ANALYSIS METHODS FOR KEVLAR SHIELD RESPONSE TO ROTOR FRAGMENTS

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ABSTRACT

Several empirical and analytical approaches to rotor burst shield sizing are compared and principal differences in metal and fabric dynamic behavior are discussed. The application of transient structural response computer programs to predict Kevlar containment limits is described.

For preliminary shield sizing, present analytical methods are useful if insufficient test data for empirical modeling are available. To provide other information useful for engineering design, analytical methods require further developments in material characterization, failure criteria, loads definition, and post-impact fragment trajectory prediction.

INTRODUCTION

Over the last couple of decades, there have been numerous efforts to develop predictive methods for blade containment design. These efforts have helped to reduce the costly full-scale testing required for design integrity validation.

Many efforts at shield sizing formulas were based on the assumption that a rotor fragment's kinetic energy can be equated to the available strain energy in the engine casing and other structures in the path of the fragment. Test data and analysis[1] usually indicate that a factor is required, namely:

$$E_f = C \sum_n U_n$$

where $\sum_n U_n$ is the sum of ultimate strain energies for the n material to be deformed, E_f is the fragment energy, and the range of the factor is roughly

$$0.05 < C < 10$$

depending on case materials, blade type, etc., as well as assumptions regarding the extent of deformed material.

Semi-empirical containment criteria have also been developed that relate fragment energy to shield thickness as well as other relevant physical parameters. These criteria can be generalized as having the form:

$$E_f = \sum_n f_n (h^b, \sigma_u, e, A, \theta)$$

where h is the material thickness, σ_u is the ultimate tensile or shear strength, e is the elongation, A is the contact area, shear area, or contact surface length, and θ = the angle of impact. Typically for metals:

$$2 \leq b < 3$$

implying that the thickness is a function of velocity (or momentum) when b = 2.

These criteria appear to generally be adequate when based on sufficient test data.

To reduce the dependence on test data, many other methods have been developed to predict impact response, especially in the field of ballistics. Before the availability of large-memory high-speed computers, such methods relied principally on quasi-static theories wherein the deformation shape was assumed a priori and various assumptions were made regarding material behavior, e.g., rigid-plastic, etc. (See reference 2 for further discussion and extensive references.)

One analytical containment criterion has recently been proposed[3] that considers both the short-term compressive and shear energy absorption in the contact region followed by longer term energy absorption due to overall structural deformation. This model, as well as the others, still neglects the contribution of bending stiffness which has been observed to be significant, although correlation with very high energy spin pit tests was found to be satisfactory.

During the last decade, transient material and structural response computer codes have advanced to the point where in weapon effects and other aerospace applications, large deformation transient response calculations are made routinely. Whether such techniques can be applied to containment prediction and specifically to the problem of Kevlar containment shielding, and whether they offer any advantages over empirical methods, will be the subject of the remainder of this paper.

BOEING KEVLAR SHIELD DEVELOPMENT PROGRAM

In 1972, an experimental program was initiated at Boeing to develop lightweight containment technology.[4,5] The initial tests used multilayered flat shields made of "S" glass fabric. Subsequent tests used Kevlar 49, then Kevlar 29. From these early tests, it was apparent that the very high strength-to-weight ratio and excellent ballistic impact properties justified further investigation, but the impact and structural behavior of Kevlar would be very different from steel or titanium alloys and would pose major installation difficulties.

The Kevlar program has been undertaken with a dual approach to the development of (math) models for shield sizing. One approach, an empirical model, has already been discussed in a previous paper.[6] The other approach is analytical and is based largely on existing transient structural analysis methods.[7] As such, the two approaches served the test program by providing complementary but independent projections.

Transient finite difference and finite element computational techniques were first applied to rotor fragment impact by Witmer et al. Under NASA funding, successive refinements have culminated in the CIVM-JET series of codes.[2,8,9] A similar approach was also adapted at Boeing to an existing finite difference large deflection plate/shell code, PETROS 3.[10] The converted program, called EBCAP, was specifically developed to predict the containment of woven fiber shields.[11]

BOEING ANALYTICAL APPROACH

The principal assumptions in EBCAP are that:

1. Fragment deformation is negligible.
2. The impact process is inelastic (i.e., zero coefficient of restitution).
3. For rotating fragments, the instantaneous coefficient of friction is essentially infinite (this would be incorrect for smooth-surfaced metal shields).
4. Multilayered Kevlar shields can be idealized as single layer membranes.

The flow diagram shown in Figure 1 illustrates the numerical procedure used to predict the motion of the fragment and shield.

For given initial conditions of fragment angular velocity, translational velocity, and incidence angle, the post-impact velocities of the fragment and shield are calculated. Next, the nodal displacement components for the first time increment, $t = \Delta t$, are found from the nodal velocities. The midsurface geometric quantities at each mesh point are then calculated from the displacements, followed by the strain increments and then the stresses. A stress failure criterion is evaluated to determine if the shield fibers could have ruptured. If not, the stresses are used to calculate stress resultants from which the new velocities are found by solving the equilibrium equation, thus specifying the new displacements. Next, the fragment's position is updated to correspond to the new time according to equations of motion. A check is made to see if the effective fragment radius overlaps any mesh points. If not, the program flow cycle is repeated. Otherwise, a collision is assumed to have occurred and the impact analysis procedure is used to calculate velocity increments that are superimposed on the vibratory motion before entering a new cycle. The process ends if a failure is predicted, a maximum time is reached, or a numerical stability condition is violated.

A principal difference between EBCAP and the CIVM-JET codes is that momentum transfer occurs over an area of the shield larger than the immediate contact area due to stress wave propagation over the duration of the numerical time step, Figure 2.

FLAT PLATE IMPACT TEST PREDICTIONS

Kevlar shields dissipate the fragment energy almost wholly by tensile deformation. The mechanical energy is distributed rapidly throughout the fabric shield, relative to metal response, due to the fiber's high wave speed and membrane response. Transverse wave propagation, while not quantitatively predictable for a nonbonded structure, is attenuated extremely quickly. The in-plane compressive stresses cause buckling, which in these analyses are only crudely taken into account by setting the compressive stiffness to zero.

The measured peak displacement as a function of time from an early Kevlar test is shown in Figure 3. In this experiment, a 1-inch nonrotating steel cube was shot at the center of a rectangular flat shield with an incidence angle of 60 degrees with respect to the plane of the shield. The projectile velocity was reduced from 876 fps at impact to 250 fps after perforation. The shield was riveted to steel reinforcements at the top and bottom which in turn were bolted to a heavy steel frame. The shield was unattached at its two sides. The shield was composed of two materials. The first layer was a thin steel plate that may be regarded as simulating a support panel. This steel panel was experimentally found to reduce the residual projectile velocity by less than 10 percent for impact velocities above 800 fps. Twelve layers of Kevlar made up the rest of the shield. The deformation of the shield was obtained by high-speed photography. Experimental uncertainties are shown by error bars on the experimental data points.

To compare results, the predicted peak displacement time histories are also shown in Figure 3. In this analysis, the shield was idealized as a single layer of fabric clamped at the top and bottom edges. Since the fabric layers are neither bonded nor sewn together, only the initial transient response prediction is meaningful.

Details of this test comparison may be found in reference 7, but the principal conclusions were that the prediction of peak displacement did not vary significantly with node spacing and was consistently lower than measured. However, the actual shield deflections were also found to be partly due to buckling of the steel reinforcements and failure of some of the rivets, which unfortunately hinders the comparison. EBCAP will predict fastener failures, but cannot change the boundary conditions to physically model this effect. Another shortcoming of the analysis was probably the lack of material data, i.e., a linear stress-strain curve based on the static mechanical fiber properties of Kevlar was used.

The most direct computational approach for predicting containment limits is to start with very high fragment velocities and successively reduce velocity until the ballistic limit, the impact velocity at which the residual velocity is zero after perforation, can be estimated by extrapolation as shown in Figure 4. As the fragment velocity is lowered, the EBCAP calculations take more time steps to predict perforation, with the result that numerical inaccuracies build up and the physical simulation becomes increasingly more questionable.

The results from a series of tests to determine the ballistic limit are compared in Figure 4. It is seen that as impact velocities approach the ballistic limit of approximately 830 fps, the number of damaged (i.e., penetrated) fabric layers increases very rapidly for small increases in velocity.

To evaluate the effectiveness of the analytical method, the predicted residual velocities are again shown for two different mesh spacings. When the region of influence contains many mesh points, the predicted ballistic limits will generally converge with increasing numbers of mesh points.

In Figure 5, the correlation with higher energy flat Kevlar shield tests is compared to EBCAP predictions. Two sets of predictions are shown, one made with static properties, the other with modulus and ultimate stress measured at elevated strain rates. The use of this Boeing strain rate data did not shift the predicted ballistic limit significantly (although in other studies, the ballistic limit was raised up to 10 percent higher). The predicted ballistic limits are seen to be within 15 percent of the experimental ballistic limit.

In general, the analytical predictions for flat shield tests were comparable in accuracy to those from the empirical model.

CURVED SHIELD IMPACT TEST PREDICTIONS

A major analytical difficulty for either flat or curved shields is modeling flexible supports. Varying the material properties at nodes adjacent to the supports will lower the overall shield stiffness, but care must be taken to make the transition sufficiently gradual that large spurious stress waves are not generated by wave reflection.

As mentioned earlier, in many of our tests in the past two years, flexible supports have been successfully used to improve containment performance and also to simulate the response of ring shields by curved segment shields. In general, analytical predictions were not very satisfactory.

SPIN PIT TEST PREDICTIONS

In a recent test (No. 218) at the Naval Air Propulsion Test Center, three 120° pie segments from a T-58 rotor were contained at a burst speed of 20,550 rpm by a 6.7-lb ring shield made of 40 layers of Kevlar 29. The shield width of 6 inches was much larger than the blade chord length (approximately 1 inch) or disk thickness. The exact ballistic limit is unknown, but is regarded to be close to 20,550 rpm for this configuration. Figure 6 shows that perforation was predicted about 17,000-18,000 rpm, or equivalently, the predicted contained rotor burst energy is approximately 25 percent too low.

As discussed earlier, MIT has developed a series of special purpose finite element transient structural computer programs to simulate the response of rotor fragment/containment ring interactions. These programs restrict containment shield motion to be two dimensional, i.e., by a beam/ring idealization, in contrast to EBCAP, which allows for three dimensional geometry and motion. However, the latest code, CIVM-JET4B, has the capability of following the impact of up to 6 rotor fragments simultaneously, whereas EBCAP cannot model more than one fragment-shield interaction. In view of this, the CIVM-JET4B code was obtained with the hope that the use of both computer programs would lead to improved analytical predictions.

The Boeing version of the CIVM-JET4B program has incorporated several changes. Special logic was added to allow the idealization of Kevlar fabric as a membrane and the equivalent of buckling by not allowing compressive stresses. A shield failure criterion based on the maximum strain in an element is used to predict the shield failure similar to the logic used in EBCAP. The overall solution procedures are also similar.

Analyses of test 218 were also made with the modified CIVM-JET4B code. The results are shown in Figure 7 where the three points at each energy level indicate the residual energies calculated for each fragment. Containment is seen to be predicted approximately at 18,000 rpm.

No significantly different conclusions were drawn from predictions based on only the fragment translational energies.

As far as possible, the ECBAP and CIVM-JET4B runs were made using comparable mode spacing, time increments, and physical assumptions. The CIVM-JET4B results appear to be slightly better. The CIVM-JET4B results are expected to improve for lower ratios of shield width to fragment thickness.

A subsequent test, NAPTC test 221, was used to obtain an order of magnitude higher energy, approximately 10,000,000 inch-lbs. In this test, a 58-lb, 120-layer, 9-inch-width Kevlar shield was successfully used to contain at least two 120° fragments from a J65 rotor burst at 8100 rpm. (The shield was intact, but lack of photographic evidence makes it difficult to ascertain if the nonimbedded fragment tumbled around the edges of the shield.) This test, however, indicated that considerably more further development work is probably required, for neither EBCAP or CIVM-JET4B came close to providing as satisfactory shield sizing predictions as the empirical model.

If future needs indicate that Kevlar or other woven fiber materials warrant more detailed consideration, then such development work should be directed toward present shortcomings such as the idealization of multilayered Kevlar wraps as a membrane, and modeling of load transfer processes when inner layers of the shield are torn. More extensive material data for Kevlar would also be useful since so little is known about its fabric properties, damage tolerance, etc.

CONCLUSIONS

At present, special purpose structural dynamics computer programs for rotor fragment containment prediction are only advantageous for Kevlar or other woven fiber shield sizing when there is insufficient test data for empirical modeling.

To be useful for engineering design, analytical methods such as JET4B should continue to be developed under NASA sponsorship, but with emphasis on shield failure and attachment loads with consideration for structural behavior differences between metals and woven fiber and in the long-term, post-impact fragment path prediction.

Development of a 3D finite element program with similar emphasis should also be continued, which could offer the capability for analysis of off-center fragment impacts, one-sided displacement constraints, and varying shield thickness or material properties in both circumferential and axial directions.

REFERENCES

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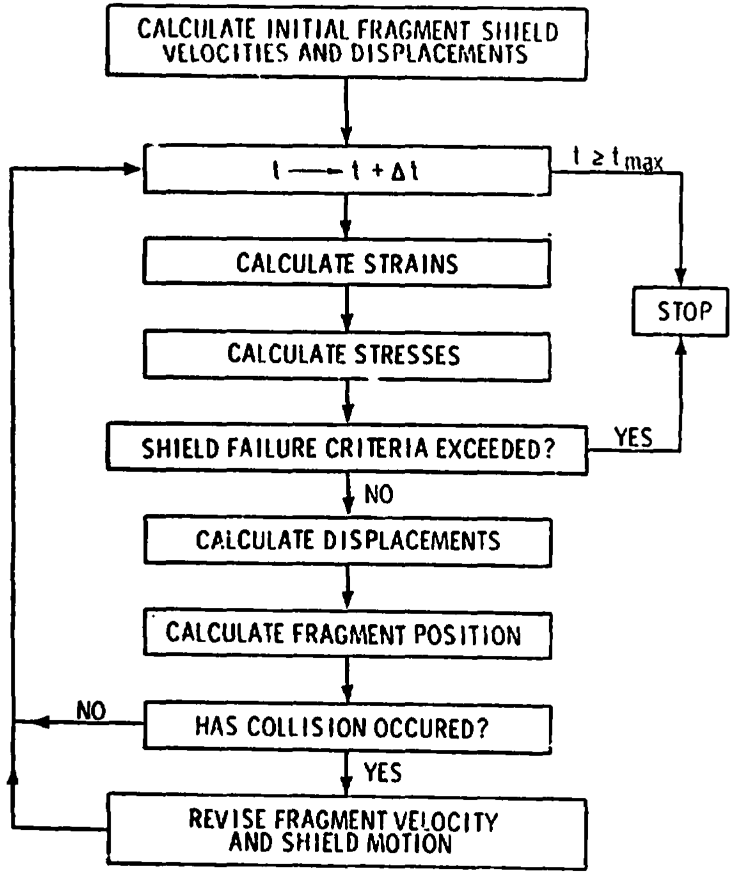

Figure 1. - Solution Procedure.

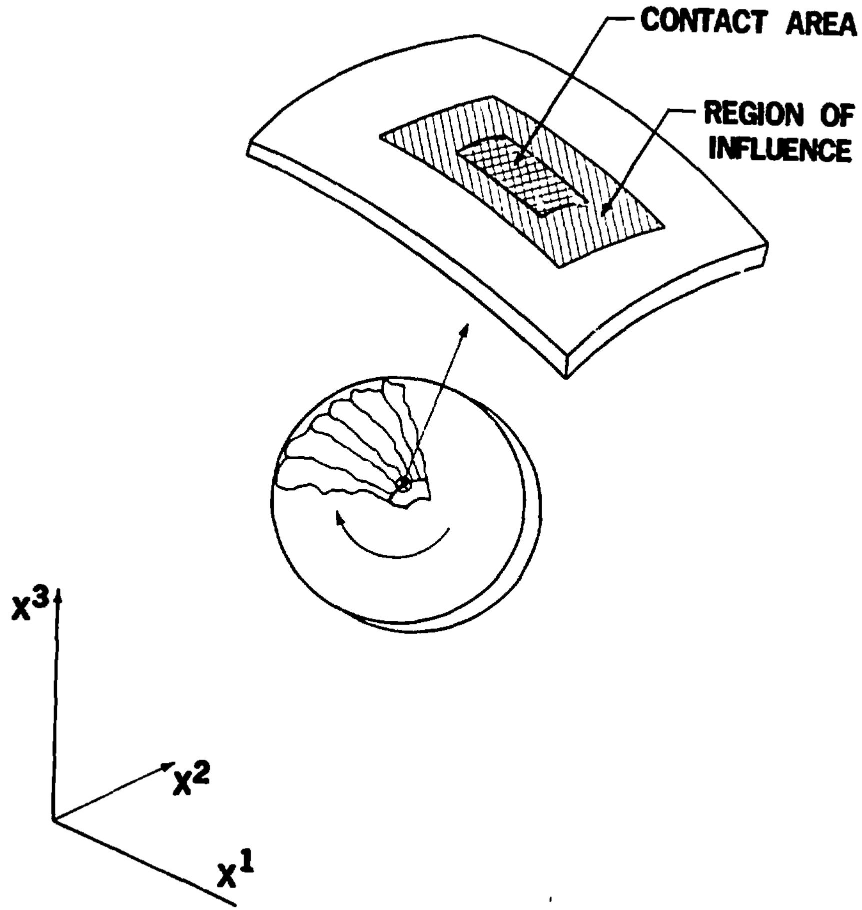

Figure 2. - Effective Instantaneous Structural Excitation Area.

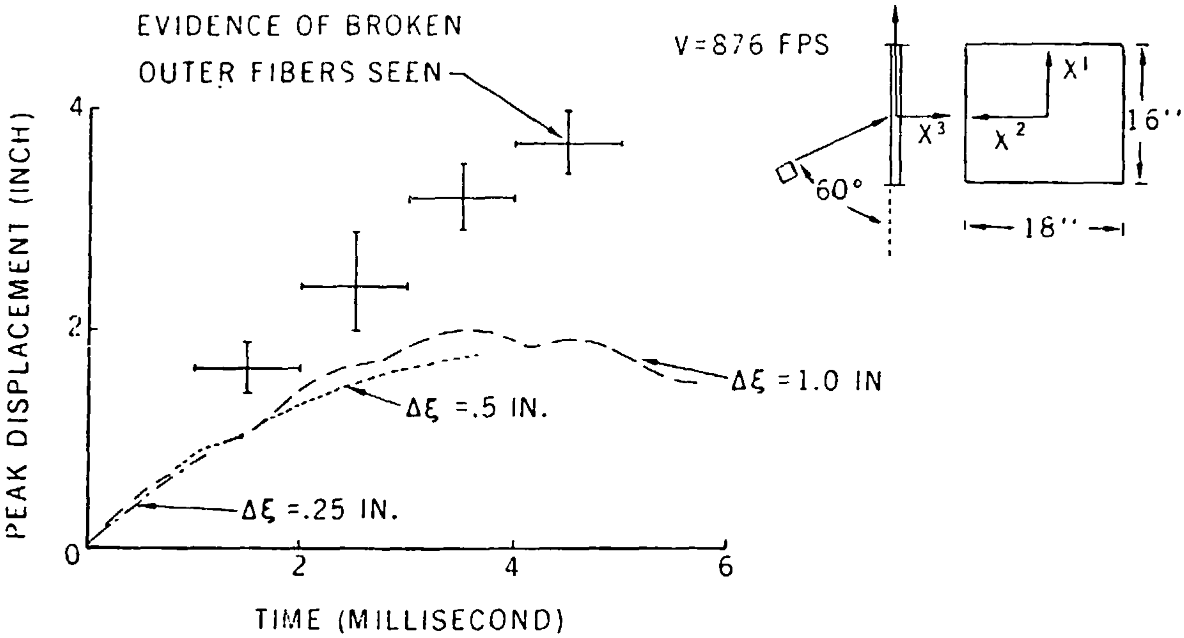

Figure 3. - Comparison of Predicted and Measured Peak Displacement in Oblique Impact Material Configuration Test.

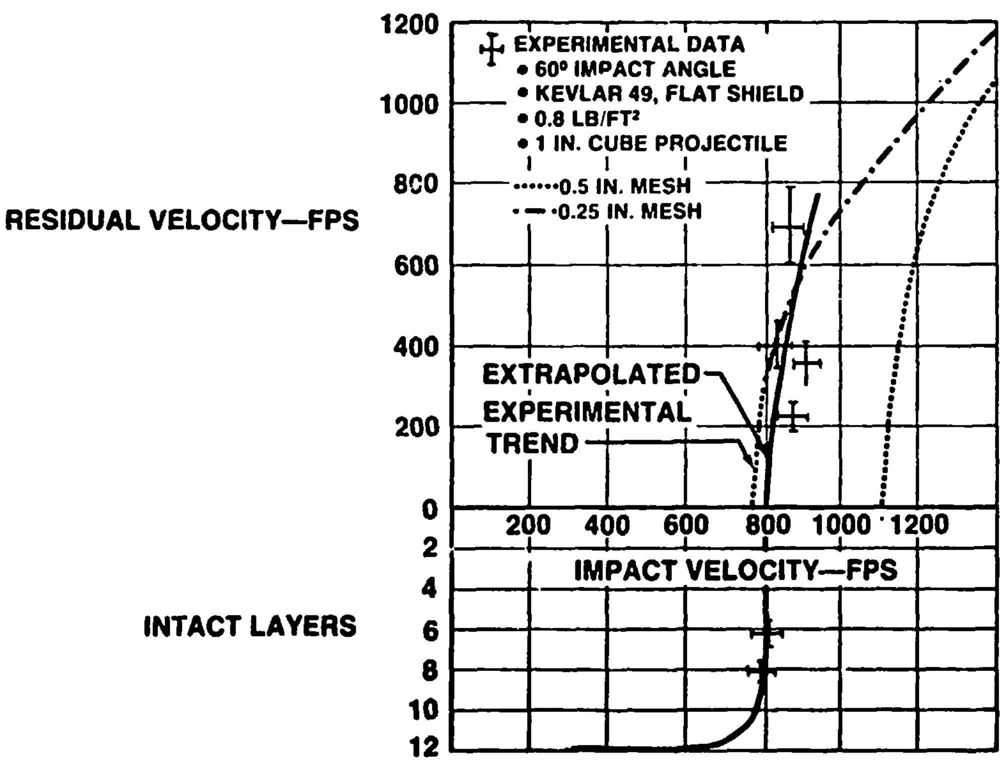

Figure 4. - Predicted and Measured Residual Velocities.

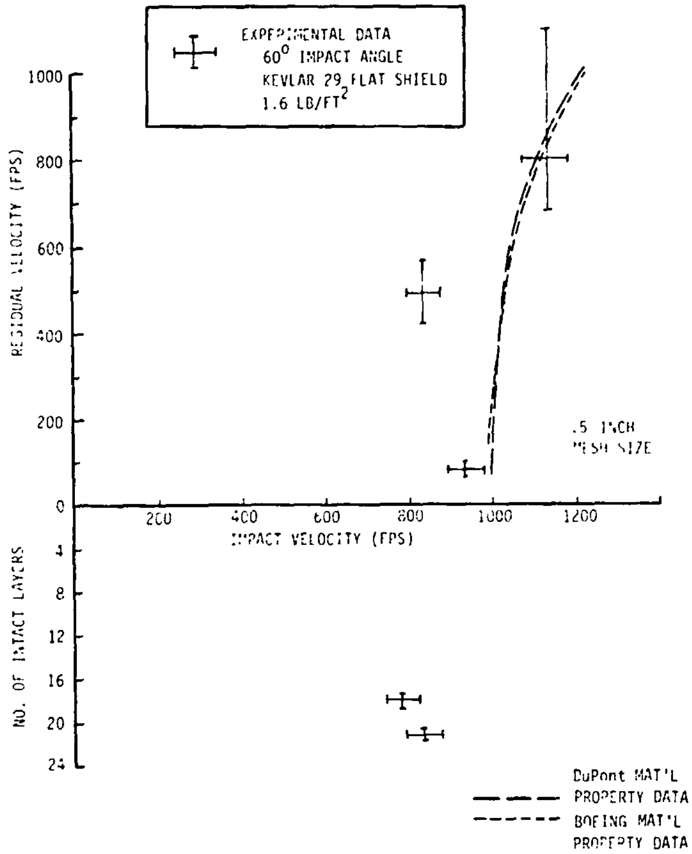

Figure 5. - Comparison of Predicted and Measured Residual Velocities For 1.5 Inch Cube Projectile.

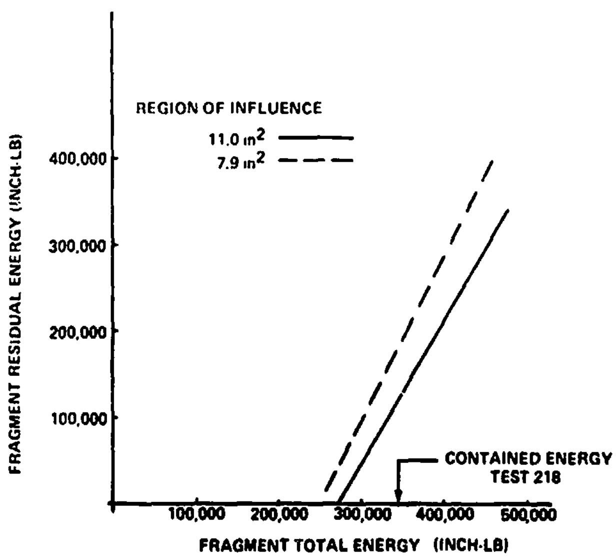

Figure 6. - EBCAP Predictions For NAPTC Spin Pit Tests.

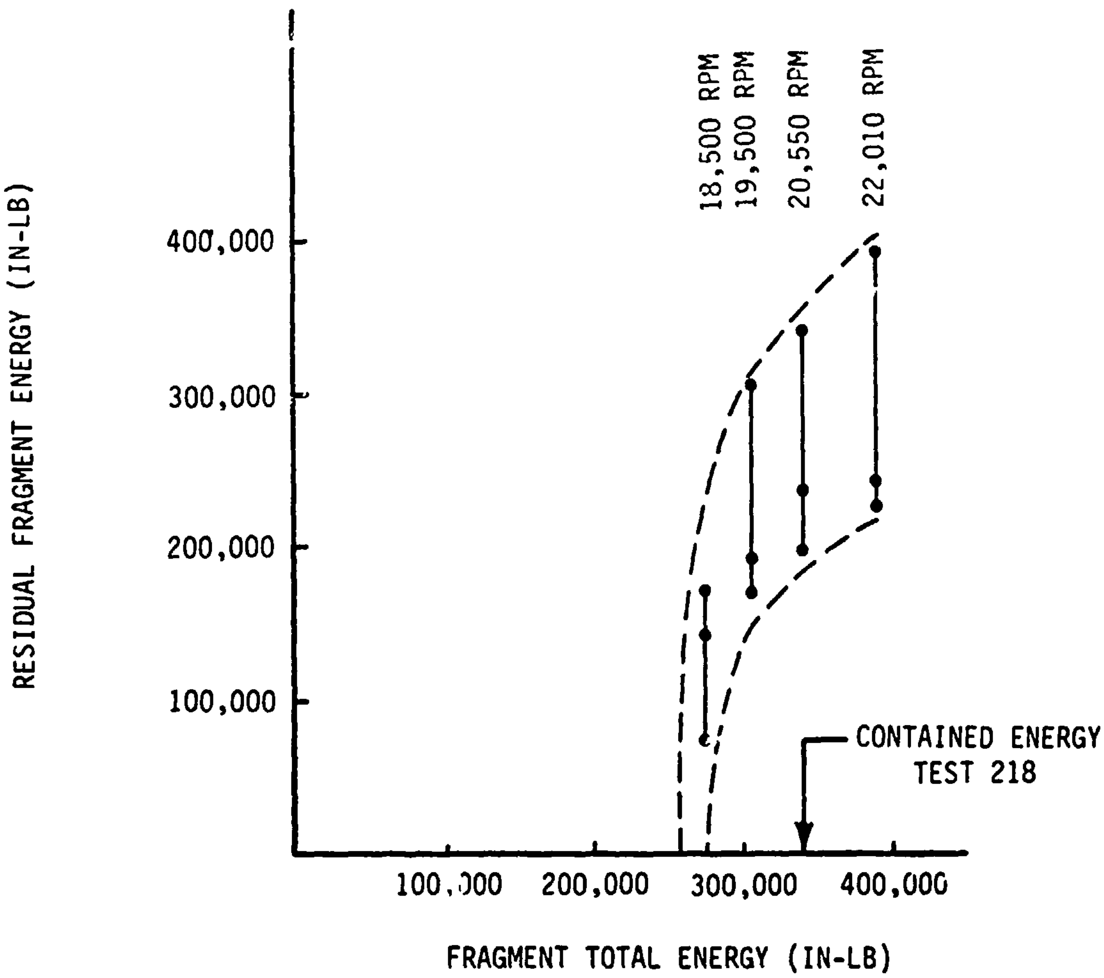

Figure 7. - JET4B Predictions For NAPTC Test 218.