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Summary Report
Continuation of
Experimental Study of Small Particle Impacts
Into Ablative Materials
[Unclassified Title]
S. M. Halperson
Sponsored by
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NATIONAL SECURITY AGENCY
WASH. DC 20330
This report is a continuation of the work described in NRL Memorandum Report 1813, entitled "Experimental Study of Small Particle Impacts Into Ablative Materials".

Utilizing the light-gas gun, impact tests with glass spheres from 3.18 mm to 100μ in diameter were made into three ablatives; phenolic nylon, carbon phenolic, and oblique tape wound refrasil. Velocities ranged from 0.74 to 7.9 km/sec and angles of obliquities ranged from 10° to 90°.

It was established that modified explosive scaling does not hold true for hypervelocity impacts into ablatives, and dimensionless damage parameter such as penetration/projectile size are dependent on both velocity and projectile dimension rather than on velocity alone.

Penetration measurements of virgin phenolic nylon targets impacted by 3.18-mm aluminum spheres showed good correlation with the theoretical formula of Walsh. It was also determined that for obliquity tests where the normal velocity component/target sound speed ≥ 1, the mass loss and depth of penetration are proportional to the normal velocity component for angles of obliquity down to twenty degrees.

Impact experiments were made with 1/2" x 1/2" x 1/4" char-layer specimens of carbon phenolic and oblique tape wound refrasil at room temperature and elevated temperatures, at normal incidence, and obliquities of 45° and 10°. Specimen mass loss was measured, and it was ascertained that for room temperature tests $C_N$ (impact energy/mass loss) tends to increase slightly with decreasing angles of obliquity. Experiments where char-layer surface temperatures were raised to approximately 1600°F showed an expected decrease in $C_N$. 
PROBLEM STATUS

This is the final report on the problem.

AUTHORIZATION

NRL Problem F04-11A
ARPA Order No. 149 Amendment No. 11
Program Code 6E30

ARPA Order No. 149 Amendment No. 12
Program Code 7E30
LIST OF SYMBOLS

\begin{itemize}
  \item \textbf{p.n.} : Phenolic nylon
  \item \textbf{c.p.} : Carbon Phenolic
  \item \textbf{o.t.w.r.} : Oblique tape wound refrasil
  \item \textbf{D} : Diameter of particle or spherical projectile
  \item \textbf{\theta} : Acute angle between target surface and trajectory
  \item \textbf{p} : Depth of penetration
  \item \textbf{v} : Impact velocity
  \item \textbf{\rho_p} : Density of projectile material
  \item \textbf{\rho_t} : Density of target material
  \item \textbf{C_t} : Sound speed of target material
  \item \textbf{K} : Coefficient in penetration equation
  \item \textbf{\alpha} : Exponent in penetration equation
  \item \textbf{V_c} : Crater volume
  \item \textbf{E} : Impact energy
  \item \textbf{n} : Number of particles striking a target
  \item \textbf{C_N} : Energy necessary to remove one gram of target material
  \item \textbf{M_{LH}} : Mass loss of target due to heating
  \item \textbf{M_{LI}} : Mass loss of target due to impact
  \item \textbf{M_L} : Total mass loss of target = \textbf{M}_{LH} + \textbf{M}_{LI}
\end{itemize}
SECRET

EXPERIMENTAL STUDY OF SMALL PARTICLE IMPACTS INTO ABLATIVE MATERIALS (U)

INTRODUCTION (U)

(S) This report is primarily concerned with extension of the work described in NRL Memorandum Report 1813, Reference 1. The problem is to simulate, in the laboratory, impact damage inflicted on thermal protection systems of ballistic missile nose-cones by minute dust particles. Erosive effects due to environmental factors such as rain or ice in the atmosphere or dust particles in clouds produced by nuclear explosions have not been previously considered by ballistic missile designers. It is estimated that nuclear dust clouds contain particles in the order of 20 μ in diameter which have a density of approximately 2.5 gm/cm$^3$, Reference 1. NRL has been specifically concerned with the small particle impact problem.

(U) The total damage to the protection system is dependent on a number of factors, many of which are interdependent. Encounter velocity, particle size, density, and trajectory with respect to the heat shield surface, environmental and thermal conditions at the heat shield surface, heat shield material and thickness are all contributing factors in evaluating the vulnerability of a R/V to dust particle impact.

(U) Impact tests have been completed at NRL with aluminum and glass spherical projectile projectiles ranging in size from 100 μ to 3.18 mm in diameter. The target materials were phenolic nylon (p.n.), carbon phenolic (c.p.), and oblique tape wound refrasil (o.t.w.r.). Measured impact velocities ranged from 0.74 to 7.9 km/sec. Appendix 1 is a compilation of pertinent test data obtained during this reporting period.

1 Secret
(U) A number of tests were conducted on specimens which had been pre-charred in a high temperature flame prior to impact. The specimens were at room temperature when impacted. This is a more realistic approximation to the actual situation than virgin material impacts, since impacts into virgin material occur only at the stagnation point or portions of the re-entry vehicle where the char has been removed by aerodynamic shear forces. Undoubtedly firing into a heated char-layer is a truer analog to an operational situation; towards this objective a small radiation heating facility has been built, and a limited amount of data has been acquired from heated char-layer target impacts.

(U) This report covers the following topics:

I. Instrumentation for small particle impact studies.

II. The effect of projectile size on impact damage.

III. Impact damage to virgin ablative materials.

IV. Impact damage to charred ablative materials.

I. INSTRUMENTATION FOR SMALL PARTICLE IMPACT STUDIES (U)

(U) All the terminal ballistic data reported were obtained with a 40-mm, 30-caliber light-gas gun; the range facility has been fully described in Reference 1.

A. Velocity Measuring Instrumentation (U)

(U) The velocity measuring system is similar to that described in Reference 1. Two Beckman and Whitley image converter cameras, Model 501, with associated instrumentation are used. Two camera stations are needed to provide sufficient information to determine projectile velocity. Camera no. 1 is a horizontally aligned camera which views the vertical plane; camera no. 2 is a vertically aligned camera which views the horizontal plane.
(U) The major difference between the current system and the previous system is in the triggering mode. For the microparticle studies, it was determined that placing a trigger plate (make-circuit) in the field of view of the first camera was more reliable than placing the trigger plate off camera and computing a camera time delay based on the expected velocity and the distance between switch and camera.

(U) In the current system, since the trigger is in the field of view, the first camera delay time is set at zero microseconds from triggering. The second camera is triggered by the first camera; the time delay is computed from the estimated velocity and the separation between the two camera stations.

(U) Figures 1a and 1b show three 400μ diameter spheres at stations no. 1 and no. 2; visible in the pictures are fiducial marks spaced 0.5 cm apart, and reference markers, 16.05 cm apart, which are spatial references at the stations. The cameras had exposure settings of 10 nanoseconds. Visible in Figure 1a is the trigger plate. Five spheres were launched, and the spray from a ball impact can also be seen in la. The timing trace for the round is shown in Figure 1c; the 5 μs marks are from a Tektronix type 180 time-mark generator.

B. Target Heating Instrumentation (U)

(U) A small radiation heating facility was built for the express purpose of heating the char-layer target specimens (1/2" x 1/2" x 1/4") during impact. A radiator was chosen because it has electromagnetic waves as its mode of transmission rather than a plasma-jet or an oxygen-acetylene torch which employs convection as the principal mode of heat transfer. The latter method would not be totally satisfactory since portions of the frangible char-layer would be removed by the gas flow, making it difficult to maintain char-layer integrity prior to impact.
Figure 2 is the schematic for the target heating system currently in operation at the NRL Small Particle Facility. The main component in this system is a tungsten coil heater, 7/8" inside diameter x 7/8" long, obtained from R.W. Mathes Company. The heater is powered from the low voltage-high current side of a transformer. Seventy ampere coil currents have produced temperatures in ablative samples slightly in excess of 2000°F. Temperature is measured with chromel-alumel thermocouples whose outputs are monitored on a Mosely type 680 recorder. The heater is mounted in a porcelain reflector open at both ends allowing the projectiles to pass through the heating chamber and impact the heated target without striking the heater or reflector. Disadvantages of this scheme are heater degradation and the resultant tungsten oxides evident on coil, reflector and specimen even at ambient pressures as low as 7-mm Hg air. This reaction is minimized by flushing out the test chamber with helium and performing the test in a reduced pressure helium environment.

II. EFFECT OF PROJECTILE SIZE ON IMPACT DAMAGE (U)

The effect of projectile size on impact damage is of extreme importance not only in this program but in other branches of hypervelocity impact. For this report the importance lies in the hypothesis that the nuclear dust cloud particle is approximately 20μ in diameter. Since the majority of meaningful impact data has been obtained with particles 200μ in diameter or greater, extrapolation of the data to the smaller size is necessary.

Until recently it has been believed that hypervelocity impact craters obeyed a modified explosive or Hopkinson scaling law. Applied to impacts, it can be stated that if two impacts are identical in all but size the craters' dimensions will be proportional to the cube root of projectile volume, i.e., to a characteristic projectile dimension, Reference 2. This can be expressed as
\[
\frac{P}{D_s} = f(v)
\]

or

\[
\frac{D_c}{D_s} = g(v)
\]

where \( P \) is depth of penetration, \( D_s \) is a projectile dimension, \( D_c \) is crater diameter, and \( f \) and \( g \) are functions of velocity. If, as is generally the case for hypervelocity impacts of compact projectiles into metals, a hemi-spherical crater is produced, this scaling law requires the crater volume \( V_c \) to be proportional to the projectile dimension cubed.

(U) If such a scaling law does not hold true then there can exist the more complex situation:

\[
\frac{P}{D_s} = f(D_s, v)
\]

\[
\frac{D_c}{D_s} = g(D_s, v)
\]

where \( f \) and \( g \) are now functions of both projectile size and velocity. As a result, determination of scaling laws becomes more complicated. A possible explanation as to why the modified scaling law does not hold true is material strain-rate effects. The yield stress is dependent upon the rate of loading of the material; this has been experimentally verified for many plastics and certain metals, References 3 and 4.

(S) Figures 3 and 4 show experimental curves which illustrate the above mentioned size effect. Figure 3 shows penetration versus sphere diameter for impacts of aluminum and glass spheres into phenolic nylon, and glass spheres into 1100F aluminum, Reference 1. For
these data the magnitude of variation in impact velocities is not considered to be a significant factor in determining the effect of particle size on damage, and a constant velocity situation is assumed. The conditions for the curves in Figure 3 can be summarized in the following equations:

\[
P_\text{mm} = 2.37D_s \quad (\text{mm})
\]

Velocity range: 6.1-7.7 km/sec

\[
P_\text{mm} = 2.42D_s \quad (\text{mm})
\]

Velocity: 6.3 km/sec

Although this report is primarily concerned with impact damage to ablative materials the aluminum data are presented to emphasize the validity of the size effect. Crater dimensions in soft aluminum can be measured more accurately than in brittle, frangible ablative materials.

(S) Numerical results for the penetration of a 20\mu particle into phenolic nylon from Equation (1) and the average value of \( \frac{P}{D_s} \), from Equation (1a) below are listed in Table 1.

\[
\frac{P}{D_s} = 2.30 \quad (\text{1a})
\]

<table>
<thead>
<tr>
<th>( D_s ) (mm)</th>
<th>( P ) (mm)</th>
<th>( P ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02</td>
<td>0.025</td>
<td>0.046</td>
</tr>
</tbody>
</table>

Equation (1a) will overestimate the depth of penetration by almost a factor of two. From the viewpoint of designing a protective system against micro-particle impact this would necessitate an undue weight penalty on the vehicle.
Since mass loss is material density, $\rho_c$, time crater volume, $V_c$, the validity of modified explosive scaling can be examined from mass loss information. This type of scaling would require the mass loss to be proportional to $D_s^3$. Equations (3) and (4) which have been obtained from experimental data show the exponents to be slightly greater than three.

Figure 4 shows $M_L$ or mass loss per impact versus particle size for phenolic nylon and o.t.w.r. ablatives. As with the penetration results, a constant velocity is assumed. The data have been fitted to straight lines on the log-log plot by the method of least squares. These curves are described by the following relationships:

\[
\frac{M_L}{n} \text{ (Grams/impact)} = 0.047 D_s^{3.503} \text{(mm)} \quad (3) \text{ Al & glass spheres } \rightarrow \text{ p.n} \\
\quad \text{Vel. range: 6.1-7.7 km/sec}
\]

\[
\frac{M_L}{n} \text{ (Grams/impact)} = 0.052 D_s^{3.169} \text{(mm)} \quad (4) \text{ Glass spheres } \rightarrow \text{o.t.w.r.} \\
\quad \text{Velocity: 6.4 km/sec}
\]

The agreement between the two curves is considered good, even though the data for o.t.w.r. are limited. For a 20$\mu$m dust particle Equation (3) will give

\[
\frac{M_L}{n} = 0.0525 \text{ micrograms/impact}
\]

while the average value of

\[
\frac{M_L}{nD_s^3} = 0.0607
\]

gives

\[
\frac{M_L}{n} = 0.486 \text{ micrograms/impact}
\]
As with the penetration predictions, the difference between the results predicted by the two equations is substantial, a factor of 9.2.

(U) Impacts into o.t.w.r. were not compared in a similar manner due to the lack of sufficient data.

III. IMPACT DAMAGE TO VIRGIN ABLATIVE MATERIALS (U)

A. Analysis of Depth of Penetration Data (U)

(S) Previously reported data (Reference 1) shown in Figure 5 for 3.18-mm aluminum spheres impacting phenolic nylon at normal incidence show good correlation with Walsh's theoretical formula, Reference 5:

\[
P_{Ds} = K \left( \frac{\rho_D}{\rho_t} \right)^{1/3} \left( \frac{V}{C_t} \right)^{0.58}
\]

where \( K \) is an experimentally determined constant obtained from one impact experiment or averaged from a series of experiments. Energy scaling, Reference 6, makes the exponent 0.667 (2/3) rather than 0.58. The numerical value for the constant, \( K = 1.20 \), is dependent on the strength of the impacted material and was averaged from all the impact data where the condition \( V/C_t > 1 \) held true.

(S) Also shown in Figure 5 is a curve obtained from a linear least squares fit on log-log paper of the data for \( V/C_t \); where \( \frac{P_{Ds}}{\rho_D} \left( \frac{\rho_t}{\rho_p} \right)^{1/3} \) was plotted as a function of \( V/C_t \).

The intercept at \( \log \frac{V}{C_t} = 1 \) gave the value of the constant, \( K \), equal to 1.284 and the slope provided the value of the exponent, 0.508; the agreement with the curve obtained from Walsh's expression is obvious.
(U) As discussed in Section II, projectile size can be of importance in determining crater dimensions. The data presented in Figure 5 are from the same size projectiles and the question of size is not pertinent.

(U) Additional data have been accumulated with 3.18-mm glass spheres into virgin p.n., virgin o.t.w.r., and virgin c.p. Velocities ranged from 0.74 to 7.9 km/sec and the firings were at angles of obliquity, 8, ranging from 45° to 90°. Also shown are data from Reference 1.

(S) Depth of penetration versus impact velocity plotted in dimensionless variables is shown in Figure 6 for the impacts described above. The ordinate is
\[
\frac{p}{D_s} \left( \frac{\rho_t}{\rho_p} \right)^{1/3}
\]
where \(P\) and \(D_s\) have been previously defined, and \(\rho_t\) and \(\rho_p\) are target and projectile densities respectively; the abscissa is the normal component of impact velocity, \(v \sin \theta\), divided by target sound speed, \(C_t\). The penetration depth is proportional to the velocity component normal to the surface with exception of very small angles of obliquity, in the order of twenty degrees and less.

(S) Two curves are shown on the graph. These were obtained from logarithmic least squares fits of all the data and for
\[
\frac{v \sin \theta}{C_t} \geq 1.
\]
An exponential equation of the form:
\[
\frac{P}{D_s} = K \left( \frac{\rho_p}{\rho_t} \right)^{1/3} \left( \frac{v \sin \theta}{C_t} \right)^{\alpha}
\]
was chosen.
For all data: \(K = 1.35, \alpha = 0.898\).
For \( \frac{v \sin \theta}{c_t} > 1 \): \( K = 1.71, \alpha = 0.453 \).

The ablatve materials can be evaluated in aggregate since they have similar pertinent physical properties: densities, sound speeds, and compressive strengths; see Table 2. The steep initial slope of the "all data" curve accounts for the 0.898 exponent. There is some indication of a transition occurring at \( \frac{v \sin \theta}{c_t} = 1 \).

The data above this value indicate that the depth of penetration is increasing at a slower rate as the velocity is increasing.

A complete theoretical solution to the high-speed impact problem is dependent upon the target material's constitutive equations. These equations describe the relationships between time dependent stress and strain fields within the material. The solution would predict crater dimensions for a given impact situation and a value of \( K \) could be determined by solving the penetration equation for \( K \). At this time the complete theoretical solution has not been successfully obtained, and experimental results are necessary to produce engineering curves for extrapolative and design purposes.

B. Analysis of Mass Loss Data

The amount of material removed from a thermal protection system due to hypervelocity impacts of dust particles is of primary importance for a vulnerability analysis of ballistic missiles. Tests have been conducted and correlations made of ablative material mass loss as a function of important test parameters such as impact energy, angle of incidence, etc., see Reference 1.
### TABLE 2
Mechanical Properties of Ablative Materials

<table>
<thead>
<tr>
<th>Materials</th>
<th>*O.t.w.r.</th>
<th>**Phenolic nylon</th>
<th>**Carbon phenolic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, gms/cc</td>
<td>1.55</td>
<td>1.19</td>
<td>1.49</td>
</tr>
<tr>
<td>Sound Speed, km/sec</td>
<td>3.0</td>
<td>2.9</td>
<td>3.7</td>
</tr>
<tr>
<td>Ultimate Tensile Strength, psi x 10^-3</td>
<td>1 - 5</td>
<td>1 - 5</td>
<td>15</td>
</tr>
<tr>
<td>Ult. Compressive Strength, psi x 10^-3</td>
<td>20 - 30</td>
<td>20 - 50</td>
<td>25</td>
</tr>
<tr>
<td>Tens. Modulus of Elasticity, psi x 10^-6</td>
<td>2 - 2.5</td>
<td>3 - 4</td>
<td>-</td>
</tr>
<tr>
<td>Comp. Modulus of Elasticity, psi x 10^-6</td>
<td>1.9 - 2.2</td>
<td>1 - 2</td>
<td>-</td>
</tr>
</tbody>
</table>


***Tests made at NRL.
An empirical equation to predict mass loss can be obtained in a straightforward manner if the hypothesis is accepted that the impact energy/crater volume is constant or has a weak dependence on velocity over the velocity region of interest. This has been experimentally proven for impacts into thick metallic targets, Reference 7.

Since the mass loss, $M_L$, is the crater volume, $V_c$, times the target density, $\rho_t$, the following relationship can be derived $M_L \propto \rho_t E$

where $E$ is the impact energy. In these tests $M_L$ was obtained in two ways: For spheres 400$\mu$m in diameter and smaller the targets were weighed before and after the tests with a precision balance, the mass loss being the difference between the two measurements; for spheres greater than 400$\mu$m in diameter the crater volume was measured by the displacement of a known volume of fine glass beads.

In Reference 1 it was determined that mass loss, $M_L$, for virgin ablative impacts was proportional to $E \sin \theta$ for angles of incidence from 90° to 20°. This is in good agreement with Reference 8 which showed that for oblique hypervelocity impacts of steel projectiles into lead targets the "cratering efficiency" defined as a ratio of the crater volume to the projectile energy is a linear function of the sine of the angle of obliquity up to about 15°. For ablative materials the mass loss is proportional to crater volume due to the absence of crater "lips".

Figure 7 is a log-log plot of $M_L$ as a function of $E \sin \theta$ for impacts of 3.18-mm glass spheres into p.n., c.p., and o.t.w.r.
at normal incidence. Data obtained during the current reporting period are shown on the graph; velocities ranged from 0.74 km/sec to 7.93 km/sec. The equation of the straight line was derived in Reference 1 from glass and aluminum impacts into the three ablative at impact angles greater than 20°. The equation reported in Reference 1 is:

$$M_L = 0.92 \ (E \sin \theta)^{1.15}$$  \hspace{1cm} (6)

where $M_L$ is in milligrams and $E$ is in joules. Experiments at angles of incidence less than 20° do not conform to the $E \sin \theta$ relationship but more closely to an $E \sin^2 \theta$ relationship, Reference 1; one possible explanation is that the component of velocity normal to the impact surface is appreciably lower than the target sound speed, therefore true hypervelocity impact conditions have not been achieved. In addition as the angle $\theta$ decreases, the projectile is "smeared" out along the frontal target surface, the energy per unit frontal area is smaller and less material is removed. It has been noted that for very shallow angles the entire projectile does not penetrate the target but portions of the projectile having considerable momentum travel along the surface and can have a severe damage potential.

IV. IMPACT DAMAGE TO CHARRED ABLATIVE MATERIALS (U)

(U) Although analysis of impact damage to virgin ablative materials has some importance in the dust erosion problem; primary interest is in damage to charred ablative material. During the re-entry portion of the ICBM trajectory virgin material will be exposed to impact only when the char material along the R/V is "scrubbed off" by aerodynamic shear forces or at the relatively thick stagnation point. The probability is that charred portions of the vehicle will be struck.
The difficulties inherent in obtaining meaningful terminal ballistics data with virgin ablative materials are compounded with charred materials. The chars are delicate and brittle, and extreme care must be taken in handling of the specimens. The specimens were 1/2" x 1/2" x 1/4" in size and nominal char thicknesses were 1/8" and 1/16".

A. Analysis of Room Temperature Char Impact Data (U).

Initial tests were made into charred phenolic nylon targets. Two hundred micron diameter glass spheres impacted specimens having nominal char thicknesses of 1/8" and 1/16". Impact angles were 90°, 45°, and 10°. Velocities were estimated from the standardized gun loading parameters when velocity measurements were unobtainable. These velocities were 6.4 km/sec ± 0.3 km/sec.

Impact damage to charred phenolic nylon targets was quite severe, large sections of char were removed from the surface and it was not possible to distinguish individual impacts. Due to the severe damage inflicted on the charred phenolic nylon targets, no correlations were made of damage characteristics such as mass loss with impact parameters. The data are listed and tabulated in Appendix 1.
(U) Meaningful information has been obtained from 200 and 400μ glass sphere impacts into carbon phenolic and o.t.w.r. specimens. Targets were weighed on a precision Mettler H16 balance to the nearest 0.1 mg shortly before and after each impact test to determine mass loss.

(S) The nature of the damage made it difficult to make an exact count of hits per target. Severe cracking and front spall- ing of the targets is evident, see Figs. 8 & 9. The following table lists the estimated error in determining the number of hits per target:

**TABLE 3**

<table>
<thead>
<tr>
<th>δn</th>
<th>n condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>n ≥ 15</td>
</tr>
<tr>
<td>2</td>
<td>10 ≤ n &lt; 15</td>
</tr>
<tr>
<td>1</td>
<td>5 ≤ n &lt; 10</td>
</tr>
<tr>
<td>0</td>
<td>5 &gt; n</td>
</tr>
</tbody>
</table>

where δn is the variation in the number of impacts, n.

(U) The experimental results are presented in terms of $C_N$, which is defined by the formula

$$C_N = \frac{nE}{M_L}$$  \hspace{1cm} (7)

where $E$ is the kinetic energy of a single particle, $n$ is the number of particles striking the target and $M_L$ is the target mass loss. Based on errors in evaluation of the number of impacts per target and the impact velocity, the variation in $C_N$, $\Delta C_N$, is:

$$\Delta C_N = \left(\frac{\delta n}{n} + 2 \frac{\delta v}{v}\right) C_N$$  \hspace{1cm} (8)

$\delta v = 0.3$ km/sec for $v = 6.4$ km/sec
A graph of $C_N$ in joules/gram versus angle of obliquity in degrees is shown in Figure 16. The 200$\mu$m and 400$\mu$m glass sphere data are averaged together, and it is the average values of $C_N$ which are plotted. Since there was only a factor of two difference in ball dimensions the effect of projectile size on damage is not considered significant. Error bars whose bounds are delineated by Eq. 8 are also shown.

The values of $C_N$ for the two materials are quite close, between two and three hundred joules/gram at the 45° and 10° obliquities. At normal incidence the carbon phenolic specimens were slightly stronger with a $C_N$ of 227 joules/gram as compared to 153 joules/gram for o.t.w.r. See Figure 10.

B. Analysis of Hot Char Impact Data

A limited number of shots have been made into char-layer samples of o.t.w.r. and c.p. that were being subjected to radiant heating. Phenolic nylon was not tested due to the extensive damage inflicted on the specimens and the difficulty in determining discrete impacts as discussed in Section IV A. The heating facility is described in Section I B. The flux rates, cal/cm²·sec, on the specimens are considerably lower than those for re-entering nose cones. Surface temperatures were measured with chromel alumel thermocouples and continuously monitored on a Mosely 680 strip chart recorder. The gun was fired when the specimen surface temperature was essentially constant; this usually took several minutes.

In analyzing the results of the hot char impact tests it is assumed that the material is removed by two independent mechanisms. The material is removed by gasification of the char
due to the intense heat, and by glass sphere impacts. This phenomenon can be expressed in equation form as:

\[ M_L = M_{LH} + M_{LI} \]  

(9)

where \( M_L \) is the total mass loss, \( M_{LH} \) is the mass loss due to heating, and \( M_{LI} \) is the mass loss due to impact. Separate heating tests were made to determine \( M_{LH} \). These tests were conducted to simulate as closely as possible the temperature history of the impact experiments. The results from the calibration tests are listed below in percentage of original target mass:

\[ M_{LH} \text{(o.t.w.r.)} = 2\% \]

\[ M_{LH} \text{(c.p.)} = 1.6\% \]

These findings were applied to heated char impacts and these results are also shown in Figure 10. Since the tests were limited in number, each is plotted individually. The data indicate a decrease of \( C_N \) for the heated targets. It takes less energy to remove a gram of heated char material than un-heated char material. This is expected since heating will cause the material to weaken and expand. The results for the tests are in reasonable agreement with those obtained in Reference 9 for impacts at 6.1 km/sec into heated carbon phenolic at a 12.5° angle of obliquity.

V. SUMMARY AND DISCUSSION OF RESULTS (U)

(U) The acquisition of meaningful terminal ballistics data from hypervelocity impacts into virgin and charred ablative materials is a difficult task. When the projectiles are micro-particles (400\( \mu \) in diameter and less) the difficulties are compounded by the necessity of keeping the targets small. However, from the investigations reported herein and in Reference 1, certain pertinent facts
about macro and micro-particle impacts into virgin and charred ablative materials have been determined.

(U) The effect of projectile size on impact damage, which has been noted for aluminum targets, manifested itself in ablative material impacts. Since the primary objective of the program is to determine the damage potential of 20μ diameter dust particles onto heat shield materials, this is an item of importance, as test projectiles were never smaller than 100μ in diameter. The majority of data was obtained with projectiles 200μ in diameter and greater.

(S) Summarized in Table 4 for virgin phenolic nylon are damage parameters, depth of penetration, P, and mass loss, M_L, described in equation form in terms of sphere diameter, D_S. These formulas can be used with some degree of confidence for purposes for extrapolation.

<table>
<thead>
<tr>
<th>Damage Parameter</th>
<th>Phenolic Nylon Target Glass &amp; Al Spheres</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity Range:</td>
<td>6.1-7.7 km/sec</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Penetration (mm)</th>
<th>= 2.37D_S^{1.167} (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass Loss (grams)</td>
<td>= 0.047D_S^{3.503} (mm)</td>
</tr>
</tbody>
</table>
(S) It was determined that depth of penetration from 3.18-mm aluminum sphere impacts into phenolic nylon can be predicted with reasonable accuracy by an equation suggested for metal to metal impacts by Walsh, Reference 5:

\[ P = \frac{K}{\sqrt{\frac{P}{\rho_t}}} \left( \frac{v}{C_t} \right)^{0.58} D_s \]

where \( K = 1.20 \) is a statistical average obtained from tests where \( \frac{v}{C_t} \approx 1 \).

(S) The effect of obliquity on penetration and mass loss of virgin ablatives was also studied, and it was concluded that both penetration and mass loss are proportional to the component of velocity normal to the impact surface for angles of obliquity between 20° and 90°. This is in good agreement with test results of hypervelocity steel projectiles into lead targets reported in Reference 8.

(S) An example will be shown of application of the results of this program. It is desired to know \( C_N \) for the impact of six interacting 20µ spheres, \( \rho_p = 2.5 \text{ gm/cm}^3 \), onto virgin p.n., and onto room temperature and hot char-layer c.p. and o.t.w.r. targets. Impact velocity is 6.3 km/sec and \( \theta = 10^\circ \). Lacking suitable 20µ impact test data, the following assumptions are made:

a) Projectile size and obliquity effects are independent of each other, and superposition of effects is valid.

b) The following equations having \( C_N \) as a function of projectile size and obliquity are valid for the specified encounters. These equations were derived in Reference 1.

\[ C_N = \frac{378}{\sin^2 \theta} \text{ (joule/gram) (9) } \theta < 20^\circ, \ D_s = \text{ constant } = 3.18 \text{ mm} \]
\[ C_N = C_1D_s^{0.418} \text{ (joule/gram)(10) } \theta = \text{ constant } = 90^\circ. \]
The constant $C_1$ is evaluated from values of $C_N$ obtained from test data or extrapolations or test data.

c) Available hot char-layer data at $\theta = 90^\circ$ can be extrapolated to $\theta = 10^\circ$ by assuming the hot char curves parallel the room-temperature char curves.

d) Damage augmentation results, Reference 1, Figure 27(b) are applicable to the stated situations.

(S) The results of the calculations are shown in Table 5 below. Appendix 2 shows detailed computations.

**TABLE 5**

<table>
<thead>
<tr>
<th></th>
<th>Without augmentation effect</th>
<th>With augmentation effect</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Virgin p.n.</strong></td>
<td>103,000</td>
<td>43,000</td>
</tr>
<tr>
<td><strong>Room temperature</strong></td>
<td>780</td>
<td>325</td>
</tr>
<tr>
<td>char-layer c.p.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>and o.t.w.r.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Hot char-layer (1600°F)</strong></td>
<td>525</td>
<td>220</td>
</tr>
<tr>
<td>c.p. and o.t.w.r.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
(U) An important unexplored aspect of the dust erosion problem is the study of the thermodynamic influences on impact damage to heated char-layer specimens. Proper thermodynamic scaling of flux rate, boundary layer thickness, etc. are necessary to create a truly realistic analog to an operational situation. The simplistic approach of de-coupling the thermodynamic and impact effects on char material removal, as used in this report, may not be realistic and this topic needs further study.
REFERENCES


Figure 1 - Photographs and timing trace for three 400w illuminator spheres, velocity: 29.2km/sec. (a) Camera No. 1, view of vertical plane. (b) Camera No. 2, view of horizontal plane. (c) Timing trace.
Figure 3 - Penetration versus sphere size for impacts of glass spheres into 1100F aluminum, and aluminum and glass spheres into phenolic nylon.
Figure 4 - Mass loss/impact versus sphere size for impacts of glass spheres into oblique tape wound refrasil, and aluminum and glass spheres into phenolic nylon.
Figure 5 - Penetration versus velocity for impacts of 3.18 mm aluminum spheres into phenolic nylon at normal incidence.
Figure 6 - Normalized depth of penetration versus normalized impact velocity for 3.18 mm glass spheres into phenolic nylon, oblique tape wound refrasil, and carbon phenolic.
Figure 7 - Mass loss versus impact energy x Sinθ for 3.18 mm glass spheres into phenolic nylon, carbon phenolic, and oblique tape wound refrasil.
Figure 8 - Before and after photographs of 1/8 inch char-layer carbon phenolic impacted by 400μ glass spheres at approximately 6.4 km/sec.
Figure 10 - $C_n$ versus angle of obliquity for 200 µ and 400 µ glass sphere impacts into room temperature and heated char-layer c.p. and o.i.w.r.
APPENDIX 1.
SUMMARY OF GLASS SPHERE IMPACT DATA (U)
MACRO-PARTICLE RESULTS

3.18 mm Diameter Spheres At Normal Incidence, \( \theta = 90^\circ \)

<table>
<thead>
<tr>
<th>Round No.</th>
<th>Mass (mg)</th>
<th>Velocity (km/sec)</th>
<th>Energy, E (joules)</th>
<th>Material</th>
<th>Penetration, P (mm)</th>
<th>Volume, ( V_c ) (cm³)</th>
<th>Mass Loss, ( M_L ) (gm) **</th>
</tr>
</thead>
<tbody>
<tr>
<td>0249</td>
<td>37.44</td>
<td>3.26</td>
<td>198.96</td>
<td>P.N.</td>
<td>6.20</td>
<td>0.26</td>
<td>0.31</td>
</tr>
<tr>
<td>0250</td>
<td>42.66</td>
<td>2.24</td>
<td>107.08</td>
<td>P.N.</td>
<td>4.06</td>
<td>0.06</td>
<td>0.07</td>
</tr>
<tr>
<td>0251</td>
<td>42.60</td>
<td>1.46</td>
<td>45.37</td>
<td>P.N.</td>
<td>1.91</td>
<td>0.04</td>
<td>0.048</td>
</tr>
<tr>
<td>0253</td>
<td>42.34</td>
<td>1.59</td>
<td>53.52</td>
<td>P.N.</td>
<td>2.92</td>
<td>0.03</td>
<td>0.036</td>
</tr>
<tr>
<td>0255</td>
<td>42.48</td>
<td>0.74</td>
<td>11.64</td>
<td>P.N.</td>
<td>1.52</td>
<td>0.04</td>
<td>0.048</td>
</tr>
<tr>
<td>0270</td>
<td>42.56</td>
<td>2.79</td>
<td>165.64</td>
<td>P.N.</td>
<td>6.32</td>
<td>0.12</td>
<td>0.14</td>
</tr>
<tr>
<td>0271</td>
<td>42.28</td>
<td>2.68</td>
<td>151.83</td>
<td>P.N.</td>
<td>5.41</td>
<td>0.28</td>
<td>0.33</td>
</tr>
<tr>
<td>0272</td>
<td>46.8</td>
<td>2.67</td>
<td>166.82</td>
<td>P.N.</td>
<td>5.94</td>
<td>0.24</td>
<td>0.29</td>
</tr>
<tr>
<td>0276</td>
<td>42.52</td>
<td>6.20</td>
<td>817.23</td>
<td>P.N.</td>
<td>10.05</td>
<td>1.45</td>
<td>1.72</td>
</tr>
<tr>
<td>0277</td>
<td>42.31</td>
<td>7.62*</td>
<td>1,227.97</td>
<td>P.N.</td>
<td>10.54</td>
<td>4.35</td>
<td>5.41</td>
</tr>
<tr>
<td>0278</td>
<td>42.32</td>
<td>7.45</td>
<td>1,174.38</td>
<td>P.N.</td>
<td>9.80</td>
<td>3.75</td>
<td>4.46</td>
</tr>
<tr>
<td>0279</td>
<td>42.10</td>
<td>7.62*</td>
<td>1,222.16</td>
<td>P.N.</td>
<td>8.61</td>
<td>3.90</td>
<td>4.64</td>
</tr>
<tr>
<td>0280</td>
<td>38.22</td>
<td>7.89</td>
<td>1,189.60</td>
<td>P.N.</td>
<td>10.05</td>
<td>4.40</td>
<td>5.24</td>
</tr>
<tr>
<td>0281</td>
<td>38.12</td>
<td>7.93</td>
<td>1,198.49</td>
<td>P.N.</td>
<td>10.31</td>
<td>3.75</td>
<td>4.46</td>
</tr>
<tr>
<td>0349</td>
<td>42.50</td>
<td>5.85*</td>
<td>727.18</td>
<td>P.N.</td>
<td>8.53</td>
<td>2.40</td>
<td>2.85</td>
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<tr>
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<td>5.93</td>
<td>670.85</td>
<td>P.N.</td>
<td>8.61</td>
<td>1.40</td>
<td>1.67</td>
</tr>
</tbody>
</table>

*Estimated from gun loading parameters.

**Obtained by multiplying \( V_c \) by \( \rho_c \).
### APPENDIX 1
SUMMARY OF GLASS SPHERE IMPACT DATA (U)
MICRO-PARTICLE RESULTS

**PROJECTILE**

<table>
<thead>
<tr>
<th>Round No.</th>
<th>Diam., D (mm)</th>
<th>Mass (mg)</th>
<th>Velocity (km/sec)</th>
<th>Energy, E (joules)</th>
<th>°</th>
<th>Material</th>
<th>Mass Loss, $M_t$ (gm)</th>
<th>No. of Impacts, n</th>
</tr>
</thead>
<tbody>
<tr>
<td>0285</td>
<td>0.1</td>
<td>0.0015</td>
<td>6.4*</td>
<td>0.403</td>
<td>90</td>
<td>O.T.W.R.</td>
<td>0.865x10^{-3}</td>
<td>13</td>
</tr>
<tr>
<td>0286</td>
<td>0.1</td>
<td>0.0015</td>
<td>6.4*</td>
<td>0.465</td>
<td>90</td>
<td>O.T.W.R.</td>
<td>0.949x10^{-3}</td>
<td>15</td>
</tr>
<tr>
<td>0282</td>
<td>0.2</td>
<td>0.012</td>
<td>6.36</td>
<td>-</td>
<td>90</td>
<td>1/8&quot; char P.N.</td>
<td>0.009</td>
<td>###</td>
</tr>
<tr>
<td>0283</td>
<td>0.2</td>
<td>0.012</td>
<td>6.37</td>
<td>-</td>
<td>90</td>
<td>1/8&quot; char P.N.</td>
<td>0.016</td>
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</tr>
<tr>
<td>0284</td>
<td>0.2</td>
<td>0.012</td>
<td>5.92</td>
<td>-</td>
<td>45</td>
<td>1/8&quot; char P.N.</td>
<td>0.028</td>
<td>###</td>
</tr>
<tr>
<td>0288</td>
<td>0.2</td>
<td>0.012</td>
<td>6.4*</td>
<td>-</td>
<td>10</td>
<td>1/8&quot; char P.N.</td>
<td>0.036</td>
<td>###</td>
</tr>
<tr>
<td>0289</td>
<td>0.2</td>
<td>0.012</td>
<td>6.4*</td>
<td>-</td>
<td>90</td>
<td>1/16&quot; char P.N.</td>
<td>0.030</td>
<td>###</td>
</tr>
<tr>
<td>0290</td>
<td>0.2</td>
<td>0.012</td>
<td>6.4*</td>
<td>-</td>
<td>90</td>
<td>1/16&quot; char P.N.</td>
<td>0.023</td>
<td>###</td>
</tr>
<tr>
<td>0293</td>
<td>0.2</td>
<td>0.012</td>
<td>6.4*</td>
<td>-</td>
<td>45</td>
<td>1/16&quot; char P.N.</td>
<td>0.034</td>
<td>###</td>
</tr>
<tr>
<td>0304</td>
<td>0.2</td>
<td>0.012</td>
<td>6.4*</td>
<td>-</td>
<td>45</td>
<td>1/16&quot; char P.N.</td>
<td>0.014</td>
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</tr>
<tr>
<td>0306</td>
<td>0.2</td>
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<td>1.47</td>
<td>90</td>
<td>1/8&quot;char O.T.W.R.</td>
<td>0.010</td>
<td>6</td>
</tr>
<tr>
<td>0307</td>
<td>0.2</td>
<td>0.012</td>
<td>6.4*</td>
<td>0.98</td>
<td>90</td>
<td>1/8&quot;char O.T.W.R.</td>
<td>0.009</td>
<td>4</td>
</tr>
<tr>
<td>0308</td>
<td>0.2</td>
<td>0.012</td>
<td>6.4*</td>
<td>1.97</td>
<td>45</td>
<td>1/8&quot;char O.T.W.R.</td>
<td>0.010</td>
<td>8</td>
</tr>
</tbody>
</table>

*Estimated from gun loading parameters.
**Obtained by multiplying $V_c$ by $\rho_c$.
#Total energy of balls striking target.
##Unable to determine number of impacts.
### APPENDIX I

**SUMMARY OF GLASS SPHERE IMPACT DATA (U)**

**MICRO-PARTICLE RESULTS**

<table>
<thead>
<tr>
<th>Round No.</th>
<th>Diam. (mm)</th>
<th>Mass (mg)</th>
<th>Velocity (km/sec)</th>
<th>Energy (Joules)</th>
<th>Impact Angle (deg)</th>
<th>Material</th>
<th>Mass Loss, M_L (gm)</th>
<th>No. of Impacts, n</th>
</tr>
</thead>
<tbody>
<tr>
<td>0309</td>
<td>0.2</td>
<td>0.012</td>
<td>6.4*</td>
<td>1.97</td>
<td>45</td>
<td>(\frac{1}{16})&quot;char</td>
<td>0.085</td>
<td>8</td>
</tr>
<tr>
<td>0312</td>
<td>0.2</td>
<td>0.012</td>
<td>6.4*</td>
<td>0.266</td>
<td>10</td>
<td>(\frac{1}{16})&quot;char</td>
<td>0.009</td>
<td>1</td>
</tr>
<tr>
<td>0313</td>
<td>0.2</td>
<td>0.012</td>
<td>6.4*</td>
<td>3.69</td>
<td>90</td>
<td>(\frac{1}{16})&quot;char</td>
<td>0.011</td>
<td>15</td>
</tr>
<tr>
<td>0314</td>
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<td>0.012</td>
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<td>4.18</td>
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<td>(\frac{1}{16})&quot;char</td>
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<td>17</td>
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<td>(\frac{1}{16})&quot;char</td>
<td>0.013</td>
<td>9</td>
</tr>
<tr>
<td>0316</td>
<td>0.2</td>
<td>0.012</td>
<td>6.4*</td>
<td>2.46</td>
<td>45</td>
<td>(\frac{1}{16})&quot;char</td>
<td>0.011</td>
<td>10</td>
</tr>
<tr>
<td>0318</td>
<td>0.2</td>
<td>0.012</td>
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<td>10</td>
<td>(\frac{1}{16})&quot;char</td>
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<tr>
<td>0323</td>
<td>0.4</td>
<td>0.087</td>
<td>6.4*</td>
<td>1.78</td>
<td>90</td>
<td>(\frac{1}{16})&quot;char</td>
<td>0.011</td>
<td>1</td>
</tr>
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<td>0325</td>
<td>0.4</td>
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<td>1.78</td>
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<td>(\frac{1}{16})&quot;char</td>
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<td>0.4</td>
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<td>3.56</td>
<td>90</td>
<td>(\frac{1}{8})&quot;char</td>
<td>0.017</td>
<td>2</td>
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</table>

*Estimated from gun loading parameters.
**Obtained by multiplying V by \(c_r\).
#Total energy of balls striking target.
##Unable to determine number of impacts.
### APPENDIX I

#### SUMMARY OF GLASS SPHERE IMPACT DATA (U)

**MICRO-PARTICLE RESULTS**

<table>
<thead>
<tr>
<th>Round No.</th>
<th>Diam. (mm)</th>
<th>Mass (g)</th>
<th>Velocity (km/sec)</th>
<th>Energy (Joules)</th>
<th>No. of Impacts</th>
<th>Material</th>
<th>Mass Loss (gm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0333</td>
<td>0.4</td>
<td>0.087</td>
<td>6.4*</td>
<td>3.56</td>
<td>90</td>
<td>¼&quot; char</td>
<td>0.018</td>
</tr>
<tr>
<td>0340</td>
<td>0.4</td>
<td>0.087</td>
<td>6.4*</td>
<td>8.90</td>
<td>45</td>
<td>½&quot; char</td>
<td>0.033</td>
</tr>
<tr>
<td>0341</td>
<td>0.4</td>
<td>0.087</td>
<td>6.4*</td>
<td>7.12</td>
<td>45</td>
<td>½&quot; char</td>
<td>0.040</td>
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</tbody>
</table>

**O.T.W.R.**

<table>
<thead>
<tr>
<th>Round No.</th>
<th>Diam. (mm)</th>
<th>Mass (g)</th>
<th>Velocity (km/sec)</th>
<th>Energy (Joules)</th>
<th>No. of Impacts</th>
<th>Material</th>
<th>Mass Loss (gm)</th>
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<tbody>
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<td>0.032</td>
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<tr>
<td>0344</td>
<td>0.4</td>
<td>0.087</td>
<td>6.4*</td>
<td>3.56</td>
<td>90</td>
<td>¼&quot; char</td>
<td>0.071</td>
</tr>
</tbody>
</table>

*Targets Heated to Approximately 1600°F.*

**Experimental Results**

- Estimated from gun loading parameters.
- Obtained by multiplying $V_c$ by $\rho_r$.
- Total energy of balls striking target.
- Unable to determine number of impacts.

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(U) Shown below are the essential computations for the figures presented in Table 5.

(S) \( C_N \) for virgin p.n. is evaluated from Eq. (9) for \( \theta = 10^\circ \). This gives \( C_N = 12,500 \text{ joules/gm} \) for 3.18 mm spheres. Using this value of \( C_N \) in Eq. (10) and solving for \( C_1 \) gives Eq. (10a),

\[
C_N = 20,230 D_s  
\]

\[
-0.418  
\]

for \( D_s = 20 \mu = 0.02 \text{ mm} \), Eq. (10a) gives \( C_N = 103,000 \text{ joules/gm} \).

(S) For room-temperature char c.p. and o.t.w.r. at \( \theta = 10^\circ \), an average \( C_N \) is 250 joules/gm, see Figure 10. Equation (10) is evaluated for an average particle size of 300\( \mu \) to determine \( C_1 \). This leads to

\[
C_N = 152 D_s  
\]

\[
-0.418  
\]

For a 20\( \mu \) sphere Eq. (10b) gives \( C_N = 775 \text{ joules/gm} \).

(S) For hot char-layer c.p. and o.t.w.r. the same procedure was used to determine \( C_N \) as for room-temperature char. The only difference was that an average \( C_N \) was obtained from extrapolating data at \( \theta = 90^\circ \) to \( \theta = 10^\circ \) by assuming the hot char curves parallel the room-temperature char curves. These techniques will give an average \( C_N \) for 300\( \mu \) sphere equal to 160 joules/gm and \( C_N = 525 \text{ joules/gm} \) for 20\( \mu \) spheres.

(S) For the effect of augmentation, Figure 27(b), Reference 1 provides a damage enhancement value of 2.4 for six interacting spheres. Hence all \( C_N \)s are divided by this number to provide values for the hypothesized encounter. Values for un-augmented and augmented \( C_N \) are shown in Table 5.
CONTINUATION OF EXPERIMENTAL STUDY OF SMALL PARTICLE IMPACTS INTO ABLATIVE MATERIALS

A Summary Report; this is the final report on this problem.

Stanley M. Halperson

This report is a continuation of the work described in NRL Memorandum Report 1813, entitled "Experimental Study of Small Particle Impacts into Ablative Materials".

Utilizing the light-gas gun, impact tests with glass spheres from 3.18 mm to 100 mm in diameter were made into three ablative: phenolic nylon, carbon phenolic, and oblique tape wound refrasil. Velocities ranged from 0.74 to 7.9 km/sec and angles of obliquities ranged from 10° to 90°.

It was established that modified explosive scaling does not hold true for hypervelocity impacts into ablative, and dimensionless damage parameter such as penetration/projectile size are dependent on both velocity and projectile dimension rather than on velocity alone.

Penetration measurements of virgin phenolic nylon targets impacted by 3.18-mm aluminum spheres showed good correlation with the theoretical formula of Walsh. It was also determined that for obliquity tests where the normal velocity component/target sound speed ≥ 1, the mass loss and depth of penetration are proportional to the normal velocity component for angles of obliquity down to twenty degrees.
(S) Impact experiments were made with 1/2" x 1/2" x 1/4" char-layer specimens of carbon phenolic and oblique tape wound refrasil at room temperature and elevated temperatures, at normal incidence, and obliquities of 45° and 10°. Specimen mass loss was measured, and it was ascertained that for room temperature tests \( C_N \) (impact energy/mass loss) tends to increase slightly with decreasing angles of obliquity. Experiments where char-layer surface temperatures were raised to approximately 1600° F showed an expected decrease in \( C_N \).
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