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Certain garments, in particular the Personnel Armor System for Ground Troops (PASGT) ballistic protection vest, seem to increase the risk of direct air blast injury. The response of fabric materials to air shock waves needs to be understood. Four areas were reviewed: blast wave characteristics, blast biology, blast protection, and blast attenuation by porous and compressible materials. A numerical model of the human chest-lung system was adapted for evaluating the effects of different materials covering the chest. The model was used to compare the internal lung pressure when the chest was covered with layers of aramid fiber cloth and when it was covered with cotton cloth. Plans for acquiring more material property data in shock tubes were outlined. Testing will include high rate mechanical compression testing in addition to the shock tube study.					
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SUMMARY

This is an interim progress report on a U.S. Army Natick Research, Development, and Engineering Center (Natick) study of the response of clothing materials to shock waves. The objective of the study is to determine why certain garments (in particular, the Personnel Armor System, Ground Troops (PASGT) ballistic protection vest) seem to increase the risk of direct air blast injury.

Four areas were reviewed: blast wave characteristics, blast biology, blast protection, and blast attenuation by porous and compressible materials.

A numerical model of the chest-lung system was adapted for evaluating the effects of different materials covering the chest. The model was used to compare the internal lung pressure when the chest was covered with Kevlar®, and when it was covered with cotton cloth.

Plans for acquiring further material property data in shock tubes were outlined. Further testing will include Kevlar® 29 and 49, Nomex®, ballistic nylon, Spectra® polyethylene, and cotton cloth. Testing will include high rate mechanical compression testing in addition to the shock tube study.

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PREFACE

The work described in this report was conducted under the Materials for Pressure Pulse Protection project (1L162723AH98CC026) under the direction of the Materials Research and Engineering Division, Individual Protection Directorate, U.S. Army Natick Research, Development, and Engineering Center, between March and June 1989.

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RESPONSE OF CLOTHING MATERIALS TO AIR SHOCK WAVES

1. INTRODUCTION

OBJECTIVE

The objective of the work described in this report is to determine how blast waves interact with soldiers' fibrous body armor. There is some evidence (described later in greater detail) that soldiers wearing fibrous body armor are more vulnerable to injury from blast waves than personnel who are not wearing the armor. The materials in the fibrous body armor apparently cause the blast wave to couple more efficiently with the soldier's chest, thus increasing the risk of injury. This "blast amplification effect", if it truly exists, may be a consequence of the layered construction and fiber properties of the present body armor. It's important to know what the material properties of fibrous armor materials are and how these materials attenuate and transform the blast wave before it reaches a soldier's body.

DIRECT BLAST THREATS

Fibrous body armor is designed to protect soldiers from the most dangerous battlefield threat -- fragments. By far, most battlefield casualties are due to high velocity projectiles from bombs, mines, and guns, rather than from direct air blast effects. The current body armor, the Personnel Armor System, Ground Troops (PASGT), is constructed of 13 layers of Kevlar® 29 cloth sandwiched between an inner and outer nylon shell fabric. The PASGT vest provides a high level of ballistic protection without greatly hindering the soldier's mobility and effectiveness. However, the PASGT vest was not designed to protect against direct blast effects.

Some battlefield threats to the soldier do involve direct blast. If the PASGT vest increases the risk of blast injury, then the magnitude of the increased risk needs to be known. Three direct blast threats to ground troops, aside from conventional bomb blasts, are discussed below.

Fuel-Air Explosives (FAE) are a battlefield threat which may become more important in the future ^{1, 2}. Canisters of a fuel such as ethylene oxide are explosively dispersed to form a low disc-shaped cloud over the battlefield. After a short delay to allow sufficient fuel-air mixing, the cloud is detonated to produce a high intensity blast wave over a very wide area. Blast overpressures within the cloud can be as high as 300 psi. Injuries can result from overpressures in the range of 10 to 20 psi. Damage and casualties from an FAE explosion are due to direct air blast effects and can be produced quite far away from the FAE cloud.

Another blast threat to soldiers is from the muzzle shock wave produced during large gun firings. Under some conditions, the 155 mm M1A2E3 Howitzer, for example, can produce a peak overpressure of nearly 10 psi at the operator's position. There has been some concern that repeated exposure of personnel to high intensity gun muzzle blast waves could produce cumulative damage injuries to gun operators. Operators wearing the PASGT vest might be even more vulnerable to cumulative damage effects if their body armor amplifies the blast wave.

Tank crews are usually well protected from fragments but may be exposed to blast waves in certain situations. Crew members do not wear the PASGT vest but use a similar body armor vest design having eight layers of a lighter

Kevlar® cloth. Tank crews are in a very confined space. Blast waves can diffract into a crew compartment through open hatches and will be intensified through reflection off walls and floors². Crew members exposed to such complex shock waves could thus also be vulnerable to body armor blast wave amplification.

For the purposes of this report no distinction will be made between the different threats. Each involves the interaction of an air shock wave with the vest material and human body. Important blast wave characteristics such as peak overpressure and duration, defined later, will be used to look at vest material response, without worrying about what caused the blast.

3. BACKGROUND AND REVIEW OF PREVIOUS WORK

The characteristics of blast waves are reviewed first. This will provide a background for understanding data reported in previous work on the interaction of blast waves with fibrous materials and the human body.

CHARACTERISTICS OF BLAST WAVES

Blast waves are generated from the rapid expansion of gases following an explosion. A shock front travelling faster than the speed of sound propagates out in all directions from the explosion source. The time history of pressure some distance out from the explosion is shown in Figure 1.

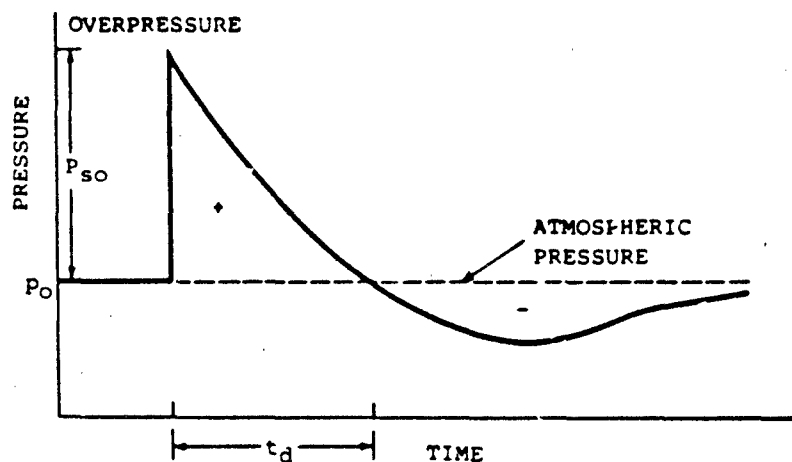


Figure 1. Blast wave pressure-time history.

Blast waves are commonly identified in terms of the peak overpressure (p_{so}) and the positive pulse duration (t_d). The overpressure can be thought of as the "strength" of the blast wave and represents the highest pressure above atmospheric pressure attained by the blast wave. As the blast wave spreads out from the source, the peak overpressure decays to lower values and the wave duration becomes longer until the shock wave degenerates into a sound wave.

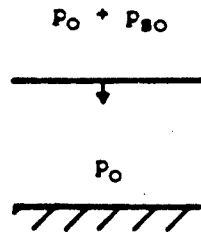
Both the peak overpressure, p_{eo} , and the positive pulse duration, t_p , need to be known before the effects of blast waves on people or structures can be determined. Two blast waves with the same peak overpressure, but having different pulse durations, will have different effects on the structures they interact with since the pressure isn't acting on the structures for the same amount of time.

Figure 1 applies to ideal blast waves that have not interacted with any structures. The ideal pressure-time curve is also called the side-on overpressure. It is equivalent to the pressure that would be measured from a pressure gauge with its flat sensing diaphragm aligned parallel to the direction of propagation of the blast wave. If a pressure gauge is aligned with the diaphragm face-on to the blast wave, the overpressure is called the reflected overpressure.

It is important to distinguish between these two types of measurements of blast wave overpressure since they will not agree. They do not agree because blast waves are shock waves and do not behave like normal sound waves.

When a blast wave hits a rigid wall face-on the wave is reflected back into the opposite direction. Since the region behind the shock front is already at a higher pressure right at the wall, the reflected shock is now propagating back into a medium that is no longer at atmospheric pressure but is at a pressure approximately the same as the peak overpressure of the original shock wave. The peak overpressure right at the wall is thus at least twice the original side-on peak overpressure of the original shock wave. This process is represented schematically in Figure 2.

INCIDENT SHOCK



REFLECTED SHOCK

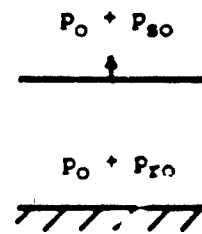


Figure 2. Reflection (p-r) of air shock wave from a rigid wall.
 p_0 = Atmospheric pressure; p_{so} = Side-on overpressure.

The measurement of peak reflected overpressure, with the pressure gauge face-on to the blast wave, is identical to the case of a shock wave reflecting off a rigid wall. The pressure sensing element of a face-on gauge reflects the shock and thus measures an overpressure at least twice the side-on overpressure. An ideal blast wave measured with both a side-on and face-on gauge is shown in Figure 3.

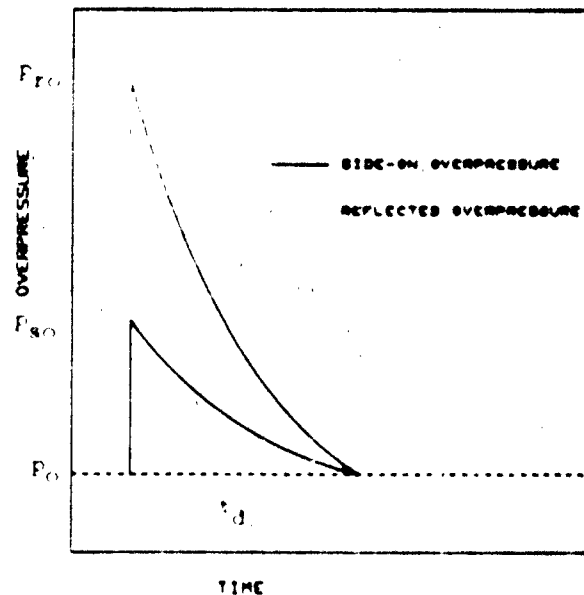


Figure 3. Side-on and face-on (reflected) measurements of an ideal blast wave.

It is very important to distinguish between the side-on overpressure p_{so} and reflected overpressure p_{ro} . In some cases one may want to treat the blast wave as a hydrostatic pressure source and see how it compresses a structure. In this case one would probably use the side-on overpressure p_{so} and ignore the dynamic effects. In other cases the pressure loading on the front face of a structure due to blast wave reflection is more important and one would use the reflected overpressure. In some of the work reviewed later in this report on the interaction of blast waves with people, one approach or the other is taken, sometimes with little justification for doing so. In some cases side-on overpressures are reported and compared to face-on overpressures without distinguishing between the two types of measurement.

For low intensity blast waves (less than 100 psi overpressure), which cover the range of interest for this report, the relationship between the peak reflected overpressure p_{ro} and the peak side-on overpressure p_{so} is given by:

$$p_{ro} = 2p_{so} + \frac{(\gamma+1)p_{so}^2}{(\gamma-1)p_{so} + 2\gamma p_o} \quad (1)$$

where γ is the specific heat ratio of the fluid medium. For air, $\gamma=1.4$.

Assuming an atmospheric pressure p_o of 14.7 psi, the dynamic pressure relation (1) reduces to:

$$p_{ro} \text{ (psi)} = 2p_{so} + \frac{6p_{so}^2}{p_{so} + 103} \quad (2)$$

For small overpressures the peak reflected pressure can be assumed to be twice the peak static overpressure. As the blast strength increases though, the reflected pressure is no longer approximately twice the side-on overpressure, but increases at a faster rate. For example, the reflected overpressure of a blast wave from the heaviest 155 mm mortar, which can have an overpressure as high as 10 psi, is not double that (20 psi), but is more like 25 psi when calculated with equation 2.

The peak side-on overpressure and the peak reflected overpressure do not take into account the momentum of the air behind the shock front. The dynamic overpressure, p_{so} , is proportional to the square of the air velocity and its density. It can provide a better measure of the blast loads applied to structures where the drag force associated with air motion is important.

The dynamic pressure p_{so} is related to the side-on overpressure p_{so} by ²:

$$p_{so} = \left(\frac{5}{2} \right) \left(\frac{p_{so}^2}{7p_{so} + p_{so}} \right) \quad (3)$$

For small side-on overpressures the dynamic pressure is insignificant compared to the peak overpressure due to the blast wave and its reflection, but the dynamic pressure can persist for a longer period of time.

It is often desirable to mathematically describe a blast wave so that it can be incorporated into a model. Later in this report ideal blast waves are input into a computer model of the human chest to determine a person's response to different "ideal" blast waves.

For blast waves of less than about 30 psi side-on overpressure, the instantaneous values of side-on overpressure and dynamic overpressure as a function of time can be approximated by *:

$$p_s(t) = p_{so} (1 - t/t_{so}) e^{(-t/t_{so})} \quad (4)$$

$$p_d(t) = p_{so} (1 - t/t_{so})^2 e^{(-2t/t_{so})} \quad (5)$$

where $p_s(t)$ = side-on overpressure at any time t , lb/in²

$p_d(t)$ = dynamic pressure at any time t , lb/in²

t = any time after the initiation of the blast pressure

(For side-on overpressures less than about 30 psi, t_{so} is approximately equal to 1.5 t_{so} .)

Equations (1), (2), and (4) are used later on to simulate blast waves impacting a computer model of the human chest. They allow all side-on and dynamic properties to be calculated from an assumed peak side-on overpressure and positive phase duration.

One more blast wave characteristic needs to be defined. As described above, an upper limit to blast loads is obtained if a rigid wall reflects a normal shock wave. The integral of the positive reflected blast overpressure curve, $p_r(t)$, is the reflected specific impulse I_r .

$$I_r = \int_{t_0}^{t_0+t_d} [p_r(t) - p_0] dt \quad (6)$$

The reflected specific impulse I_r takes into account the effect of blast duration. It is equivalent to a force-time product, and is often needed when analyzing blast loads on structures.

BLAST BIOLOGY

The study of blast effects on people is complicated by the interactions of shock waves with the irregularly shaped human body. Blast wave diffraction around the body results in a complex loading process. Figure 4 illustrates how a blast wave interacts with an irregularly shaped object. •

Initially a portion of the blast wave is reflected from the front of the object. The outer parts of the shock wave continue on and diffract around to the rear, where they are greatly weakened. Rarefaction waves move across the front face and reduce the peak pressure of the reflected shock while vortices form at the rear of the object. The complicated gas flow following the shock front passage continues to load the object for some time.

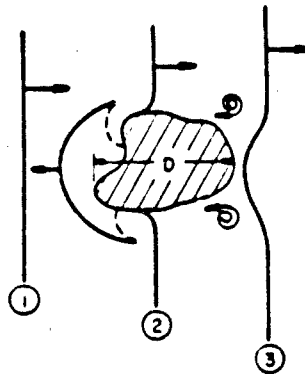


Figure 4. Shock wave interaction with irregularly shaped object.

(from Reference 8)

Scientists studying blast biology are faced with a tremendously difficult analytical problem. Even if the external loading on the human body can be estimated in some way, the mechanical response of the body's internal structure to blast loading is even more difficult to determine. Great progress in analytical methods has been made, particularly with the recent application of finite element modeling, but the most reliable data have been built up over many years of careful experimentation involving laboratory animals.

Blast overpressure damages the body most where large density differences are present. The lungs and the intestines are the vital organs most susceptible to blast overpressure². The chest wall is rapidly compressed during the passage of a blast wave. The sudden acceleration, deceleration, and oscillations due to chest wall compression, combined with direct shock wave transmission, reflection, and focusing in the body tissues, are the causes of blast tissue injury.

Two groups, one in Sweden¹⁰⁻¹⁴, and the other at the Lovelace Foundation in the U.S.¹⁵⁻¹⁷, have done most of the basic work defining the response of mammals to blast waves.

These groups have established that the most important factors in direct blast injury are the ambient pressure, peak overpressure, pressure rise rate, pressure pulse shape, duration of the positive phase of the blast wave, and the orientation of the body with respect to the blast.

The work of these groups has resulted in human overpressure tolerance curves, which are used to prepare exposure limits for personnel¹⁶. Figure 5 is an example of an typical exposure curve.

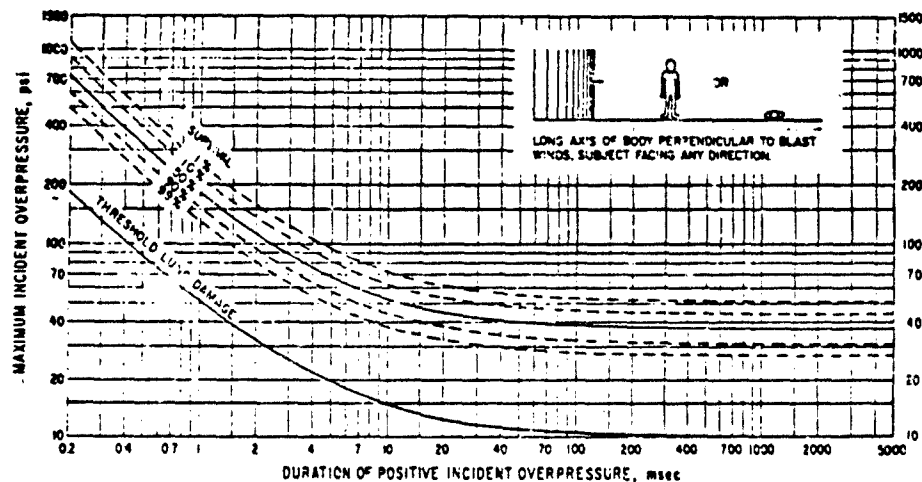


Figure 5. Exposure limit curve for humans away from reflecting surfaces.

(From Reference 16)

These curves are based on abundant data from 13 animal species of various sizes. Similar tolerance curves have been prepared for situations in which a person is standing next to a wall and is exposed to a reflected shock wave.

The injury criteria are based on lung damage and do not consider intestinal or ear damage. The threshold injury curves assume that 1 percent of the people exposed would be casualties.

MODELING OF CHEST RESPONSE TO BLAST WAVES

Extrapolating experimental animal test results to people allowed relative human exposure limits to be developed. Efforts to model the physics of blast wave interaction with the chest and lungs are based on the actual mechanics of the shock wave's interaction with the human body. Chest models are much more promising tools than animal experiments if one wants to look at the effect of changing things like the shape of the pressure pulse or adding a fabric layer to the chest wall.

Lumped-parameter models of the human body, consisting of springs, dashpots, gas-filled chambers, and pistons, have been developed over many years. There is evidence that the human chest-lung system behaves like a damped oscillator under pressure loading. In fact, the natural frequency of the human chest-lung system has been determined to be in the range of 40 to 60 cycles per second¹⁹. This means that blast waves with a duration comparable to the natural period of the human chest are able to couple more efficiently with the chest and lungs, thus causing a higher internal lung pressure, which correlates with an increasing chance of injury.

A model developed at the Lovelace Foundation²⁰, in conjunction with animal testing, correlates well with experimental results for simple blast waves. This model has also been applied to analyzing the effect of complex blast waves on people²¹. A simplified version of this model is described later in this report, where it is used to determine the effect of a Kevlar® vest on the blast response of a human chest. However, the parameters upon

which these models are based are still found largely through extrapolating from experimental results.

Finite element models of the chest have also been developed²². These models include the important structural elements of the chest and lungs, together with appropriate tissue properties. These models place the rib, lungs, heart, and skeletal muscles in their correct configuration and load the structure with a blast wave. The finite element models seem to perform well as predictors of lung response to blast overpressure. Their advantage is that they are based on fundamental engineering principles, require less calibration with experimental results, and are more amenable to analyzing the effects of variables, such as ballistic vests covering the chest.

BLAST PROTECTION

People can be protected from blast effects if they are behind rigid walls or within enclosures. Rigid vests enclosing the chest have also been shown to be a good way to protect people against blast waves ²³.

Soft materials do not have a similar protective effect. At first glance, it seems obvious that foam rubber would cushion a blast wave and reduce blast injuries. On the contrary, workers in Sweden found that layers of sponge rubber covering rabbits and anthropometric mannikins significantly increased blast wave effects over the unprotected condition ²⁴. Soft materials do not offer much protection from blast and often seem to increase the damage.

The Walter Reed Army Institute of Research (WRAIR) clearly demonstrated the blast-enhancing qualities of ballistic vests in work conducted over the past few years. In one study ²⁵, human volunteers were exposed to low level blast waves. The volunteers' internal lung pressure was measured during tests in which the volunteers wore different types of protective clothing. The study showed that the PASGT ballistic vest caused the greatest increase in internal lung pressure. This implies that the ballistic protection vest would increase the risk of lung damage at higher blast levels.

WRAIR extended this study to cover higher blast overpressures²⁶. Sheep were exposed to various blast levels. Half of them were fitted with actual PASGT vests (size large!). The level of lung damage was measured by the percent increase in lung weight of the sheep, which was assumed to be directly related to blast damage. The sheep wearing ballistic protection vests showed

significantly higher internal lung pressures, higher mortality rates, and more lung damage, than sheep not wearing the vests.

Figure 6 is taken from this study and shows how the ballistic protection vest (CBV in the figure) decreases the blast level needed to cause death. The authors of this study estimated that the use of the PASGT reduced the overpressure necessary to obtain a given level of mortality by 25%.

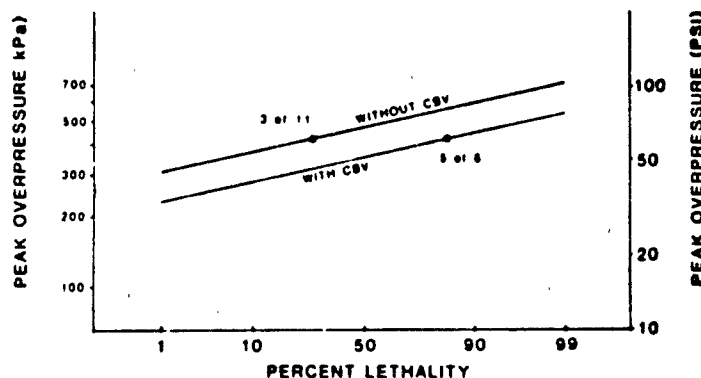


Figure 6. Plot of % lethality vs. overpressure exposure level
(From Reference 26, p. S151)

The authors suggest the mass of the vest is insignificant but that the larger surface area it presents to the blast wave may be important. Perhaps most important is the transformation of a steeply rising blast wave to a more slowly rising waveform as the wave is transmitted through the vest. The vest might convert the blast wave into a form which couples more efficiently with the natural period of the chest-lung system, cited previously to be 25-15 msec (40-60 Hz).

INTERACTION OF SHOCK WAVES WITH POROUS AND COMPRESSIBLE MATERIALS

Fibrous body armor does not protect against blast overpressure; indeed, soft body armor can intensify blast lung damage. Is this property of body armor unique to Kevlar® fabric or would it be true of all compressible materials?

There is a large body of literature on the shock wave attenuation characteristics of porous materials. Much of it has to do with the blast attenuation properties of aqueous foams, but some measurements are applicable to the soft body armor problem.

Shock tube test data are available for many types of foams, metal felts, steel and copper wool, cloth (including Kevlar®, polypropylene, Nomex®), batting (including Kevlar®), and insulation materials ²⁷⁻²⁹. In general, these studies were concerned with how well materials reflect and transmit shock waves. The studies noted that compressible materials have a smoothing and stretching effect on the leading edge of the shock wave. This means that after a blast wave passes through a compressible material it has a more rounded shape, which can couple more efficiently with the human chest.

Extensive shock tube testing on Kevlar® 29 fabric and cotton cloth was carried out by the JAYCOR company for the U.S. Army Medical R&D Command²⁸. Fabric backed by a rigid plate was exposed to blast generated in a shock tube. A face-on pressure gauge recorded the pressure-time curve under the fabric. Since the gauge was face-on, it recorded the reflected overpressure under the fabric. The JAYCOR study covered a range of blast overpressure levels and

looked at the effect of the number of cloth layers for both the Kevlar® and cotton fabrics. As the number of layers was increased the peak pressure measured under the fabric also increased. After 20 to 30 layers, the peak pressure began to decline again. The JAYCOR data also showed the smoothing effect that transmission through soft materials has on blast waves. A sample oscilloscope trace of the pressure for a typical test is shown in Figure 7.

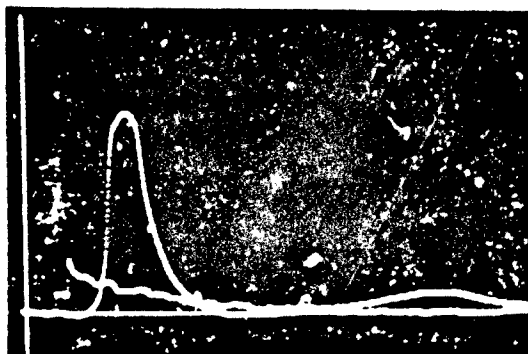


Figure 7. Oscilloscope trace of 20 layers of Kevlar® fabric exposed to 3 psi overpressure. Large trace is pressure under Kevlar® (peak of 30 psi); small trace is incident and reflected shock wave; $p_{ao} = 3$ psi, $p_{ro} = 6$ psi.

The JAYCOR data is used later in this report as an input load to the computer model of the human chest.

The pressure amplification effect and the wave form smoothing effect seen in the JAYCOR experimental results have been investigated independently by workers in the U.S.S.R. Experimental work on the interaction of shock waves with compressible materials such as polyurethane foam was used to verify numerical modeling experiments²⁰⁻²².

The modeling predicts the peak pressure and wave-form of the reflection pressure very well. What is interesting about the Russian work is that the foam can be modeled as a pseudogas by a method developed in the U.S.²². This method is also applicable to the Kevlar® fabric layers. The only properties required are the volume fraction of fiber, the apparent density of the fabric, and the specific heat of the solid polymer.

A plot of an experiment on polyurethane foam is shown in Figure 8. A piece of foam covered an end plate on the end of a shock tube. Curves 1 and 2 are the experimental and theoretical pressure under the foam layer. This is similar to the kind of trace seen in the JAYCOR fabric experiments. Curves 3 and 4 are the side-on overpressure blast traces. The side-on gauge in the Russian experiments was farther away from the end plate than in the JAYCOR experiments, so there was a longer delay in the reflected pressure trace.

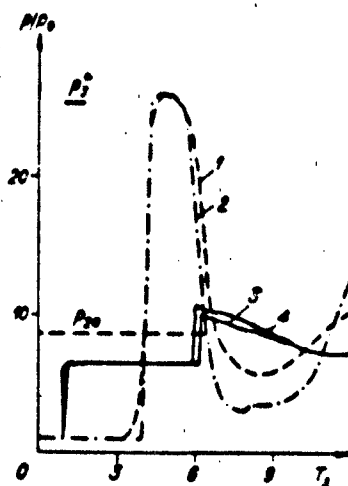


Figure 8. Theoretical and experimental pressure profiles under a layer of compressible material backed by a wall. T_0 is a reduced time variable incorporating layer thickness and incident shock wave velocity. p_0 is the expected reflection overpressure in the absence of the material. p/p_0 is the ratio of incident overpressure to ambient pressure. p_0^* is the pressure under the compressible layer (from Reference 30).

The calculation scheme and system of mass, momentum, energy, conservation, and gas dynamic equations are outlined in sufficient detail in these references so that the numerical model could be adapted to the Kevlar® work. This would make determining the effect of different material variables on blast wave smoothing and stretching much easier. These models probably would not help much in determining the cause of the layering effect discovered by JAYCOR, since the models treat the compressible material as a homogeneous mixture.

3. APPROACH

The response of materials to air shock waves is the major focus of this study, not human chest model development. The computer model described below is used only as an evaluation method to look at the differences between materials.

The approach relies on both modeling and experiment. Shock tube testing of compressible materials is relatively straightforward. The experimental data generated in the testing effort provides the load function for input into the human chest model. The experimental data includes that already available in the literature as well as data that will be generated under this project. The human chest model is used to evaluate the effect of different chest coverings on chest response to a given blast wave.

The human chest model will be described first. Then the available experimental data and plans for future testing will be summarized. Examples of how the experimental data are used will be shown. Possible ways to redefine the standard exposure limits for personnel based on the material the ballistic vest is made of will also be demonstrated.

HUMAN CHEST MODEL

The lumped parameter chest model described below was developed by the Lovelace Foundation, as described earlier ²⁰. This basic model was simplified somewhat by Bolt, Baranak, and Newman, Inc. (BBN) under a previous Natick R,D, and E Center project ²². The present computer model is very similar to the one used by BBN in that project. The model schematic is shown in Figure 9.

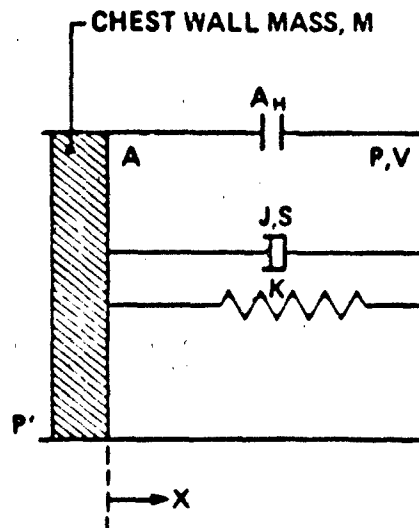


Figure 9. Lumped-parameter model of chest and lungs.

The parameters and variables associated with this model are given by ²²:

- A : effective area of chest piston
- A_H : effective air flow area of throat
- M : effective mass of chest piston
- V_0 : initial gas volume of lungs
- K : spring constant for ribcage stiffness
- J : dashpot damping coefficient for viscous resistance
- S : power of velocity to which damping force is proportional (assumed=1)
- t : time
- $P'(t)$: external air pressure
- $P(t)$: internal lung pressure
- $V(t)$: gas volume of lungs
- $X(t)$: chest wall piston displacement

More detailed versions of this model have been developed which include variations such as two lungs, a diaphragm, and additional viscous damping ²¹, but the single-chamber model is sufficient for this study. The lung is a gas-filled chamber connected to the outside atmosphere by an orifice of area A_w , which simulates the throat passage. A movable chest wall mass acts as a piston which compresses the gas in the lung cavity when acted upon by a force. The elastic resistance and viscous damping of the chest tissues are provided by the spring and dashpot connected to the chest wall mass. Additional compression resistance is provided by the gas in the lung cavity.

The system of equations for this model, in centimeter-gram-second units, are:

$$K \frac{d^2 X}{dt^2} + J \left| \frac{dX}{dt} \right| + KX = A(P' - P)$$

$$\frac{dP}{dt} = -\gamma \frac{P}{V} \frac{dV}{dt} + \frac{1.334 \times 10^7 A_w}{V} \left| P' - P \right| \frac{P' - P}{|P' - P|}$$

$$V = V_0 - AX$$

where γ is the adiabatic gas exponent (assumed to be 1.4 for air).

The constants in these equations were obtained through extensive animal experimentation on many different sizes of mammals. The extrapolated values for humans are given as follows :

$$K = 6.07 \text{ lb/in}$$

$$N = 5.29 \text{ lb}_m$$

$$A_m = 0.025 \text{ in}^2$$

$$J = 92.6 \text{ lb-sec/in}$$

$$A = 98 \text{ in}^2$$

$$V_0 = 127 \text{ in}^3.$$

These equations can be solved numerically to give the chest wall displacement, internal lung pressure, and internal lung volume over time in response to an external load on the chest.

The external load is determined from the overpressure-time characteristics of the blast wave.

In the simplest case, the person is assumed to be standing face-on to the blast source. The loading on the chest piston is given by the incident side-on overpressure plus the reflected overpressure, acting over the positive impulse time t_{eo} . The ideal pressure-time curve for such a blast wave is given by equations 1, 2, and 4. The dynamic effects of the blast wind will be ignored since this chest model is not very realistic in terms of body geometry. More realistic models can take the dynamic wind pressure into account^{20, 21}. A listing of the computer program is included in the Appendix.

A sample run of the computer program is shown in Figure 10.

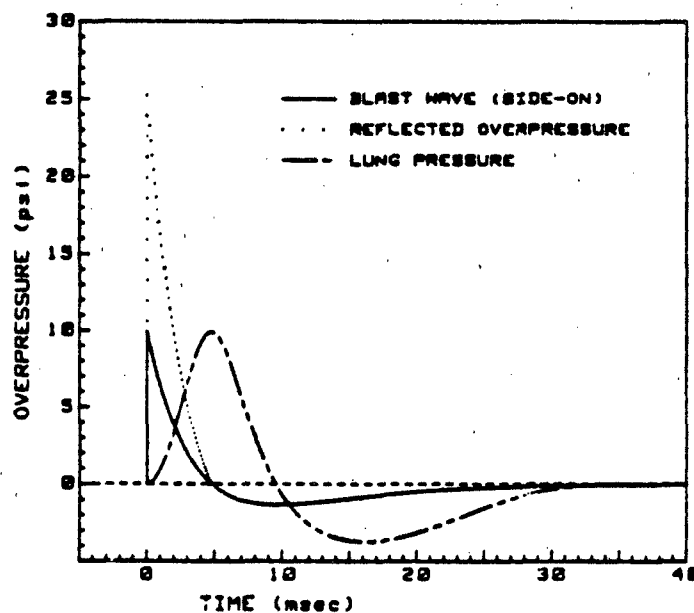


Figure 10. Internal lung pressure variation due to blast wave.
 $p_{eo} = 10$ psi, $t_{eo} = 4.8$ msec.

The chest model was subjected to an air shock wave of about 10 psi side-on overpressure and a positive pulse duration of 4.8 msec. The peak reflected overpressure is thus about 25 psi. The side-on overpressure blast wave is shown on the plot, but the reflected overpressure function is used to load the chest-lung model. Both the incident blast wave (side-on) and the positive phase reflected overpressure are shown in Figure 10.

The lung pressure rises to a peak of about 12 psi above atmospheric pressure some time after the passage of the blast wave. It then decays and eventually damps out.

If a blast wave of the same peak pressure, but with twice the duration is input to the chest model, the lung pressure increases as shown in Figure 11.

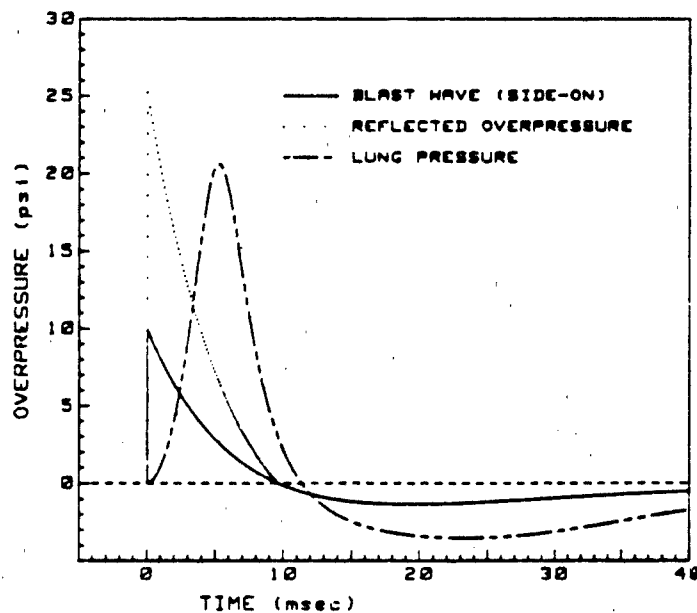


Figure 11. Internal lung pressure variation due to blast wave.

$p_{so} = 10$ psi, $t_{so} = 9.6$ msec.

The blast wave lasted for a longer time in this case. Its duration was more comparable to the natural period of the chest-lung system, so that the chest and lung had more time to respond to the blast pressure. This trend of increasing risk of lung injury for long duration blast waves is well known and is contained in the experimental data in Figure 5, presented earlier.

The reflected blast overpressure represents the very highest load the chest might see. For the real human body the reflected pressure would only be felt on the portions of the body directly facing the blast. Diffracted blast and side-on loads would be felt on the sides and rear of the chest. The reflected pressure is used here so that the experimental reflected pressure fabric data obtained in shock tubes can be used directly in the model.

The internal lung pressures predicted by the model will be used only for correlation purposes, mostly for comparing different materials. If the actual lung pressures were needed one would have to use a loading function more appropriate to the original model such as the side-on overpressure combined with dynamic pressure loading ²¹.

EXPERIMENTAL DATA

The material property shock tube data obtained under programs run by the Walter Reed Army Institute of Research (VRAIR) are the best data available for ballistic vests ²⁶. The same test methods will be applied to a wider range of materials in this study. Most of the other shock tube studies of textile materials deal with their attenuation properties for acoustic applications²⁷.
28

The VRAIR work studied how shock waves were modified by transmission through fabric layers. Layers of Kevlar® and cotton fabric were tested face-on to a blast wave. The side-on overpressure of the incident blast wave and the face-on overpressure under the fabric were measured. There was a significant enhancement of the reflected pressure under the fabric compared to that when no fabric was present. The effect of the number of fabric layers was tested at several different blast wave intensity levels. Both the cotton and Kevlar® showed a trend of increasing pressure with number of layers up to a certain point. The Kevlar® and cloth layer data are shown in Figures 12 and 13.

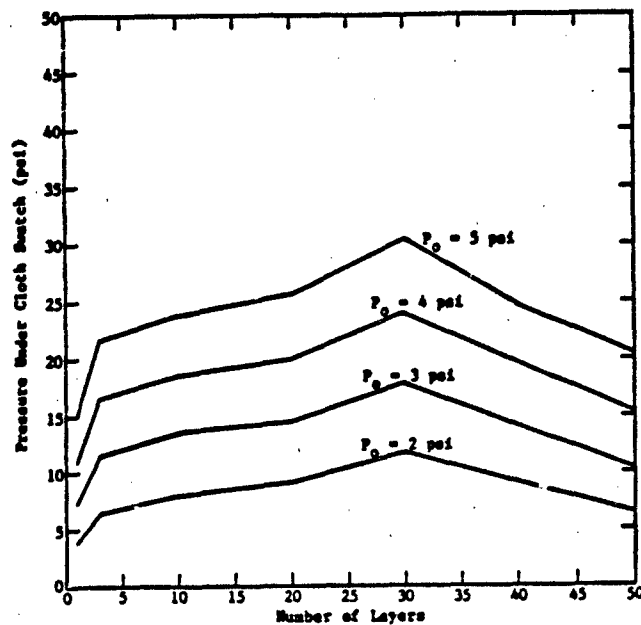


Figure 12. Pressure variation under cloth swatch vs. number of layers for different side-on pressure levels (p_o). (Reference 29, p.43)

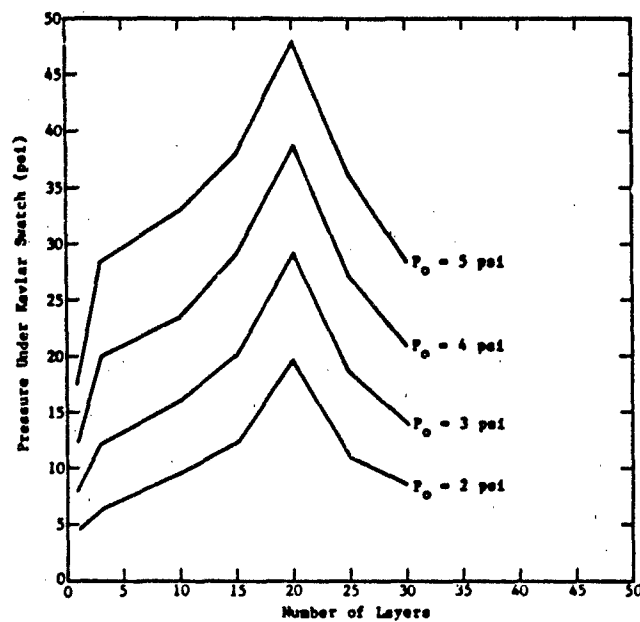


Figure 13. Pressure variation under Kevlar® swatch vs. number of layers for different side-on pressure levels (p_o). (Reference 29, p. 42)

An example of a typical pressure trace under a fabric sample (20 layers of Kevlar®) was shown previously in Figure 2-7. A similar plot for a test of a PASGT vest mounted against a flat plate is shown in Figure 14.

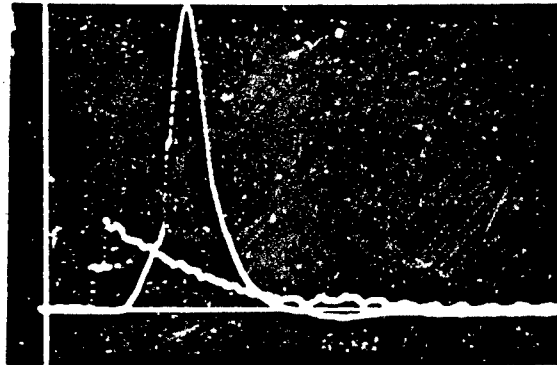


Figure 14. Pressure variation under a PASGT vest mounted over a flat plate.
 $p_{eo} = 2.5$ psi, maximum reflected pressure under jacket = 18 psi.

When data like this are available, it is a straightforward matter to determine the effect of clothing on internal lung pressure using the computer model. The reflected pressure measured under the fabric is used to provide the loading for the chest piston, rather than the incident blast wave. One can thus determine the lung pressure increase due to the presence of the fabric.

This determination can be illustrated by using the data from Figure 14.

First the ideal blast wave, with a side-on overpressure of 2.5 psi and a positive pulse duration of about 3 milliseconds, is input into the chest model. The resultant internal lung pressure is shown in Figure 15.

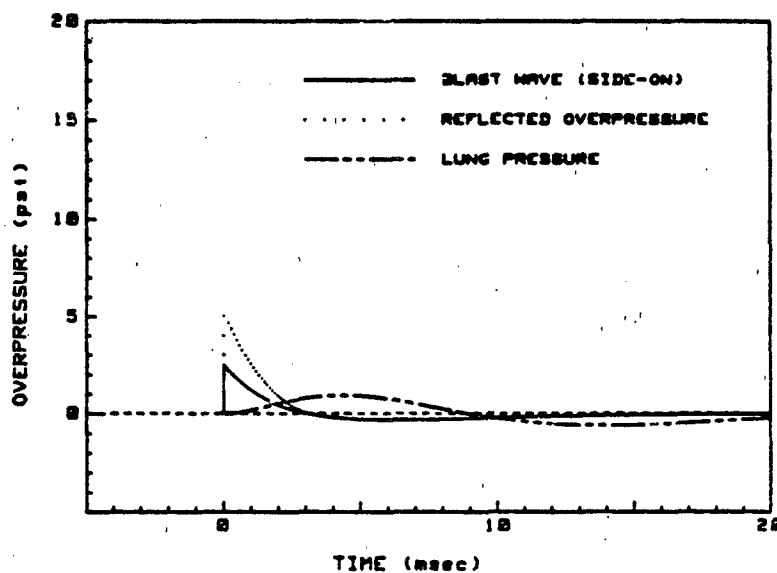


Figure 15. Chest model loaded with ideal blast wave from Figure 14.

Next the same blast wave of Figure 14, transformed by passing through a PASGT vest, is used to load the computer model.

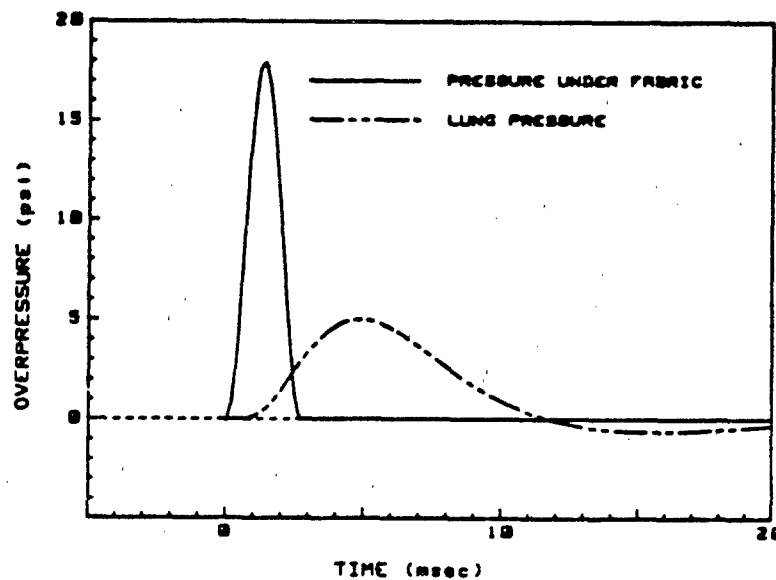


Figure 16. Chest model loaded with measured pressure pulse under a PASGT ballistic protection vest.

The difference in the two plots is quite noticeable. The reflected pressure under the fabric rises much more slowly than the sharp-rising shock front of an ideal blast wave. The chest-lung system has more time to respond to the transformed blast wave and so it shows a higher response when the PASGT vest is present.

The same type of comparison can be made for the shock tube testing of cotton cloth fabric. For an ideal blast wave nearly identical to that in Figure 15, a cotton cloth fabric sample 30 layers thick resulted in a measured reflected overpressure under the sample of about 14 psi. The response of the chest model to this load is shown in Figure 17.

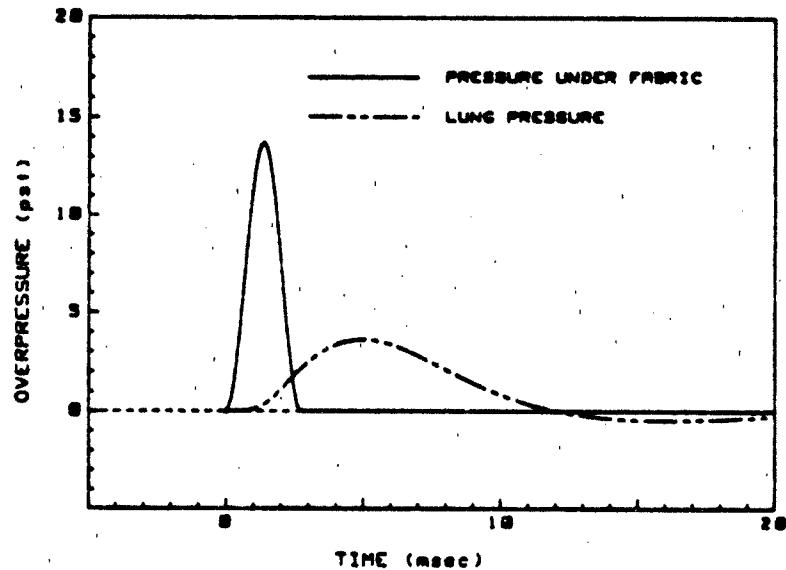


Figure 17. Chest model loaded with pressure pulse measured under 30 layers of cotton cloth. Blast wave side-on peak overpressure = 2.5 psi. Maximum pressure under cotton cloth = 13.8 psi.

Compare Figure 17 with Figure 16. There isn't much difference between the two. Several layers of cotton cloth enhance blast effects almost as much as Kevlar® cloth does. It may be that the material of which a vest is made is insignificant when compared to other factors, such as the number of layers and the apparent density of the fabric stack.

The kind of data used above is very useful, but it exists only for Kevlar® and cotton cloth. Plans for acquiring more data on ballistic protection vest materials will be discussed later.

USE OF EXPERIMENTAL DATA IN COMPUTER MODEL

One more example of the use of experimental data in the computer model will be given to help illustrate the model's usefulness.

As previously discussed, VRAIR performed a study in which human volunteers were exposed to low level blast waves²⁰. Their internal lung pressure was recorded during the tests. The test condition in which volunteers wore PASGT vests resulted in the highest internal lung pressures.

VRAIR also funded a study by JAYCOR in which a PASGT vest was tested in a shock tube²⁰. In that study the transformed pressure pulse after passage through the PASGT vest was recorded.

By combining these two sources of data, one should be able to compare the predicted lung pressure response from the computer program to the measured lung pressure response from the VRAIR study.

From the volunteer study²⁰, the incident overpressure level was 2.7 psi and the positive phase duration was 4.6 msec. This is the input blast wave for an unprotected human. If the side-on overpressure wave is used to load

the computer chest model, the peak internal lung pressure is about 1 psi, which is close to the value measured for volunteers wearing only fatigues, which was 1.07 psi $\pm$.102.

However, the PASGT shock tube data from JAYCOR is measured against a rigid plate. It is more appropriate, therefore, to load the human chest model with the reflected pressure to facilitate comparison with the JAYCOR data. Figure 18 shows the chest model loaded with the reflected overpressure resulting from the incident blast wave used in the VRAIR volunteer study.

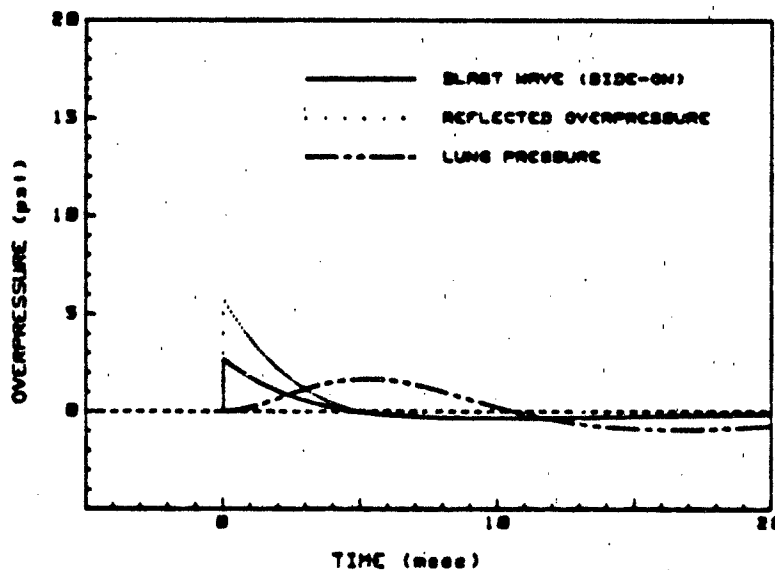


Figure 18. Chest model loaded with blast wave; $p_{so}=2.7$ psi, $t_{so}=4.8$ msec.

Maximum lung overpressure about 2 psi.

The peak internal lung pressure is about 2 psi. This represents the unprotected human chest response.

The chest load for the case of the human chest covered by a PASGT vest can be determined from Figure 19. This figure is data generated by JAYCOR, in which an instrumented dummy wearing a PASGT vest was subjected to blast. The pressure variation between the chest and the inner layer of the vest was measured for different blast levels. The curve corresponding to the case where a labcoat and a t-shirt were also under the vest was chosen as corresponding most closely to the volunteer study conditions, in which fatigues were worn under the vest.

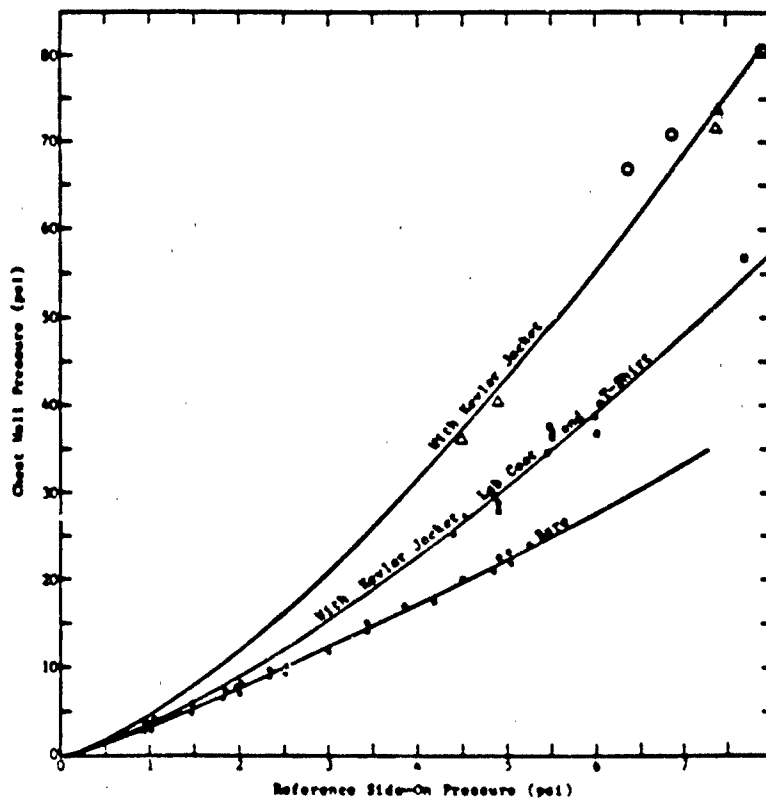


Figure 19. Effect of Kevlar® jacket on mannikin chest wall pressure.

A transformed pressure pulse, with a peak pressure of 12 psi, and an estimated duration of 3 milliseconds, is used to load the chest model. This load represents the equivalent load felt by the people in the VRAIR volunteer study when wearing the PASGT vest.

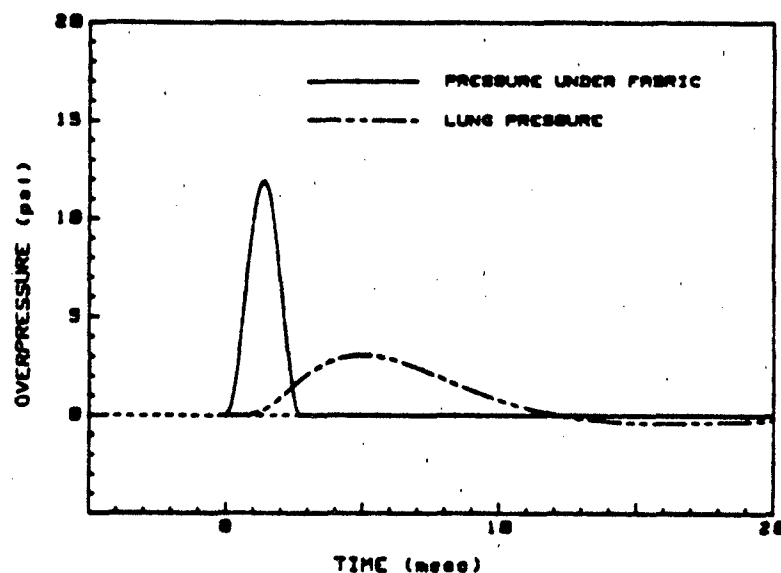


Figure 20. Chest wall model subjected to blast wave transformed by passage through Kevlar® vest. Maximum lung pressure is about 3 psi.

The % increase between the peak internal lung pressure of the unprotected chest model and the chest model covered by a Kevlar® vest is about 50%. The measured increase in the peak lung pressure for the people in the volunteer study wearing Kevlar® vests was about 20%.

This lack of precise agreement shows that the numerical model isn't a good predictor of the actual lung pressure in human subjects exposed to low-level blast waves. Several sources of possible error in this example are present, but the main purpose is to illustrate that the model does work well enough to illustrate the effect of different vest materials on chest response to blast waves.

4. PLANS

SHOCK TUBE DATA

More shock tube data on candidate ballistic protection vest materials is needed. VRAIR's capability for this type of testing will be used to determine the response of several fibrous materials to high-intensity short-duration blast waves. VRAIR has a blast wave generator^{2*} which can generate overpressures of 60 to 375 psi with blast durations of 0.5 to 1.0 msec. These are quite short blast durations -- battlefield blast threats would typically have much longer positive phase durations. VRAIR also has a 12 inch diameter shock tube, which can generate blast waves with intensities of 20 to 30 psi and durations of 6 msec. This blast duration is more realistic in terms of real-world situations.

The VRAIR blast wave generator or shock tube will be used to characterize 6 cloth materials: Kevlar® 29 and 49, ballistic nylon, cotton, Nomex®, and Spectra®. The cotton cloth is included to help in comparing the data at the short blast duration times to the JAYCOR data gathered previously.

The testing will follow the approach used by JAYCOR^{2*}. The reflected pressure under a fabric layer backed by a rigid plate will be measured. These measurements will also be made for fabric stacks of various thicknesses. Various fabric combinations may also be tested (i.e. layers of different fabrics tested together).

More JAYCOR test data on fabrics may become available during the course of this project. VRAIR is continuing to fund blast overpressure injury research, and in particular is continuing to fund the modeling and testing efforts of JAYCOR. The VRAIR contract with JAYCOR will include more materials testing.

Some shock tube testing can probably be done at Natick. The appropriate pressure transducers, amplifiers, instrumentation, and pressurized air systems needed for a shock tube already exist in the ballistics lab at Natick. The shock tube itself can be easily made out of any kind of pipe. Additionally, the U.S. Army Materials Technology Laboratory (MTL) was involved in shock tube testing several years ago. It may be possible to acquire leftover shock tube components from MTL, or it may be more convenient to do the testing at MTL.

The primary source of shock tube data would be VRAIR, supplemented with JAYCOR material property data and any generated at Natick or MTL. The Natick/MTL data would extend the testing over longer duration blast waves than is the case for the VRAIR or JAYCOR blast wave testing.

FABRIC MATERIAL PROPERTY MEASUREMENTS

Measuring fabric response to blast waves generated in shock tubes seems to give good results, but the testing is time-consuming, expensive, and applicable only to that fabric.

One way to get around the expensive empirical testing approach is to model the response of compressible materials to air shock waves. The Russian work on numerical modeling has already been mentioned as one promising approach²⁰. The modeling is only useful, though, if pressure vs. time information can be obtained. Since the shape of the pressure pulse is so important, a modeling method that only gives the peak amplified pressure under the fabric would not be very useful. The "pseudogas" approach may work only for materials of low density. The polyurethane used in the Russian work, for example, had a density of about 3 lb/ft³, while stacked Kevlar® 29 fabric has a nominal bulk density of about 40 lb/ft³. The order-of-magnitude greater density of Kevlar® fabric may render the pseudogas assumptions invalid for ballistic vest materials.

Another way to get around shock tube testing is to find some other set of material properties to help predict the blast transmission and attenuation characteristics of porous/compressible materials. Of course, just trying to correlate properties without any physical rationale is pointless.

An air shock wave impinging on a compressible material can be thought of in some ways as a solid object. The material compresses under the influence of the shock wave to a higher density. This compression is influenced by the

material itself plus the air trapped inside. The compressive modulus of a stack of fabric will thus be dependent to a large extent on the amount of air trapped within the fabric. The compressive modulus of fabrics will also be very rate-dependent. Measurements of static compressive modulus, where the trapped air does not contribute to the material's mechanical response, do not take loading rate effects into account.

Fabric stack compressive properties will be measured at very high loading rates at NTL. This should provide information on fabric bulk modulus and compressibility at loading rates more comparable to those seen during shock wave compression. It may be possible to combine the mechanical property data with the calculated material acoustic velocity and material shock wave velocity²² to predict roughly the pressure pulse amplification of specific fabrics.

5. CONCLUSIONS

Soft body armor does not protect soldiers from blast effects. The present soft body armor may actually increase the risk of blast injury. Protecting soldiers against fragments is the most important function of body armor. Any changes to the present vest design to lessen blast amplification effects must not compromise the fragment protection function of the vest.

Changes to the present ballistic protection vest fabric material are unlikely. Even if other materials are found which perform better at decreasing the coupling between blast waves and the human body, it is doubtful they could compete with Kevlar® for ballistic protection applications. Testing on other materials will aid in the determination of which properties of Kevlar® are most important to the blast amplification effect.

If the response of layered fabrics to air blast can be understood, then approaches to lessening the coupling effect can be taken. For example, layering different fabrics in the vest could be explored. Different fabrics inside the vest, or on the outside or inside of the vest, might change the coupling process between the Kevlar® layers in a beneficial way.

Another approach would be to incorporate rigid elements into soft body armor. Rigid plates in the PASGT vest seem to reduce the blast amplification effect²⁵. This approach is taken in the Explosive Ordnance Disposal (EOD) Suit. The EOD suit uses Kevlar® extensively, but also incorporates fiberglass

plates which eliminate blast amplification in addition to providing more fragment protection.

The most pressing need is to understand the attenuation and transmission of air shock waves through layers of fabric (Kevlar® in particular). Even if changes to the present PASGT vest turn out to be impractical, the information gained will be very useful in terms of threat and casualty assessments. At the present time, overpressure exposure limits are based on unprotected personnel. Knowledge of the interaction of shock waves with vest materials will allow the presence of fabric layers over the human chest to be taken into account when preparing new safety criteria and blast overpressure exposure limits.

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APPENDIX

BASIC Program of Chest-Lung Model

REM BLAST PROGRAM

DIM P(1200,1), T(1200,1), F(1200,1), I(1200,1), Tt(1200,1), Ff(1200,1)

DIM Pso(1200,1), Pfalse(1200,1), Tfalse(1200,1), F1(1200,1)

!*****CONSTANTS FOR EQUATIONS*****!

Twind = .06

Hp=600

Hdp=10

D=Twind/Hp

Gaw=1.2

Po=14.7

Ppo=1.0133E+6

S=1.0

Const=1.334E+7

To=3.

Pso=2.5

Pro=2.*Pso+(6.*Pso*Pso)/(Pso+103.)

Pdo=20.

K=6.07

M=5.29

G=8.17

Ah=.025

A=98.

Vo=127.

Kk=K*1.75E+5

Mm=M*453.6

Gg=2.*SQRT(Kk*Mm)*G

Aah=Ah*6.4516

Aa=A*6.4516

Vvo=Vo*16.3871

!*****GRAPHICS COMMANDS*****!

GINIT

```

PRINT "DO YOU WANT A PLOT? ENTER 1 FOR YES."
INPUT Zzzz
IF Zzzz=1 THEN Drawing
GOTO Screen
Drawing: PLOTTER IS 705, "HPGL"
OUTPUT 705;"VS5"
Screen: X_gdu_max=100*MAX(1,RATIO)
Y_gdu_max=100*MAX(1,1/RATIO)
PRINT "DO YOU WANT BLAST WAVES OR ARBITRARY PULSES?"
PRINT "INPUT 1 FOR ARBITRARY PULSES"
INPUT Plots
LONG 6
CSIZE 3.3
DEG
LDIR 90
CSIZE 3.5
MOVE 0,Y_gdu_max/2
LABEL "OVERPRESSURE (psi)"
LONG 2
LDIR 0 MOVE X_gdu_max/2.2,.07*Y_gdu_max
LABEL "TIME (msec)"
VIEWPORT .1*X_gdu_max,.99*X_gdu_max,.15*Y_gdu_max,.9*Y_gdu_max
WINDOW -5,20,-5,20
FRAME
LONG 8
AXES 1,1,-5,-5,5,5,3
CLIP OFF
CSIZE 3.0,.75
LINE TYPE 1
LONG 6
FOR I=0 to 100 STEP 10
MOVE I,-5.20
LABEL USING "#,K";I
NEXT I
LONG 8
FOR I=0 to 50 STEP 5

```

```

MOVE -5.20,1
LABEL USING "%,DD";1
NEXT I
MOVE 0,0
!*****!
FOR J=1 TO 1
CLIP ON
!*****!
!*****LABELS*****!
CSIZE 2.5,.75
PRINT "WHERE IS LABEL X LOCATION?"
INPUT Lab1
PRINT "WHERE IS Y LOCATION?"
INPUT Lab2
PRINT "WHAT IS SPACE AFTER LINE SYMBOL?"
INPUT Spc2
PRINT "WHAT LINE LENGTH?"
INPUT Spc1
PRINT "WHAT IS SPACING BETWEEN LABELS?"
INPUT Spc3
LONG 2
!*****!
LINE TYPE 1
MOVE Lab1, Lab2
DRAW Lab1+Spc1,Lab2
MOVE Lab1+Spc1+Spc2,Lab2
LABEL "PRESSURE UNDER FABRIC"
!*****!
MOVE Lab1,Lab2-Spc3-Spc3
LINE TYPE 8,10
DRAW Lab1+Spc1,Lab2-Spc3-Spc3
MOVE Lab1+Spc1+Spc2,Lab2-Spc3-Spc3
LINE TYPE 1
LABEL "LUNG PRESSURE"
!*****!
MOVE 0,0

```



```

LINE TYPE 1
PLOT Tfalse(I,J),P(I,J)
Last1: NEXT I
!*****!
GO TO Lungtrace
!*****!
!*****REFLECTED OVERPRESSURE*****!
Real: FOR I=1 TO Np
MOVE 0,0
LINE TYPE 3,3
IF I>1 THEN GOTO First
DRAW 0,Pro
First: IF P(I,J)<0. THEN GOTO Last
PLOT T(I,J),P(I,J)
Last: NEXT I
!*****!
!*****LUNG RESPONSE MODEL*****!
Lungtrace: X2=0.
P2=Ppo
MOVE 0,0
LINE TYPE 8,10
Qq=1.334E+7
FOR I=1 TO Np
Vv=Vvo-Aa*X2
Delp=Pf(I,J)+Ppo-P2
Dptr=0.
IF Delp>0. OR Delp<0. THEN Dptr=Delp/((SQR(ABS)Delp))
Id=(X2-X1+D*D*(Aa*Delp-Gg*Id-Kk*X2)/Hn
P3=P2+D*(Gam*P2*Id*Aa+Qq*Ah*Dptr)/Vv
I(I,J)=I3/2.54
P(I,J)=(P3-Ppo)/68947.6
IF Plots =1. THEN T(I,J)=Tfalse(I,J)
PLOT T(I,J),P(I,J)
X1=X2
X2=X3
P2=P3

```

NEXT I

! ~~~~~ !

LINE TYPE 4,2

MOVE -10,0

DRAW 100,0

NEXT J

KUD