic energy of the fragments, blast energy, and initial fragment velocities were estimated using the Gurney analysis.[2] After all tests were completed, the shield panels were removed from the aircraft and the individual layers were characterized according to the amount of damage they sustained. In each test condition, the multilayered shield panels protected the aircraft from both the blast energy and exploded fragments of luggage. The results obtained from the tests are being used to estimate the kinetic energy of the exploded fragments based on shield damage, and to improve the design of future shielding.

EXPERIMENTAL PROCEDURE

The test matrix used in this study is shown in Table 1. Two shield configurations (having areal densities of 1 g/cm^2 and 1.5 g/cm^2) were evaluated against two different charge sizes (340 g and 680 g). Under each test condition, the shielding was exposed to either a bare charge or a charge contained within a filled suitcase (caged charge). A total of eight tests was performed.

	Shield Density	
Charge Size	1.0 g/cm^2	1.5 g/cm^2
340 g	Bare charge	Bare charge
	Caged charge	Caged charge
680 g	Bare charge	Bare charge
	Caged charge	Caged charge

Table 1. Experimental design test matrix

A schematic describing the individual shield layers and arrangements for the two shield densities used in this study is shown in Figure 1. The panels were assembled using hand layup techniques and the layers were attached to each other using an epoxy resin. A 6-mesh galvanized wire screen was used as the top surface layer. The purpose of the screen was to break up large incoming fragments of luggage into smaller, less-damaging pieces with reduced kinetic energies. The G10 fiberglass sheet located between the screen and honeycomb served to transmit the load uniformly across the honeycomb. It also provided resistance to penetration and fracture. The fiberglass sheet was 0.16 cm thick and consisted of layers of woven fiberglass impregnated with an epoxy resin. A 1.27 cm thick section of aramid honeycomb (cell size $\approx$ 0.32 cm) was bonded between two sheets of G10 fiber-glass epoxy. The honeycomb had a typical crush strength of 6.5 MPa and absorbed the kinetic energy of the exploded fragments by plastic deformation. A back plate consisting of a second sheet of G10 fiberglass epoxy was used to catch or hold any projectiles able to penetrate through the honeycomb layer. This configuration is shown in Figure 1(a) and had an areal density of 1 g/cm^2. Figure 1(b) shows the heavier panel which had an additional layer of fiberglass and honeycomb. The areal density for this configuration was 1.5 g/cm^2. The shield panels were 91 cm high and 122 cm wide, and were mounted to the aircraft frame with the top surface facing the charge.

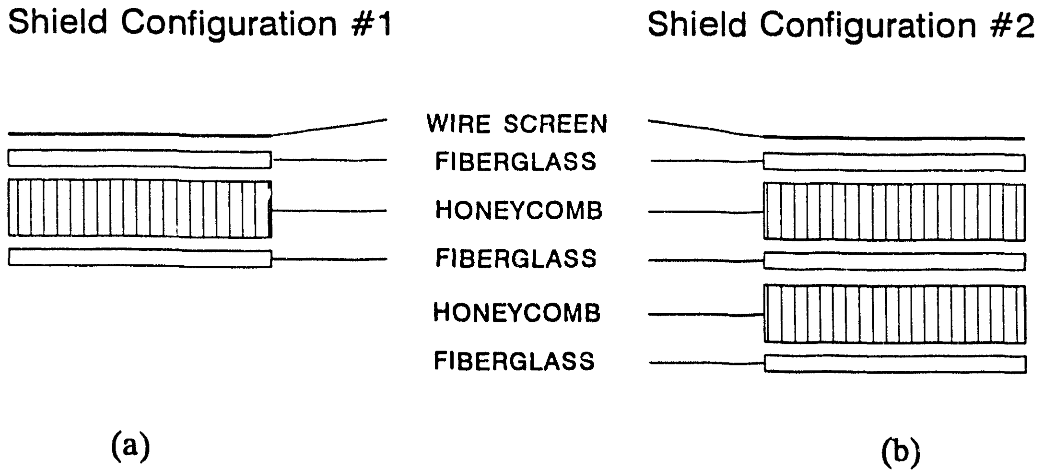

Figure 1. Schematic diagram of shield panels

A schematic showing the location of the charges and the shield panels within the aircraft is shown in Figure 2. Aircraft used in this study were decomissioned B52's stored at Davis-Monthan AFB. C-4 was the explosive material used in this study. All of the C-4 charges were molded into a spherical geometry. For the caged condition, the charges were set in the center of hard plastic suitcases. Typical contents surrounding the bomb in the suitcase included camera film, shoes, books, clothing, and souvenirs such as ceramic pottery. Both the caged and bare charges were suspended from the ceiling of the aircraft, keeping the flatside of the suitcase parallel with the shield panel surface. The center of the charge was located 122 cm from the exposed surface of the shield panels, which were mounted directly to the aircraft frame. Located behind the panels were wire bundles. The integrity of the wire bundles and aircraft skin was used to evaluate the shielding ability of the protective panels.

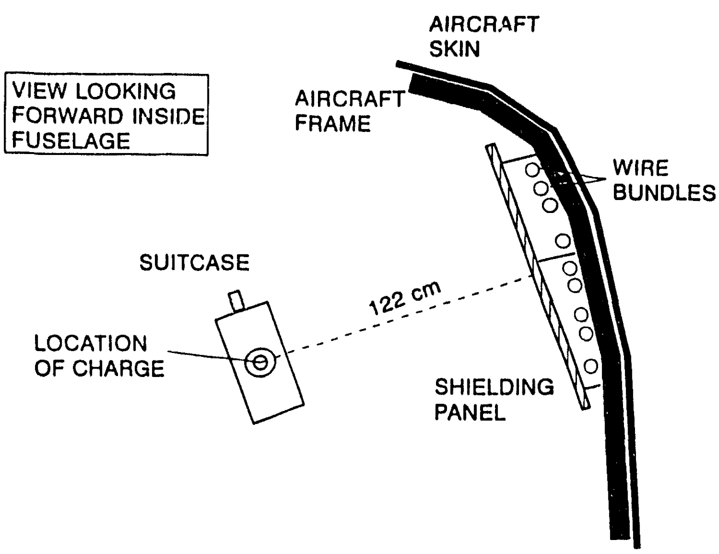

Figure 2. Schematic diagram of test arrangement

Immediately following each test, a visual assessment was performed on the aircraft and shield panels. Any fires which may have been present were quickly extinguished with water. Once the fire had been extinguished, debris from the exploded suitcase was collected, measured, and categorized according to mass and size for each test. The exterior and interior of the fuselage were filmed and photographed before and after conducting each test. The tested shield panels were removed from the aircraft. The damage to shield panels was assessed by two methods. The first method involved counting the number and measuring the size of hits (including penetrations) caused by the luggage fragments. The second method consisted of measuring damage penetration through the shield panels. In order to accomplish this, the individual layers of the shields were separated and the shape, depth, and area of damaged sections were measured. For the heavier shield panels the damage associated with the wire screen and honeycomb was expressed as a ratio of damaged area to total area of the panel.

CALCULATIONS

The initial fragment velocity, momentum, and kinetic energy values resulting from the test explosions were estimated using the Gurney analysis.[2] The initial velocity of the exploded fragments was determined using the Gurney equation, which assumes (1) that all of the fragments move out at the same initial velocity, and (2) that the velocity is at a maximum at the moment of break-up. Using the Gurney analysis, the initial fragment velocity can be determined by the following relation

$$u_f = G\left(\frac{(C/M)}{1+k(C/M)}\right)^{1/2} , \tag{1}$$

where G is the Gurney constant, C is the mass of the charge, M is the total mass of fragments, and k is a numerical shape factor. In this study the mass of a packed suitcase was measured to be approximately 9.1 kg. After putting in the values of the Gurney constant for C-4 and the shape factor for planar sandwiches, equation (1) reduces to

$$u_f = 2801\left(\frac{(C/M)}{1+0.33(C/M)}\right)^{1/2} , \tag{2}$$

where u_f is expressed in terms of m/s. The total fragment momentum is calculated by multiplying the intial fragment velocity, u_f, times the total mass (9.1 kg) of the fragments. The total kinetic energies for the fragments was obtained by using the well known equation

$$KE = \frac{1}{2}Mu_f^2 . \tag{3}$$

It is important to remember that these values are based on u_f, which is the estimated initial fragment velocity. The total internal energy was determined using the heat of explosion per gram associated with the composition C-4. Values for the blast energy were then calculated by subtracting the total fragment kinetic energy from the internal energy of the charge at each condition.

The peak overpressure, as a function of scaled distance, was calculated from

$$p^{o}/P_{a} = \frac{808\left[1+\left(\frac{Z}{4.5}\right)^{2}\right]}{\sqrt{1+\left(\frac{Z}{0.048}\right)^{2}}\sqrt{1+\left(\frac{Z}{0.32}\right)^{2}}\sqrt{1+\left(\frac{Z}{1.35}\right)^{2}}}, \qquad (4)$$

where p^{o}/P_{a} is the ratio of overpressure to ambient atmospheric pressure. Z is called the scaled distance, which is an actual distance that has been adjusted for explosion yield and atmospheric conditions.[2]

RESULTS AND DISCUSSION

The initial fragment velocity, momentum, and kinetic energy of the resulting test explosions are shown in Table 2. As expected both the total internal energy and resulting fragment kinetic energy are directly proportional to charge size. Because the Gurney analysis assumes that all of the internal energy is converted into the fragment kinetic energy and blast energy, the calculated values are probably much higher than the actual values. In reality, significant amounts of the internal energy are dissipated by the soft luggage (clothing, etc.). Also, part of the internal energy is used up as work done in fracturing. Increasing the charge size from 340 g to 680 g raised the calculated initial fragment velocity from 540 m/s to 760 m/s; this represents a 40 percent increase in velocity and momentum. The energy partioning associated with the caged charges as a function of fragment mass is shown in Figure 3. The fragment energy and blast energy curves for each charge size are horizontally symmetric and the curves approach a constant value for mass sizes greater than 3 kg. The energy levels associated with the 680 g charge are substantially higher than for the 340 g charge. It is also important to note that the difference between the partitioned energies is proportionally greater for the larger charge size than for the smaller charge size. The calculated peak overpressures occuring at the shield surface were much higher for the bare charges than for the caged charges, because all of the internal energy of the bare charges was converted into blast energy.

	Charge size	
	340 g	680 g
Internal energy, kJ	1750	3500
Total fragment kinetic energy, kJ	1320	2620
Initial fragment velocity, m/s	540	760
Total fragment momentum, kgm/s	4900	6900
Peak overpressure at 122 cm (kPa):		
Bare charge	276	483
Caged charge	55	83

Table 2. Characterization of explosions

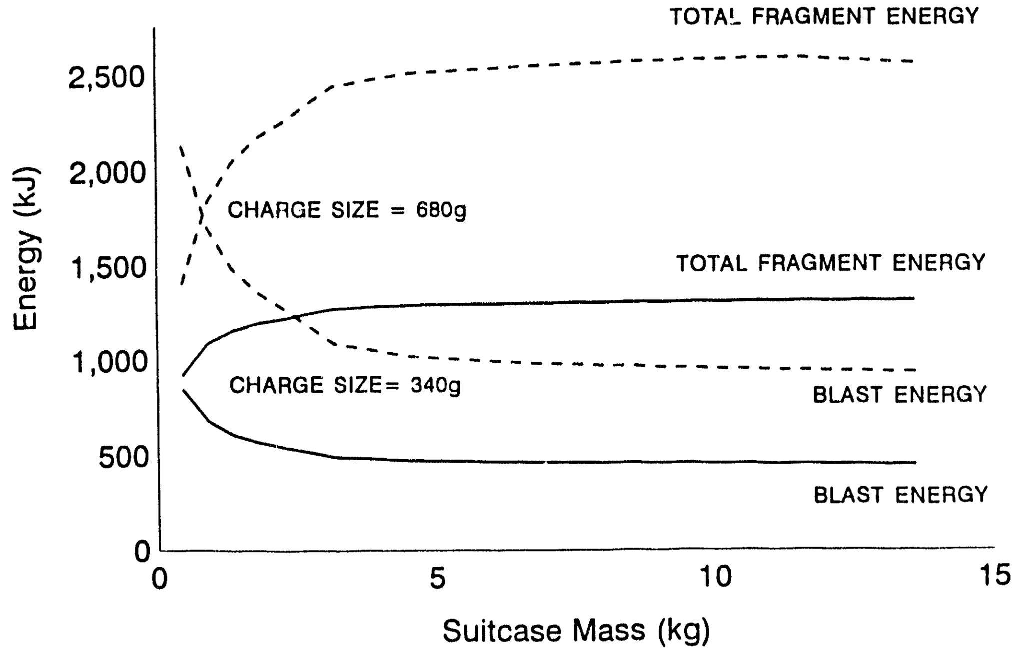

Figure 3. Calculated energy partitioning for the caged charges

Each shield panel exposed to a bare charge suffered partial delamination between the fiberglass sheets and the honeycomb layers but were otherwise unharmed. Most of the visible damage to the aircraft was plastic deformation of the rivets, which held the aircraft skin to the frame; this only occured to those sections not protected by the shielding. One of the 680 gram charge tests tore open the skin on the unprotected side of the fuselage. For each test using a bare charge, the multilayered shield panels not only survived, but were found to be effective barriers to blast wave damage. Table 3 summarizes the number of hits to each shield caused by the caged charges. The total number of hits was tabulated by counting the number of penetrations and indentations for each shield. As a result, fragments which may have struck the shield without leaving a permanent mark were not counted. Therefore, the actual number of hits is probably higher. Overall, the total number of measureable hits was fairly constant except for the test in which the 1 g/cm^2 shield was exposed to the 340 gram charge. It should be noted that this test condition contained significantly more soft luggage than did the others; thus the work that went into fragmentation was substantially less.

	Shield density	
Charge Size	1 g/cm^2	1.5 g/cm^2
340 grams	75 hits	183 hits
680 grams	177 hits	183 hits

Table 3. Number of hits to shield panels exposed to caged charges

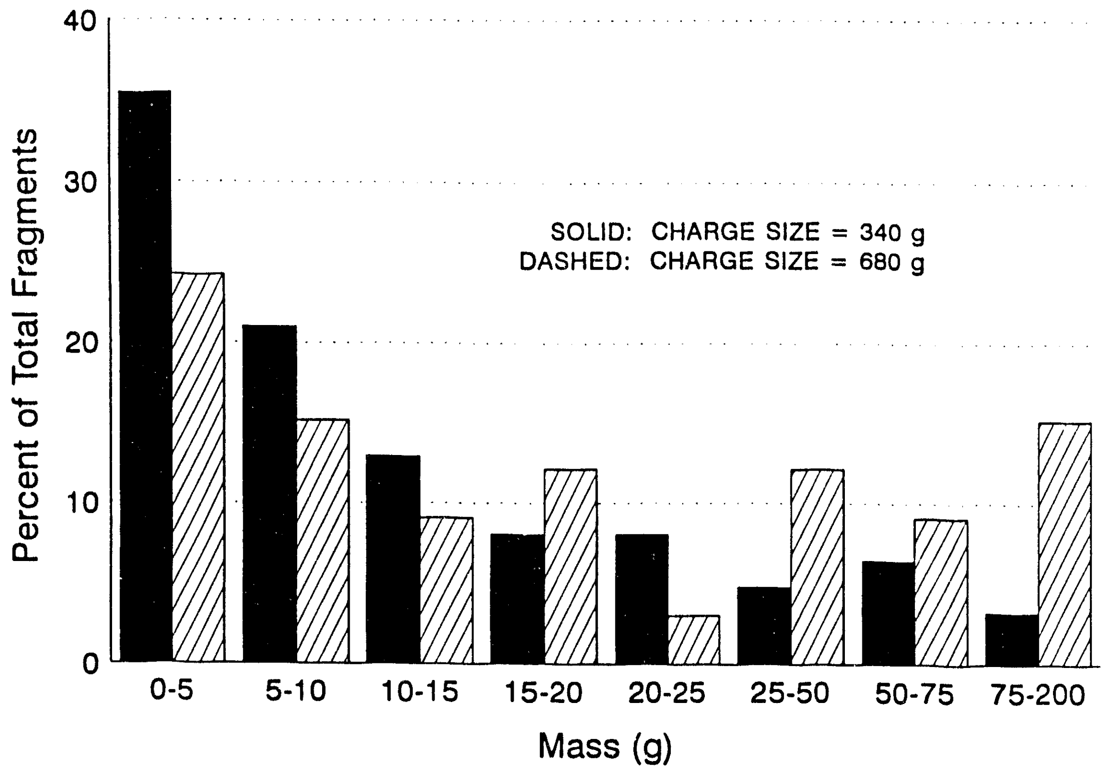

Figure 4. Debris mass distribution versus charge size for exploded luggage

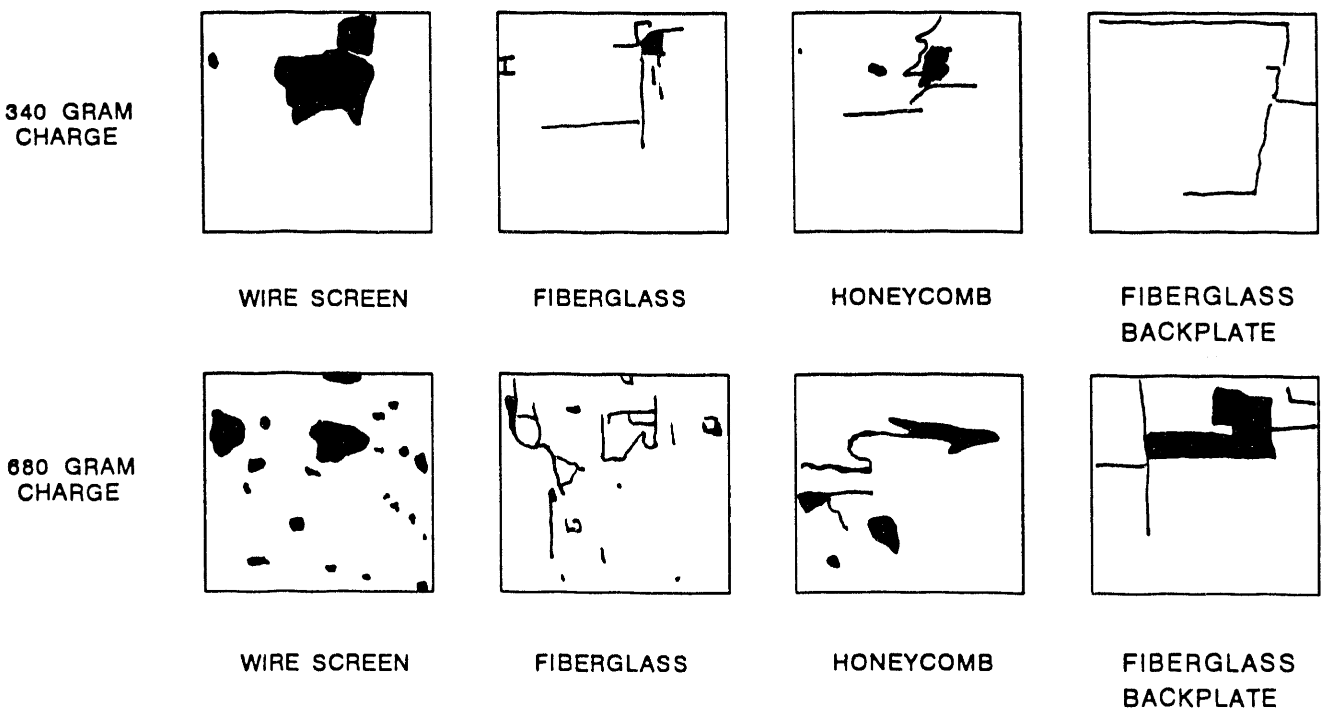

Figure 5. Damage characterization of individual layers for the 1 g/cm^2 shielding

Visual observations indicated that the caged charges caused much more damage to the aircraft than did the bare charges. For each test condition the luggage fragments pierced the skin of the aircraft; however, the areas protected by the shield panels were untouched by the shrapnel. Fires were noted in each case as well. The 680 gram caged charge tore holes in the aircraft skin approximately 2 to 3 meters in diameter on the unprotected side of the fuselage. Luggage fragments collected throughout the fuselage interior were used to calculate debris mass distribution. A graph depicting the debris mass distribution for each the charge size is shown in Figure 4. The majority of the debris was found to weigh less than 15 grams and consisted of plastic fragments from the luggage container. Each of the shield panels suffered many hits from flying shrapnel, but the only shield which was penetrated by the fragments was the 1 g/cm^2 shield which was exposed to the 680 gram caged charge. One of the wire bundles located behind this shield was severed, but the aircraft skin located directly behind it survived intact. The damage done to the individual layers in a 1 ft^2 section of the 1 g/cm^2 shield panels is shown graphically in Figure 5. A visual comparison reveals that the 680 gram caged charge caused much more damage per layer than did the 340 gram charge. There were more penetrations per layer associated with the larger charge, and the damage traveled further into the shielding. In Figure 6, the damage to the 1.5 g/cm^2 shielding is expressed as a ratio of damaged area to total area for the screen and honeycomb layers. The fiberglass sheets were not included because their failure mechanism made it impossible to make a direct comparison with the other damaged layers. The damage done to the wire screens was the same (50%), but the first honeycomb layer suffered considerably more damage with the larger charge than for the smaller charge. The damage done to the second ply of honeycomb was slight in either case and no penetrations were noted.

Charge size	1st layer wire screen	3rd layer honeycomb	5th layer honeycomb
340 grams	50% damage (penetration)	14% damage (penetration)	0.7% damage (no penetration)
680 grams	50% damage (penetration)	40% damage (penetration)	0.5% damage (no penetration)

Figure 6. Damage characterization for the 1.5 g/cm^2 shield panels

CONCLUSIONS

For each test condition the multilayered shielding was effective at absorbing both the blast energy and the kinetic energy of the exploded fragments. The resulting energy values associated with each explosion were estimated using the Gurney relation, and the peak overpressures were estimated at the shield surface. The damage to the aircraft was characterized using visual inspection, and the debris mass distribution revealed that the majority of fragments were pieces of plastic which weighed less than 15 grams. The damage to the shield panels was characterized and evaluated according to several different methods. A key factor in using the multilayered shielding is the ability to estimate the kinetic energy of the fragments caught in the shielding. Future work will include estimating the fragment energy from the damage to shield layers. The results of this study be used to develop better shields which have an areal density closer to that of liners currently used in aircraft.

AKNOWLEDGEMENTS

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[2] Kinney, G. F. and Graham, K. J. 1985. *Explosive Shocks in Air*. New York: Springer-Verlag (27-34)

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