DEVELOPMENT OF FIBER SHIELDS FOR ENGINE CONTAINMENT

by
R. J. Bristow and C. D. Davidson
Senior Engineers

THE BOEING COMPANY
Seattle, Washington 98124

SUMMARY

A partial review is given of the progress at Boeing toward achieving a lightweight means for containing engine burst debris. This paper describes only the empirical work. Another paper at this meeting, by Dr. J. H. Gerstle, deals with the Boeing theoretical approach. The testing described was conducted in both translational launchers and spin pits. Empirical model development relating fragment characteristics to shielding requirements is given. The change in relative importance of shield mounting provisions as fragment energy is increased is given.

INTRODUCTION

The current shield design concepts have resulted from an evolutionary development that began in the early 1960's. Since that time, a group at Boeing has developed shielding for a wide range of threats: meteoroids, bullets, blast, hail, rain, and free-falling rocks, to mention a few. In all of these efforts, it was clear that shielding weight could be reduced if the projectile deceleration distance was increased. For lower velocity regimes, this could be accomplished by combining the properties of high shear resistance and elasticity in the direction of projectile motion. Certain fibrous materials can provide these properties.

Various fibrous materials have been used since the days of spears and arrows to shield against projectiles. More recently, fibrous shields have been used as "flak vests". At Boeing, glass fiber blankets have been used experimentally as blast shielding. It was natural, then, to try fiber blankets for engine containment. The first fibers tried, glass, performed better than metallic shields but the data was inconsistent. DuPont's Kevlar fabric was then tried and has developed into today's design concept.

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The development of the Kevlar shield has been undertaken with a two-pronged approach. An analytical computer model (EBCAP) was developed based on a theoretical approach, the M.I.T. Model JET 4B and other published data. The second approach used the empirical data to generate two empirical models that have in turn been used to solve design problems. The first empirical model (Figure 1) defined the weight of shield for various projectile sizes and the velocities at which the projectiles would be contained; this at a constant dynamic stiffness. The second model related the shield mount load to mount dynamic stiffness. Both approaches, analytical and empirical, were coordinated with the test program and are complementary.

BACKGROUND

In order to maintain continuity, earlier program results published in a previous paper* will be summarized.

Translational testing consisted of firing steel cubes from a smoothbore cannon into a test shield as shown schematically in Figure 2. Figure 3 is a photograph of the test range. The target assembly, shown in Figure 4, consisted not only of the test shield, but a series of thin aluminum plates. The plates, called "witness sheets," were used to determine the residual energy of the cube if the test shield was penetrated. The cubes were launched from the cannon by means of a polycarbonate sabot as shown in Figure 5. The ballistic limit was found by plotting penetration versus velocity as shown in Figure 6. (Ballistic limit is the limiting velocity below which shield penetration will not occur.) The figure shows the abscissa to be made up of shield layers plus numbers of witness sheets. The slanted line shows the number of witness sheets penetrated when the shield was removed. The "S"-shaped curve shows penetration with the shield in place. The number of Kevlar layers penetrated increased gradually with velocity until the ballistic limit was approached. At the ballistic limit, the penetrability of the cube increased greatly. At a velocity a little above the ballistic limit, the number of witness sheets penetrated was nearly equal to that with no shield at all. This signified that above the ballistic limit, the shield absorbed very little energy. From these data, the first empirical model was developed (Figure 1):

* Bristow, R. J., et al, "Advances in Engine Burst Containment, "AGARD-R-648, presented at the 42nd Structures and Materials Panel Meeting, NATO-AGARD, Ottawa, Canada, April 1976.
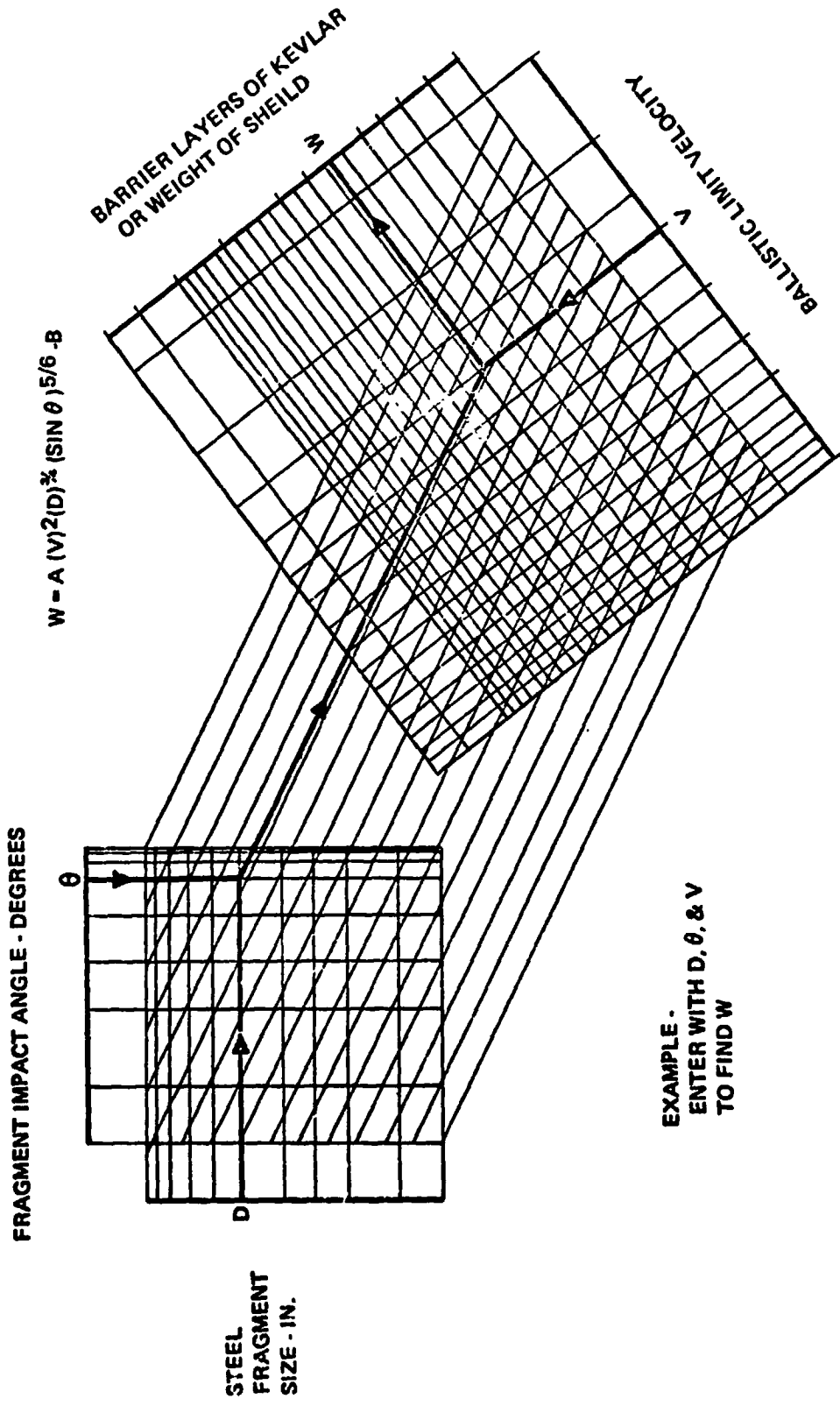
FRAGMENT IMPACT ANGLE - DEGREES

BARRIER LAYERS OF KEVLAR
OR WEIGHT OF SHEILD

BALLISTIC LIMIT VELOCITY

$W = A (V)^2 (D)^{3/4} (\sin \theta)^{5/6} - B$

STEEL
FRAGMENT
SIZE - IN.

EXAMPLE -
ENTER WITH D, θ, & V
TO FIND W

Figure 1. - Ballistic Limit Model.

$$N = A(V)^2(D)^{3/4}(\sin\theta)^{5/6} - B \qquad\qquad (1)$$

where:

      N = number of shield layers (Kevlar)

      V = cube velocity at ballistic limit - fps

      D = cube size - inches

      θ = angle between shield surface and flight path

  $A \& B$ = constants.

Other areas covered by the previous paper include temperature effects and the effect of spinning on fragment penetration. Since neither of these areas are pertinent to the subject of the current paper, they will not be reviewed.

One of the major efforts during the last year was the development of an attachment load model. The load involved was that in the mount of a particular shield arrangement with a particular dynamic stiffness. However, the form of the model should be general in nature and provides a great deal of information on shield design requirements. The data for the model were obtained using the test arrangement shown in Figure 7. One post was calibrated to read equivalent load at the centerline of the shield. In order to change effective mounting stiffness, a series of nylon ropes were run through the shield ends and looped around the posts as shown in Figure 8. The stiffness was varied by changing the length or diameter of the ropes. The resulting model was of the form

$$P = CV(D)^3(K)^{1/2}(N + E)^{-1/2} \qquad\qquad (2)$$

where:

      P = peak impact load (lb)

      K = stiffness of mount + attachments (lb/in)

  $C \& E$ = constants.

It should be pointed out that the form of the term involving the number of shield layers may be different for other shield arrangements.

Once an empirical model like the one above has been obtained, it is often constructive to examine it in detail in order to get an insight into the phenomenology involved. Notice that the peak load is directly proportional to the fragment velocity and mass. It is not too surprising that the load would be
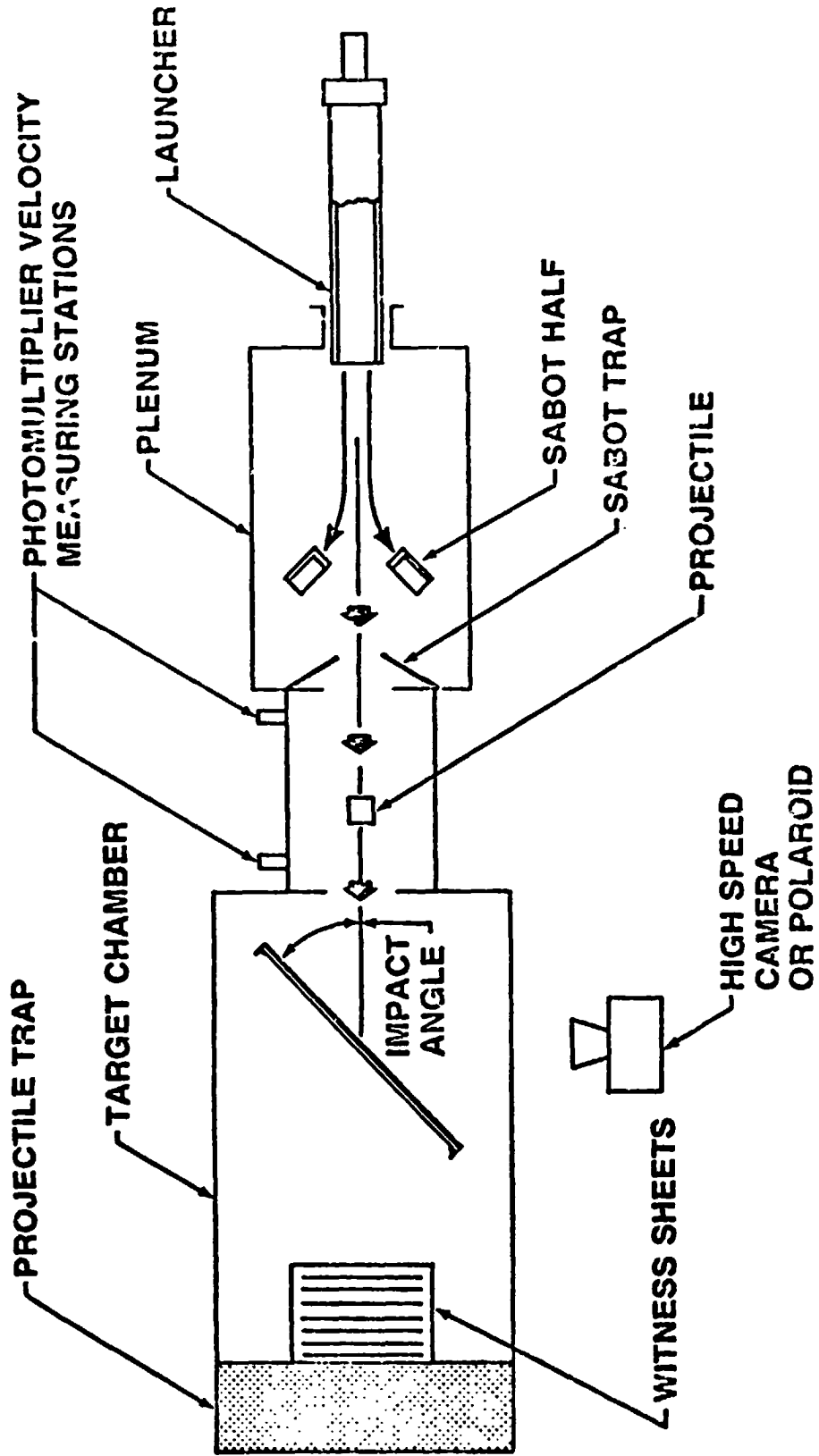
Figure 2. – Test Range Schematic.
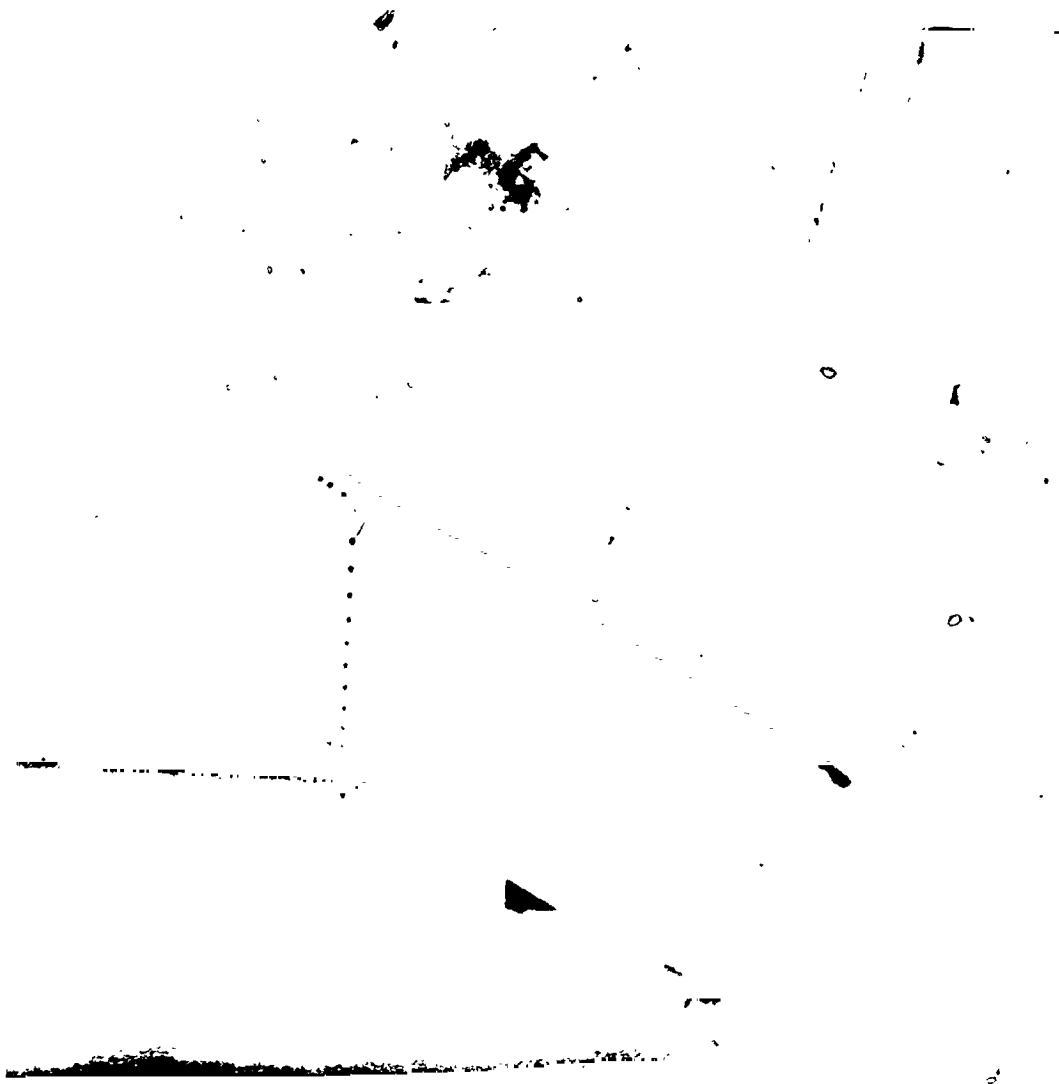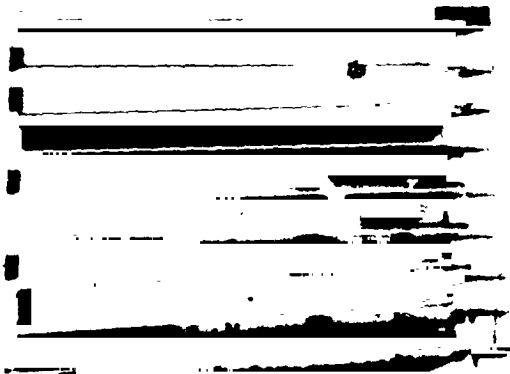
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Figure 3. – Test Range No. 2.

Figure 4. – "Flat" Shield and Witness Sheets.

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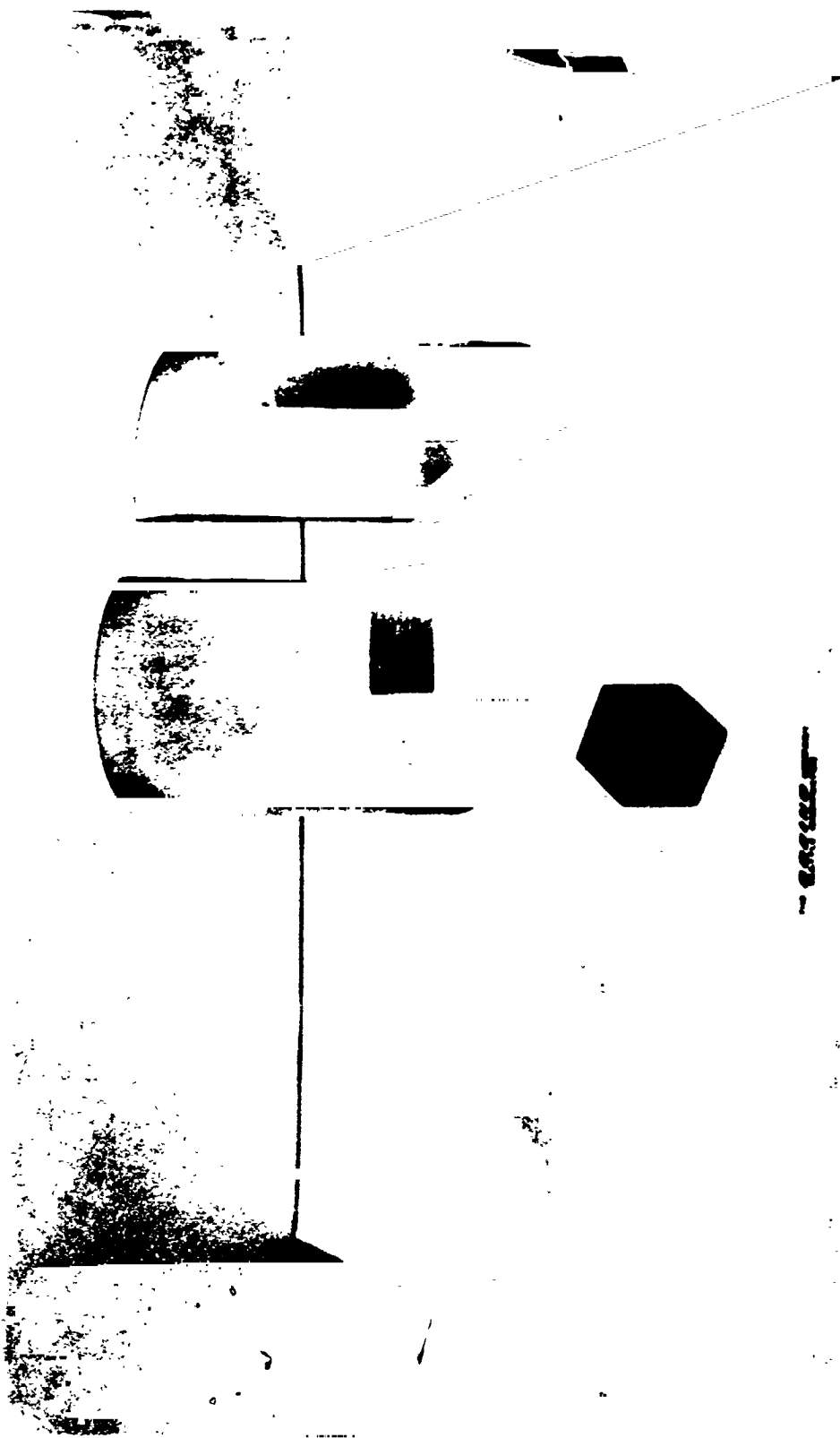
Figure 5. – Steel Cubes and Sabots.

Figure 6. – Test Date.

TOP
VIEW

BASE

POST

CUBE

SHIELD

POST

CUBE

SHIELD

BASE

STRAIN
GAGES

SIDE
VIEW
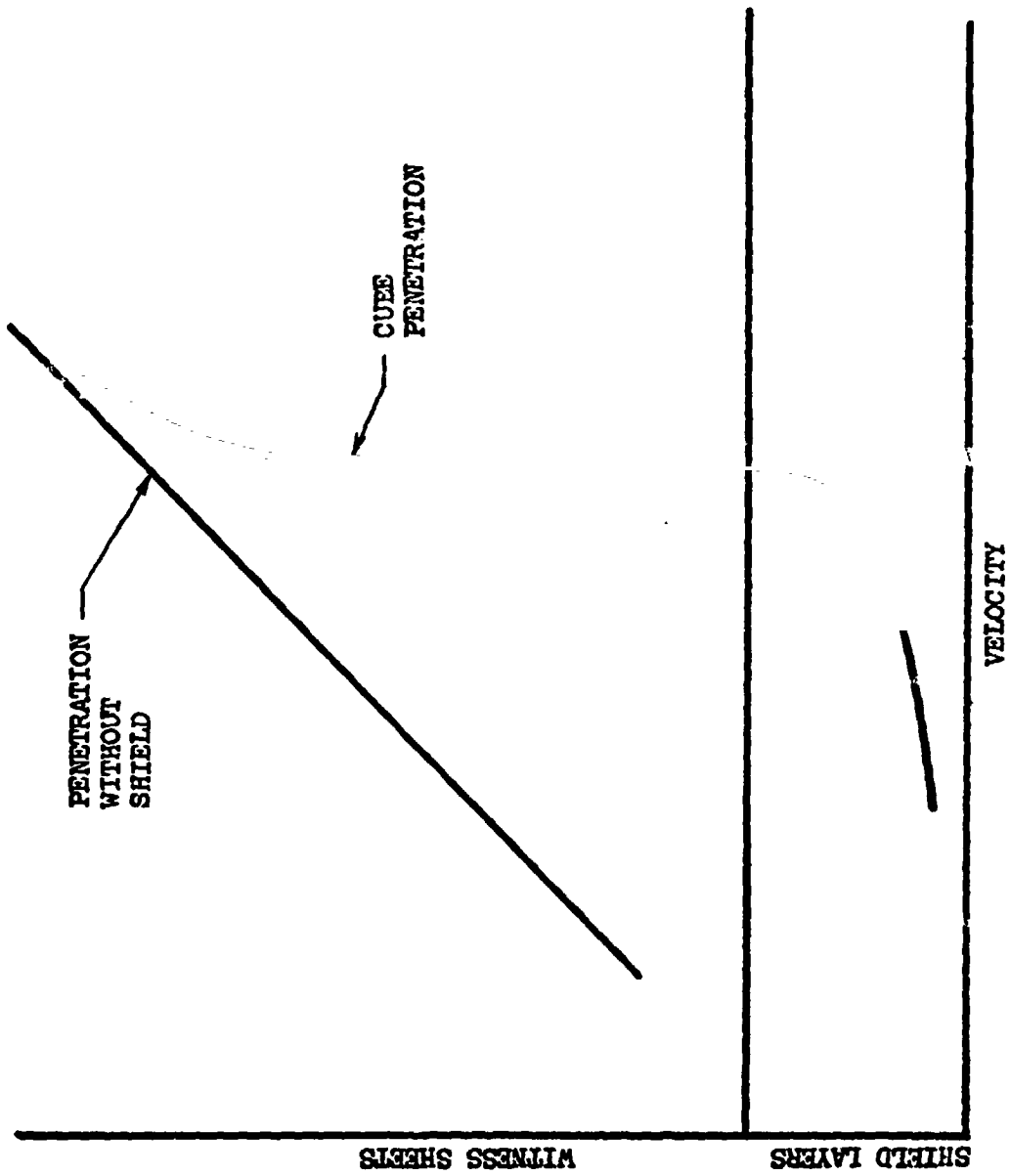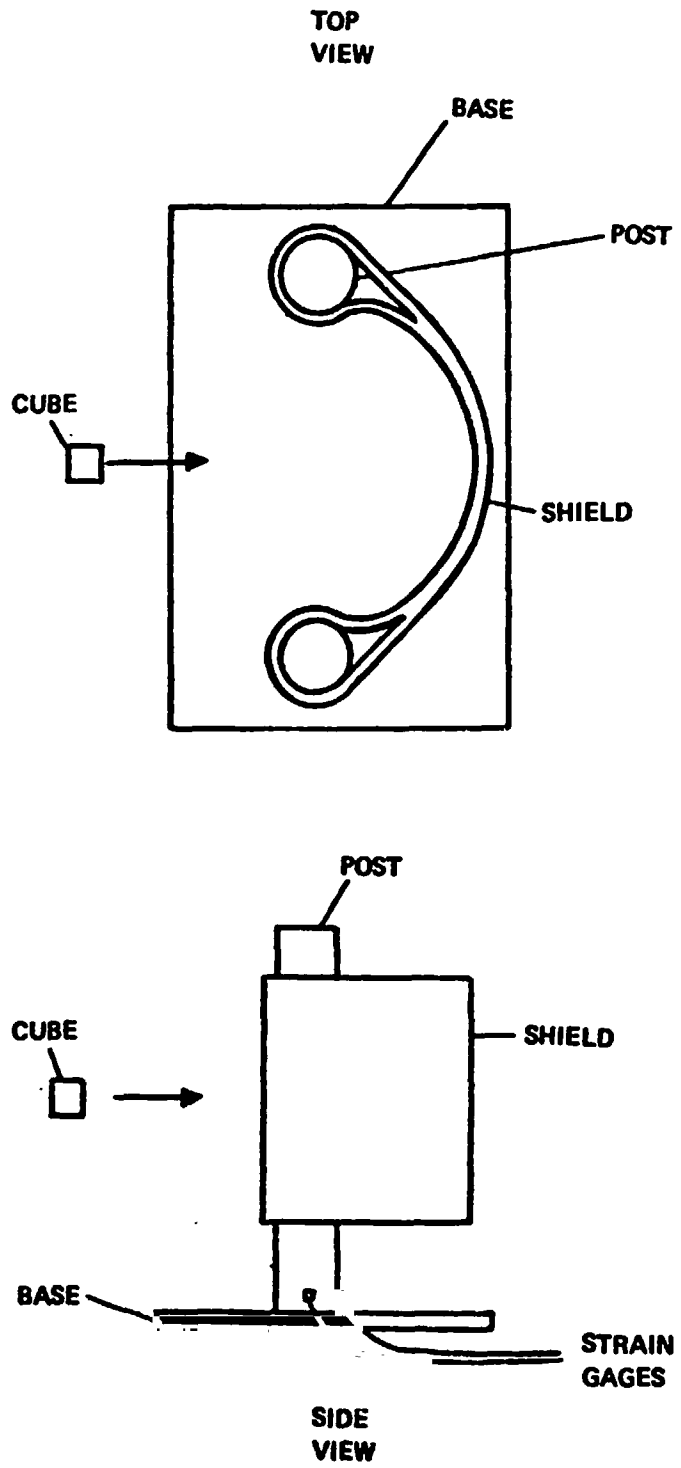
Figure 7. – Test Arrangement Schematic.

Figure 8. - Test Arrangements - Elastic Mount.

proportion⁻¹ to the fragment momentum. However, the load being proportional to the square root of the stiffness is a bit surprising. This is because we are accustomed to seeing the load in a spring being proportional to the spring constant times the deflection.

Once the relationship between peak load and stiffness was determined, it was tempting to try to use this relationship to get an equivalent relationship between stiffness and ballistic limit. The two models (Equations 1 and 2) show that in one case, load is directly proportional to velocity, while in the other, the number of shield layers required at the ballistic limit is proportional to the square of the velocity. Holding fragment size constant, and equating velocity between the two models, we get a relationship showing that the shield layers required should be directly proportional to the stiffness:

$$N \sim K \tag{3}$$

The above equation has not been substantiated. In fact, its validity is questionable because Equation 1 had to be simplified somewhat in order to derive the above equation. It is critical to any design procedure to know the relationship between ballistic limit and stiffness. The determination of this relationship is currently being derived at Boeing.

The last term in Equation 2 shows that the magnitude of the peak load is a function of the number of shield layers:

$$P \sim (N + const)^{-1/2} \tag{4}$$

This equation indicates that the peak load drops with an increase in shield layers. This is because the greater mass of shield material acts to transfer the load over a longer time interval. However, Equation (4) does not mean that an increase in shield layers will always decrease the load. The stiffness of the shield is also a function of the numbers of shield layers. The greater the number of shield layers, the greater the stiffness and hence, the greater the load. The result is that for a shield with few layers, the stiffness effect predominates and an increase in shield layers will result in an increase in load. For heavier shields, the mass effect predominates and the peak load then tapers off with an increase in shield layers. Figure 9 shows the change in peak load with changes in shield layers.
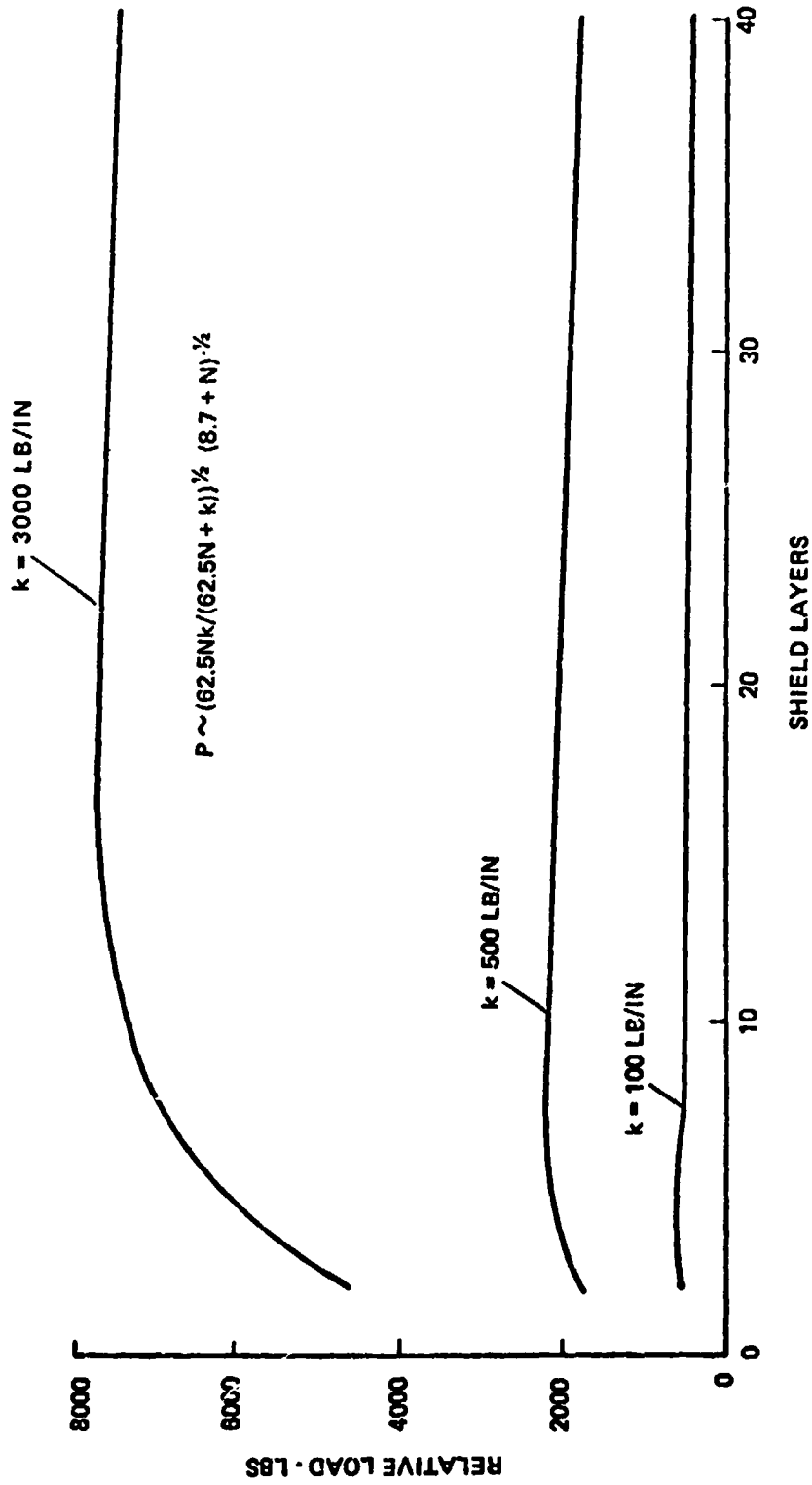
Figure 9. - Effects of Shield Density.

$$P \sim (62.5Nk/(62.5N + k))^{\frac{1}{2}} \ (8.7 + N)^{-\frac{1}{2}}$$

k = 3000 LB/IN

k = 500 LB/IN

k = 100 LB/IN

SHIELD LAYERS

RELATIVE LOAD - LBS

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The above paragraphs have shown that stiffnes is an important consideration in any Kevlar fabric shield design. The stiffness, as viewed by the projectile, can be written:

$$[K] = [k_S] + [k_A]$$ (5)

where:

K = total equivalent dynamic stiffness (lb/in)

k_S = shield stiffness (lb/in)

k_A = attachment stiffness (lb/in).

Algebraically, Equation (5) becomes:

$$K = \frac{k_S + k_A}{k_S \, k_A}$$ (6)

As discussed previously, the shield stiffness (k_S) depends on the number of shield layers. Because of this, for a shield with few layers, the shield stiffness soon predominates over the attachment stiffness. This is shown in Figure 10. The four-layer shield in Figure 10 results in a rapidly increasing load at low attachment stiffness levels. However, the attachment stiffness soon becomes so high that only the shield stiffness needs to be retained in Equation (6). As can be seen in the figure, this is also true for heavier shields except that the point where the attachment stiffness can be neglected occurs at a higher total attachment stiffness.

Another area receiving emphasis during the last year concerned large fragments. Steel cubes up to 3.75 in. in size were launched in translational accelerators. These large cubes were contained at energy levels of up to 544,000 in. lb.

These tests were interesting in that a new failure mode was discovered. It was found that at high energy levels with large cubes, a tensile failure occurred at some distance from the impact point. (Before, the normal failure had been shearing or local tension around the periphery of the projectile.) However, it was further found that reduction of the effective shield stiffness would again switch the failure mode to one of local failure at the impact point. This local failure was desirable since it occurred at a higher energy level than the tensile failure.
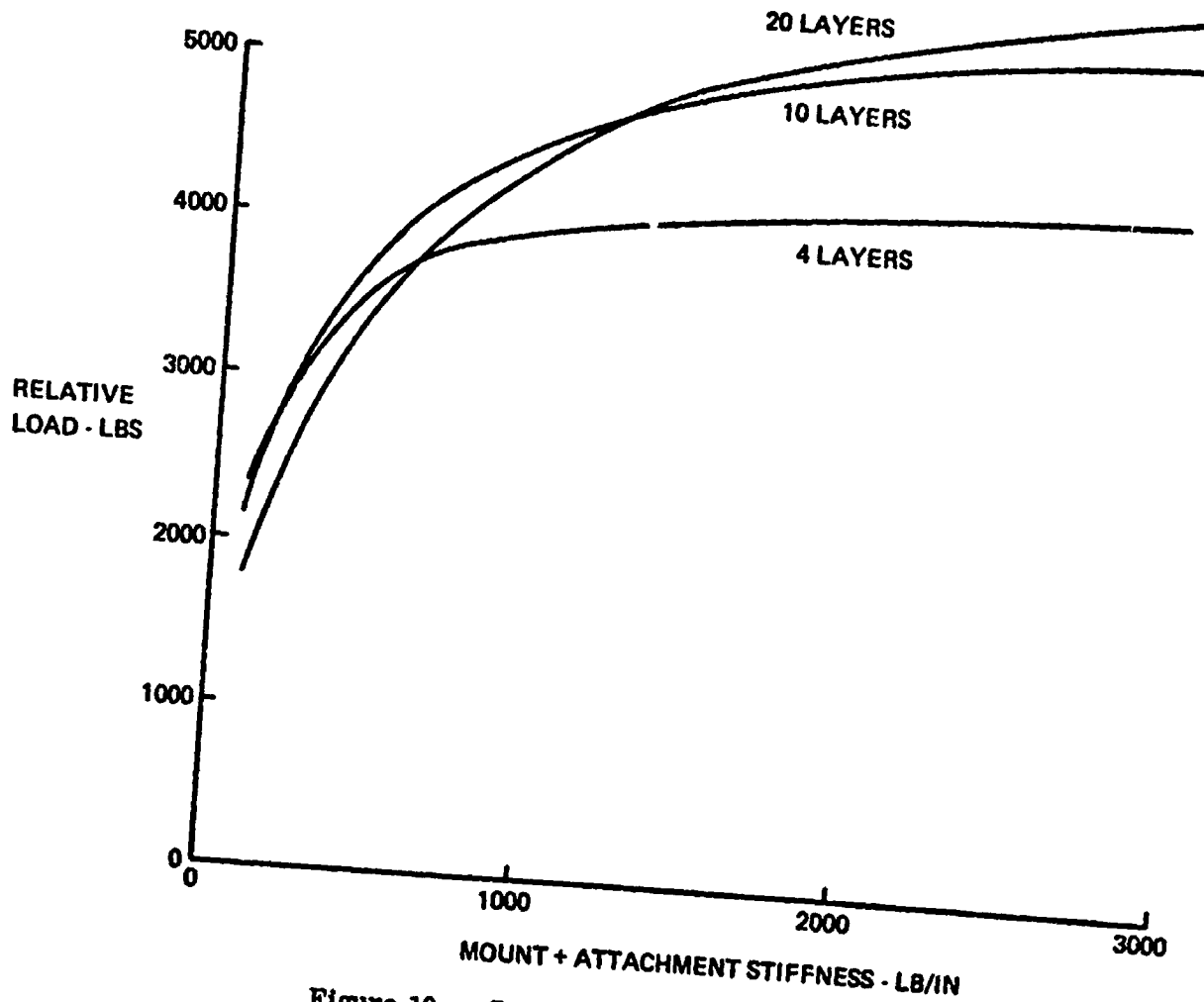
Figure 10. – Support Stiffness Effects.

Axis labels: RELATIVE LOAD - LBS; MOUNT + ATTACHMENT STIFFNESS - LB/IN

Curve labels: 20 LAYERS; 10 LAYERS; 4 LAYERS

The above tests, plus the load model, made it abundantly clear that stiffness is a major consideration in any fibrous shield design.

In order to check out the results obtained in the Boeing Impact Mechanics Laboratory translational accelerators, the Navy has been most cooperative with the use of the NAPTC spin pits. Several tests have been conducted with 14-inch-diameter rotors at about one million inch pounds of total energy. The shields consisted of a light aluminum ring (one pound) with a number of wraps of Kevlar (varying from 25 to 40). Recently, a successful test was made where a rotor with 8.7×10^6 in lb of total energy was contained by a 120 layer shield. It is expected that on later tests, this number of layers can be significantly reduced. In all cases, the spin pit test results were near those obtained with translational accelerators when adjusted for stiffness of the system.

FUTURE WORK

The largest task yet to complete is a model relating ballistic limit to stiffness. This model will then be combined with the earlier ballistic limit model to give required shield weight as a function of fragment size and velocity, angle of obliquity, and overall shield/mount stiffness. Another area of study involves techniques that will reduce the inherent Kevlar stiffness without losing its inherent strength. One method currently being examined involves wrapping the shield in such a manner that the material is stressed in the bias direction. Further tests in the spin-pit with the J 65 turbine are programmed; these will be useful in confirming the empirical models at higher energy levels and will identify the effects of multi-layer configurations. A number of other smaller study efforts will be made to fill in gaps or answer questions remaining from previous studies.

CONCLUSIONS

Boeing has been studying engine burst containment as part of a comprehensive damage mechanisms program. The last three years have been devoted to a study of Kevlar material as the basic containment medium. Models for ballistic limit and attachment load are available. The models have closely predicted the results obtained in spin pits. The importance of overall shield stiffness has been determined and shield designs are being worked out that will have the proper stiffness. Translational test energies have been pushed up to over 540,000 in lb,

while successful spin pit tests up to 8.7×10^6 in lb have been made. An areal weight of 1.7 lb/ft^2 was required for the spin pit rotor having one million inch pounds of energy while 8 lb/ft^2 was used for the 8.7 million inch pound energy rotor. This latter shield was not optimized and a lower areal weight is expected.

DISCUSSION

Unknown Speaker

What are the effects of moisture and temperature/time on Kevlar?

R.B. Bristow, Boeing

There is a report put out by du Pont on that subject, which indicates that Kevlar strength does indeed fall off with temperature and time. However, we were rather surprised during our tests to find that when we heated the Kevlar targets and fired the fragments into them, we actually had a higher ballistic limit. The reason being that the strain rate effects increased faster with higher temperature than does the degradation of the strength. This was covered in a previous paper that I mentioned, and is cited in my paper here as a reference. As far as moisture goes, I can't answer that.

D. Oplinger, Army-AMMRC

I was interested in your attachment or support load dropoff. With armor, that's usually considered to occur because the projectile shatters at a certain speed so that it becomes blunt. It's hard to visualize what would be causing this in the case of Kevlar.

R.B. Bristow, Boeing

I haven't been able to figure it out. One reason I brought it up was that we have many experts here and I'd like to find out what's causing it, if possible. I also might mention that I feel we've come a long ways with Kevlar but we're a long way from having something that's suitable for putting on an airplane. There's lots of design considerations that we haven't even begun to consider.

P. Gardner, Norton Co.

That projectile that you passed around, the large cube, had some blunted edges on it. Was that from the impact with the Kevlar or did it fall on the floor after going through the first test panel?

R.B. Bristow, Boeing

The steel projectile was not deformed by going through the Kevlar. We fired it in tests both below and above the ballistic limit, so we could find that dividing line. This one has gone through the shield and struck a steel plate behind, and suffered this blunting of the edges.