DESIGN OF A SYSTEM FOR CUTTING SHAPED CHARGE JETS FOR PENETRATION EXPERIMENTS

ROBERT E. FRANZ
WILLIAM LAWRENCE

JUNE 1987

APPROVED FOR PUBLIC RELEASE, DISTRIBUTION UNLIMITED.

US ARMY BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND
Destroy this report when it is no longer needed. Do not return it to the originator.

Additional copies of this report may be obtained from the National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia 22161.

The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

The use of trade names or manufacturers' names in this report does not constitute indorsement of any commercial product.
Design of a System for Cutting Shaped Charge Jets for Penetration Experiments

Franz, Robert E. and Lawrence, William

An experimental system to selectively cut a copper jet from a 34.9 mm diameter shaped-charge is described. Parameters for the uncut jet are also given. The system was designed to be used in the study of jet penetration in glass and ceramic targets.
### TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Paragraph</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>EXPERIMENTAL PROCEDURE</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>EXPERIMENTS WITH THE CONE-LINER SHAPED CHARGE</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>DESIGNING A CUTTING CHARGE</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>EXPERIMENTAL SYSTEM FOR CUTTING JETS</td>
<td>6</td>
</tr>
<tr>
<td>6</td>
<td>CONCLUSIONS</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>DISTRIBUTION LIST</td>
<td>15</td>
</tr>
</tbody>
</table>
LIST OF ILLUSTRATIONS

FIGURE | Description                                                                 | Page
--------|-----------------------------------------------------------------------------|------
1.      | Conical-Liner Shaped Charge                                                 | 9    
2.      | Velocity vs. Distance for Jet Particles, from Test 14                      | 10   
3.      | Linear Charge with Triangular Liner                                        | 11   
4.      | Linear Charge with Line Wave Generator                                     | 13   
5.      | Linear Charge with Semi-Circular Liner                                     | 14   
6.      | Jet Cutting System                                                         | 16   
7.      | X-ray of Cut Jet                                                           | 17   
8.      | X-ray of Cut Jet                                                           | 18   
9.      | X-ray of Cut Jet after Penetrating Mild Steel Plate                        | 18   

v
1. INTRODUCTION

A shaped charge is a jet forming device consisting of an explosive charge containing a cavity. The cavity is lined with a thin metallic layer called a liner. 1 Circular cylindrical charges with either conical or hemispherical lined cavities are extensively used as penetrators in many anti-armor applications. There are also charges with linear cavities having triangular or semicircular cross section, so called "cutting charges". These charges, as the name implies, are used to cut plates or similar configurations usually made of metal.

When a regular cone-liner shaped charge is detonated, the high pressure detonation products collapse the metal liner upon itself and form a high velocity, cylindrical, metallic jet. The jet produced can penetrate high strength materials. During the collapse process different parts of the jet experience different collapse velocities producing a velocity gradient in the jet. The tip of the jet travels faster than each succeeding portion. This gradient causes the jet to stretch and eventually fracture into a series of discrete particles. In the case of the cutting charge, the jet formed has lateral extent, which produces a slit or cut in the target instead of the circular hole produced by a conical liner.

The subject of this report is experiments in which a 150 KV flash X-ray system was used to determine the parameters of the jet formed by a regular conical liner shaped charge and to design a cutting charge. The cutting charge was used to selectively cut the jet produced by the conical shaped charge so that different velocities or lengths could be directed to the targets. This experimental system was designed to be used in the study of jet penetration in glass and ceramic target materials.

2. EXPERIMENTAL PROCEDURE

A two channel 150 KV flash X-ray system* was used to observe the jet following the standard shadowgraph technique in which the jet interrupts a short duration X-ray beam and produces a shadow of itself on film mounted behind. Two exposures at different times on the same film allow the determination of the velocity and position of each jet particle. The position of the film with respect to the base of the charge and the magnification of the image caused by the beam divergence were determined by fiducial marks exposed on the film prior to the experiment. This was done by placing a lead sheet, 3.12 mm thick with a pattern of 3.3 mm diameter drilled holes, in the proposed jet path. The X-ray tubes were then fired with the film in place. This produced a double pattern of circular images on the film with known separation distances in the plane of the jet. The lead sheet was subsequently removed when the experiments were performed.


*Hewlett-Packard, McMinnville, OR
The X-ray film and suitable intensifier screens* were placed in a felt-lined steel cassette with a 12.7 mm thick polyethylene cover plate on the side exposed to the X-ray beams. This protected the film from the explosive blast and the disturbances caused by the propagating jet. The times between X-ray pulses were measured with both the trigger signals and the signals from the X-ray tube current monitors and were displayed on digital oscilloscopes**. The detonators were fired using a high voltage (4KV) pulse power supply which permitted sub-microsecond timing of the explosive event.

3. EXPERIMENTS WITH THE CONE-LINER SHAPED CHARGE

The unconfined shaped charge used in this study is shown in Figure 1. The copper liner is 0.91 mm thick and has a rounded apex. The figure gives other essential dimensions of the charge and the parts of the explosive train. Various jet parameters were measured in 6 experiments examining three complete jets and three jets truncated with the cutting charge.

The velocities and the distance from the base of the charge were measured for all particles which appeared on both dynamic exposures of the films. A linear least squares fit was made of these velocity-distance data for each jet at the two exposure times. The intersections of these lines with the distance axis gave the virtual origin of the jet. For the 6 experiments, 12 values were obtained. The average value for the distance of the origin from the base of the liner was -45.5 ± 0.8 mm. Figure 2 shows a plot of the data from test No. 14. The average jet tip velocity was 7.84 ± 0.04 km/s. The breakup time of the jet was measured from particle lengths to be 40.1 microseconds after detonator firing or 20.7 microseconds from the time the jet tip reached the base of the charge. This corresponds to 4.64 charge diameters. The jet diameter was approximately 1.0 mm with an average particle length of 2.6 mm.

4. DESIGNING A CUTTING CHARGE

The cutting charge was designed with two purposes in mind. The first purpose was to produce a leading particle of sufficient areal extent and velocity to quickly cut a passing jet fired perpendicular to it. The second was to deflect the remaining jet and slug so that they would miss a hole in a plate of armor steel through which the first part of the jet had passed. It was supposed that a charge of sufficient size to accomplish the first purpose would also achieve the second.

Preliminary experiments were performed using triangular liners made from 1.35 mm thick copper sheet bent to form a trough with a 45° apex angle. A rectangular box made of acrylic plastic was placed around the

---

*Kronex NDT 91 X-ray Film, 3M TriMax12 Screens
**Nicolet Oscilloscope Div., Madison, WI. (Model 2000, 204A Plug-in)

Figure 1. Conical-Liner Shaped Charge
Figure 2. Velocity vs Distance for Jet Particles, from Test 14
High Energy Detonator

M 18 Detonator
PBX Pellet
Thickness 12.7 mm
Diameter 19.1 mm

C-4 Explosive

78 mm

Plastic Box

39 mm

38 mm

1.37 mm Thick Copper Liner

Figure 3. Linear Charge With Triangular Liner
liner and filled with C-4 plastic explosive. Figure 3 gives dimensions and details of the charge and the explosive train. This charge did not produce a leading particle of sufficient size. One experiment was performed in which the liner length was increased from 39 mm to 75 mm. The explosive was detonated along a center line above the liner apex with a Detonator line wave generator instead of at the center of the charge (see Figure 4). This design did not form a good leading particle either, although the velocity of the particle that did form was higher (5.73 km/s).

A new charge was then designed using a liner with a semi-circular cross section. The liner was made by cutting regular commercial copper tubing into two halves. The tubing had a wall thickness of 1.57 mm, an outside diameter of 34.9 mm, and a length of 50.8 mm. The charge was a cube of C-4 plastic explosive 50.8 mm on a side with a cavity for the liner in the middle of one face. An acrylic plastic box surrounded the explosive and liner. The charge was detonated along the cylindrical axis of the liner in the same manner as the charge of Figure 4. Figure 5 shows the charge and gives dimensions.

This design yielded a usable leading particle which traveled at a comparably reduced yet acceptable velocity of 3.03 km/s. Experiments were then performed to cut the regular conical liner jets. These experiments are described in Section 5. In order to make construction of the cutting charges easier, reusable aluminum molds were made and Composition B explosive replaced C-4 in a charge of the same dimensions. This charge gave a slightly higher leading particle velocity of 3.16 km/s. Table I gives details of the four different cutting charge designs.

5. EXPERIMENTAL SYSTEM FOR CUTTING JETS

The experimental system that was finally used is shown in Figure 6. The conical shaped charge is supported by a piece of aluminum alloy tubing with a 12.7 mm wide slot cut into its side so as not to disturb the cutting jet. The initial portion of the penetrating jet passes through a 9.5 mm diameter hole in a 25.4 mm thick plate of armor steel. The rest of the jet and the slug are deflected by the cutting charge, miss the hole, and are stopped by the steel plate. Different lengths of jet can be cut by changing the position of the cutting charge with respect to the aluminum tube support or by changing the timing of the detonation of the charges. The spacing and timing must be controlled so that the cutting charge does not interfere with the formation of the penetrating jet. Figure 7 is an X-ray of a jet cut when it was approximately 98 mm long, just before breakup.

In order to select different velocities or sections of the jet, the jet was made to penetrate mild steel plates and wipe off its leading part. Figures 8 and 9 show X-rays of a jet cut off at the same length but in the case of Figure 9 also penetrating a 6.36 mm mild steel plate placed at a 60° angle to the jet path. As can be seen, the first particles of the jet are wiped off and the tail is cleaned up. Table II gives velocities of the individual jet particles in the two X-rays.

*E. I. Du Pont de Nemours and Co., Inc., Explosives Product Division, Wilmington, DE 19898.
Figure 4. Linear Charge With Line Wave Generator

PBX Pellet
12.7 mm Thick
19.1 mm Diameter

Data-Sheet Line
Wave Generator

C-4 Explosive

87 mm

38 mm

75 mm

Plastic Box

0.91 Thick Copper Liner

Figure 4. Linear Charge With Line Wave Generator
Figure 5. Linear Charge With Semi-Circular Liner
<table>
<thead>
<tr>
<th>DESIGN NO.</th>
<th>WIDTH OR DIAMETER (mm)</th>
<th>LENGTH (mm)</th>
<th>THICKNESS (mm)</th>
<th>SHAPE</th>
<th>EXPLOSIVE</th>
<th>LEADING PARTICLE VELOCITY (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>37</td>
<td>39</td>
<td>1.37</td>
<td>V</td>
<td>C-4</td>
<td>5.34</td>
</tr>
<tr>
<td>2</td>
<td>38</td>
<td>75</td>
<td>1.37</td>
<td>V</td>
<td>C-4</td>
<td>5.73</td>
</tr>
<tr>
<td>3</td>
<td>34.9</td>
<td>50.8</td>
<td>1.57</td>
<td>SEMI-CIRCULAR</td>
<td>C-4</td>
<td>3.03</td>
</tr>
<tr>
<td>4</td>
<td>34.9</td>
<td>50.8</td>
<td>1.57</td>
<td>SEMI-CIRCULAR</td>
<td>COMPB</td>
<td>3.16</td>
</tr>
</tbody>
</table>
Figure 6. Jet Cutting System
Figure 7. X-ray of Cut Jet

$T_1 = 58$ microseconds

$T_2 = 68$ microseconds
Figure 8. X-ray of Cut Jet

\[ T_1 = 52.15 \text{ microseconds} \]

\[ T_2 = 62.00 \text{ microseconds} \]

Figure 9. X-ray of Cut Jet after Penetrating Mild Steel Plate

\[ T_1 = 61.8 \text{ microseconds} \]

\[ T_2 = 72.25 \text{ microseconds} \]
<table>
<thead>
<tr>
<th>PARTICLE NO.</th>
<th>JET PARTICLE VELOCITY  KM/S</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEST NO.</td>
<td>20</td>
</tr>
<tr>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>7.05</td>
</tr>
<tr>
<td>8</td>
<td>6.95</td>
</tr>
<tr>
<td>9</td>
<td>6.87</td>
</tr>
<tr>
<td>10</td>
<td>6.68</td>
</tr>
<tr>
<td>11</td>
<td>6.59</td>
</tr>
</tbody>
</table>
6. CONCLUSIONS

A system has been designed to selectively cut a shaped-charge jet from a comparatively small conical liner. This will allow the study of the effect of jet velocity and length in penetration of different materials. This system was designed to be used in studying penetration in glass and ceramic targets in a small indoor blast chamber where these highly fragmenting targets are contained in steel and recovered. A similar system could be designed for larger charges and targets of different materials.
<table>
<thead>
<tr>
<th>No. of Copies</th>
<th>Organization</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>Administrator</td>
</tr>
<tr>
<td></td>
<td>Defense Technical Info Center</td>
</tr>
<tr>
<td></td>
<td>ATTN: DTIC-FDAC</td>
</tr>
<tr>
<td></td>
<td>Cameron Station, Bldg 5</td>
</tr>
<tr>
<td></td>
<td>Alexandria, VA 22304-6145</td>
</tr>
<tr>
<td>1</td>
<td>Deputy Assistant Secretary of the Army (R&amp;D)</td>
</tr>
<tr>
<td></td>
<td>Department of the Army</td>
</tr>
<tr>
<td></td>
<td>Washington, DC 20310</td>
</tr>
<tr>
<td>1</td>
<td>HQDA</td>
</tr>
<tr>
<td></td>
<td>DAMA-ARP-P, Dr. Watson</td>
</tr>
<tr>
<td></td>
<td>Washington, DC 20310</td>
</tr>
<tr>
<td>1</td>
<td>HQDA</td>
</tr>
<tr>
<td></td>
<td>DAMA-ART-M</td>
</tr>
<tr>
<td></td>
<td>Washington, DC 20310</td>
</tr>
<tr>
<td>1</td>
<td>HQDA</td>
</tr>
<tr>
<td></td>
<td>DAMA-MS</td>
</tr>
<tr>
<td></td>
<td>Washington, DC 20310</td>
</tr>
<tr>
<td>1</td>
<td>C.I.A.</td>
</tr>
<tr>
<td></td>
<td>OIR/DB/Standard</td>
</tr>
<tr>
<td></td>
<td>GE47 HQ</td>
</tr>
<tr>
<td></td>
<td>Washington, DC 20505</td>
</tr>
<tr>
<td>1</td>
<td>Commander</td>
</tr>
<tr>
<td></td>
<td>US Army War College</td>
</tr>
<tr>
<td></td>
<td>ATTN: Lib</td>
</tr>
<tr>
<td></td>
<td>Carlisle Barracks, PA 17013</td>
</tr>
<tr>
<td>1</td>
<td>Commander</td>
</tr>
<tr>
<td></td>
<td>US Army Command and General Staff College</td>
</tr>
<tr>
<td></td>
<td>ATTN: Archives</td>
</tr>
<tr>
<td></td>
<td>Fort Leavenworth, KS 66027</td>
</tr>
<tr>
<td>1</td>
<td>Commander</td>
</tr>
<tr>
<td></td>
<td>US Army Materiel Command</td>
</tr>
<tr>
<td></td>
<td>ATTN: AMCDRA-ST</td>
</tr>
<tr>
<td></td>
<td>5001 Eisenhower Avenue</td>
</tr>
<tr>
<td></td>
<td>Alexandria, VA 22333-0001</td>
</tr>
<tr>
<td>1</td>
<td>Commander</td>
</tr>
<tr>
<td></td>
<td>US Army Armament, Munitions and Chemical Command</td>
</tr>
<tr>
<td></td>
<td>ATTN: AMSMC-IMP-L</td>
</tr>
<tr>
<td></td>
<td>Rock Island, IL 61299-7300</td>
</tr>
<tr>
<td>1</td>
<td>Commander</td>
</tr>
<tr>
<td></td>
<td>U.S. Army ARDEC</td>
</tr>
<tr>
<td></td>
<td>ATTN: SMCAR-TDC</td>
</tr>
<tr>
<td></td>
<td>Dover, NJ 07801-5001</td>
</tr>
<tr>
<td>1</td>
<td>Commander</td>
</tr>
<tr>
<td></td>
<td>U.S. Army ARDEC</td>
</tr>
<tr>
<td></td>
<td>ATTN: SMCAR-TSS</td>
</tr>
<tr>
<td></td>
<td>Dover, NJ 07801-5001</td>
</tr>
<tr>
<td>1</td>
<td>Director</td>
</tr>
<tr>
<td></td>
<td>U.S. AMCCOM ARDEC CCAC</td>
</tr>
<tr>
<td></td>
<td>Benet Weapons Laboratory</td>
</tr>
<tr>
<td></td>
<td>ATTN: SMCAR-CCB-TL</td>
</tr>
<tr>
<td></td>
<td>Watervliet, NY 12189-4050</td>
</tr>
<tr>
<td>1</td>
<td>Commander</td>
</tr>
<tr>
<td></td>
<td>US Army Aviation Systems Command</td>
</tr>
<tr>
<td></td>
<td>ATTN: AMSAV-ES</td>
</tr>
<tr>
<td></td>
<td>4300 Goodfellow Boulevard</td>
</tr>
<tr>
<td></td>
<td>St. Louis, MO 63120-1798</td>
</tr>
<tr>
<td>1</td>
<td>Director</td>
</tr>
<tr>
<td></td>
<td>US Army Aviation Research and Technology Activity</td>
</tr>
<tr>
<td></td>
<td>Ames Research Center</td>
</tr>
<tr>
<td></td>
<td>Moffett Field, CA 94035-1099</td>
</tr>
<tr>
<td>1</td>
<td>Commander</td>
</tr>
<tr>
<td></td>
<td>US Army Communications - Electronics Command</td>
</tr>
<tr>
<td></td>
<td>ATTN: AMSEL-ED</td>
</tr>
<tr>
<td></td>
<td>Fort Monmouth, NJ 07703-5301</td>
</tr>
<tr>
<td>1</td>
<td>Commander</td>
</tr>
<tr>
<td></td>
<td>CECOM R&amp;D Technical Library</td>
</tr>
<tr>
<td></td>
<td>ATTN: AMSEL-IM-L (Reports Section), B.2700</td>
</tr>
<tr>
<td></td>
<td>Fort Monmouth, NJ 07703-5000</td>
</tr>
<tr>
<td>No. of Copies</td>
<td>Organization</td>
</tr>
<tr>
<td>--------------</td>
<td>--------------</td>
</tr>
<tr>
<td>1</td>
<td>Commander US Army Development and Employment Agency ATTN: MODE-ORO Fort Lewis, WA 98433-5000</td>
</tr>
<tr>
<td>1</td>
<td>Commander US Army Harry Diamond Laboratory ATTN: SLCHD-DE-OS 2800 Powder Mill Road Adelphi, MD 20783</td>
</tr>
<tr>
<td>1</td>
<td>Commander MICOM Research, Development and Engineering Center ATTN: AMSMI-RD Redstone Arsenal, AL 35898-5500</td>
</tr>
<tr>
<td>1</td>
<td>Director Missile and Space Intelligence Center ATTN: AIAM-S-YDL Redstone Arsenal, AL 35898-5500</td>
</tr>
<tr>
<td>1</td>
<td>Commander US Army Ballistic Missile Defense Systems Command ATTN: SENSC, Mr. Davidson P. O. Box 1500 Huntsville, AL 35804</td>
</tr>
<tr>
<td>3</td>
<td>Director BMD Advanced Technology Center ATTN: ATC-T, M. Capps ATC-M, S. Brockway ATC-RN, P. Boyd P.O. Box 1500, West Station Huntsville, AL 35807</td>
</tr>
<tr>
<td>2</td>
<td>Commander US Army Mobility Equipment Research &amp; Development Command ATTN: DRDME-WC DRDME-RZT Fort Belvoir, VA 22060</td>
</tr>
<tr>
<td>1</td>
<td>Commander US Army Natick Research and Development Center ATTN: DRXRE, Dr. D. Sieling Natick, MA 01762</td>
</tr>
<tr>
<td>1</td>
<td>Commander US Army Tank Automotive Command ATTN: AMSTA-TSL Warren, MI 48397-5000</td>
</tr>
<tr>
<td>1</td>
<td>Commander USAG ATTN: Tech Lib Fort Huachuca, AZ 85613-6000</td>
</tr>
<tr>
<td>1</td>
<td>Commander US Army Research Office P. O. Box 12211 Research Triangle Park, NC 27709</td>
</tr>
<tr>
<td>1</td>
<td>Director US Army TRADOC Analysis Center ATTN: ATOR-TSL White Sands Missile Range, NM 88002-5502</td>
</tr>
<tr>
<td>No. of Copies</td>
<td>Organization</td>
</tr>
<tr>
<td>--------------</td>
<td>--------------------------------------------------------</td>
</tr>
<tr>
<td>1</td>
<td>Commandant</td>
</tr>
<tr>
<td></td>
<td>US Army Infantry School</td>
</tr>
<tr>
<td></td>
<td>ATTN: ATSH-CD-CS-OR</td>
</tr>
<tr>
<td></td>
<td>Fort Benning, GA 31905-5400</td>
</tr>
<tr>
<td>2</td>
<td>Office of Naval Research</td>
</tr>
<tr>
<td></td>
<td>Department of the Navy</td>
</tr>
<tr>
<td></td>
<td>ATTN: Code 402</td>
</tr>
<tr>
<td></td>
<td>Washington, DC 20360</td>
</tr>
<tr>
<td>1</td>
<td>Commander</td>
</tr>
<tr>
<td></td>
<td>US Naval Air Systems Command</td>
</tr>
<tr>
<td></td>
<td>ATTN: AIR-604</td>
</tr>
<tr>
<td></td>
<td>Washington, DC 20360</td>
</tr>
<tr>
<td>1</td>
<td>Commander</td>
</tr>
<tr>
<td></td>
<td>Naval Sea Systems Command</td>
</tr>
<tr>
<td></td>
<td>ATTN: Code SEA 62D</td>
</tr>
<tr>
<td></td>
<td>Department of the Navy</td>
</tr>
<tr>
<td></td>
<td>Washington, DC 20362-5101</td>
</tr>
<tr>
<td>4</td>
<td>Commander</td>
</tr>
<tr>
<td></td>
<td>Naval Surface Weapons Center</td>
</tr>
<tr>
<td></td>
<td>ATTN: Code Gr-9, Dr. W. Soper</td>
</tr>
<tr>
<td></td>
<td>Dr. W. H. Holt</td>
</tr>
<tr>
<td></td>
<td>Dr. W. Mock</td>
</tr>
<tr>
<td></td>
<td>Tech Lib</td>
</tr>
<tr>
<td></td>
<td>Dahlgren, VA 22448-5000</td>
</tr>
<tr>
<td>3</td>
<td>Commander</td>
</tr>
<tr>
<td></td>
<td>Naval Surface Weapons Center</td>
</tr>
<tr>
<td></td>
<td>ATTN: Dr. R. Crowe</td>
</tr>
<tr>
<td></td>
<td>Code R32,</td>
</tr>
<tr>
<td></td>
<td>Dr. S. Fishman</td>
</tr>
<tr>
<td></td>
<td>Tech Lib</td>
</tr>
<tr>
<td></td>
<td>Silver Spring, MD 20902-5000</td>
</tr>
<tr>
<td>1</td>
<td>Commander and Director</td>
</tr>
<tr>
<td></td>
<td>US Naval Electronics Laboratory</td>
</tr>
<tr>
<td></td>
<td>ATTN: Lib</td>
</tr>
<tr>
<td></td>
<td>San Diego, CA 92152</td>
</tr>
<tr>
<td>No. of Copies</td>
<td>Organization</td>
</tr>
<tr>
<td>--------------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>1</td>
<td>Air Force Wright Aeronautical Laboratories</td>
</tr>
<tr>
<td></td>
<td>Air Force Systems Command Materials Laboratory</td>
</tr>
<tr>
<td></td>
<td>ATTN: Dr. John P. Henderson</td>
</tr>
<tr>
<td></td>
<td>Wright-Patterson AFB, OH 45433</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Director</td>
</tr>
<tr>
<td></td>
<td>Environmental Science Service Administration</td>
</tr>
<tr>
<td></td>
<td>US Department of Commerce</td>
</tr>
<tr>
<td></td>
<td>Boulder, CO 80302</td>
</tr>
<tr>
<td>1</td>
<td>Director</td>
</tr>
<tr>
<td></td>
<td>Lawrence Livermore Laboratory</td>
</tr>
<tr>
<td></td>
<td>ATTN: Dr. M. L. Wilkins</td>
</tr>
<tr>
<td></td>
<td>P. O. Box 808</td>
</tr>
<tr>
<td></td>
<td>Livermore, CA 94550</td>
</tr>
<tr>
<td>6</td>
<td>Sandia National Laboratories</td>
</tr>
<tr>
<td></td>
<td>ATTN: Dr. L. Davison</td>
</tr>
<tr>
<td></td>
<td>Dr. P. Chen</td>
</tr>
<tr>
<td></td>
<td>Dr. L. Bertholf</td>
</tr>
<tr>
<td></td>
<td>Dr. W. Hermann</td>
</tr>
<tr>
<td></td>
<td>Dr. J. Nunziato</td>
</tr>
<tr>
<td></td>
<td>Dr. S. Passman</td>
</tr>
<tr>
<td></td>
<td>P. O. Box 5800</td>
</tr>
<tr>
<td></td>
<td>Albuquerque, NM 87185</td>
</tr>
<tr>
<td>1</td>
<td>Director</td>
</tr>
<tr>
<td></td>
<td>Jet Propulsion Laboratory</td>
</tr>
<tr>
<td></td>
<td>ATTN: Lib (TDS)</td>
</tr>
<tr>
<td></td>
<td>4800 Oak Grove Drive</td>
</tr>
<tr>
<td>1</td>
<td>Director</td>
</tr>
<tr>
<td></td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td></td>
<td>Lyndon B. Johnson Space Center</td>
</tr>
<tr>
<td></td>
<td>ATTN: Lib</td>
</tr>
<tr>
<td></td>
<td>Houston, TX 77058</td>
</tr>
<tr>
<td>1</td>
<td>A.R.A.P. Group, Titan Systems, Inc.</td>
</tr>
<tr>
<td></td>
<td>ATTN: Dr. Coleman Donaldson</td>
</tr>
<tr>
<td></td>
<td>1800 Old Meadow Rd., #114</td>
</tr>
<tr>
<td></td>
<td>McLean, VA 22102</td>
</tr>
<tr>
<td>1</td>
<td>Denver Research Institute</td>
</tr>
<tr>
<td></td>
<td>University of Denver</td>
</tr>
<tr>
<td></td>
<td>ATTN: Dr. R. Recht</td>
</tr>
<tr>
<td>No. of Copies</td>
<td>Organization</td>
</tr>
<tr>
<td>--------------</td>
<td>------------------------------------------------------</td>
</tr>
<tr>
<td>3</td>
<td>Rensselaer Polytechnic Institute</td>
</tr>
<tr>
<td></td>
<td>ATTN: Prof. E. H. Lee</td>
</tr>
<tr>
<td></td>
<td>Prof. E. Krempl</td>
</tr>
<tr>
<td></td>
<td>Prof. J. Flaherty</td>
</tr>
<tr>
<td></td>
<td>Troy, NY 12181</td>
</tr>
<tr>
<td>1</td>
<td>Southwest Research Institute</td>
</tr>
<tr>
<td></td>
<td>ATTN: Dr. Charles Anderson</td>
</tr>
<tr>
<td></td>
<td>6220 Culebra Road</td>
</tr>
<tr>
<td></td>
<td>P. O. Drawer 28510</td>
</tr>
<tr>
<td></td>
<td>San Antonio, TX 78284</td>
</tr>
<tr>
<td>1</td>
<td>Southwest Research Institute Department of Mechanical</td>
</tr>
<tr>
<td></td>
<td>Sciences</td>
</tr>
<tr>
<td></td>
<td>ATTN: Dr. U. Kindholm</td>
</tr>
<tr>
<td></td>
<td>8500 Culebra Road</td>
</tr>
<tr>
<td></td>
<td>San Antonio, TX 78228</td>
</tr>
<tr>
<td>1</td>
<td>University of Dayton Research Institute</td>
</tr>
<tr>
<td></td>
<td>ATTN: Dr. S. J. Bless</td>
</tr>
<tr>
<td></td>
<td>Dayton, OH 45469</td>
</tr>
<tr>
<td>6</td>
<td>Brown University</td>
</tr>
<tr>
<td></td>
<td>Division of Engineering</td>
</tr>
<tr>
<td></td>
<td>ATTN: Prof. R. Clifton</td>
</tr>
<tr>
<td></td>
<td>Prof. H. Kolsky</td>
</tr>
<tr>
<td></td>
<td>Prof. L. B. Freund</td>
</tr>
<tr>
<td></td>
<td>Prof. A. Needleman</td>
</tr>
<tr>
<td></td>
<td>Prof. R. Asaro</td>
</tr>
<tr>
<td></td>
<td>Prof. R. James</td>
</tr>
<tr>
<td></td>
<td>Providence, RI 02912</td>
</tr>
<tr>
<td>2</td>
<td>Catholic University of America School of Engineering</td>
</tr>
<tr>
<td></td>
<td>and Architecture</td>
</tr>
<tr>
<td></td>
<td>ATTN: Prof. A. Durelli</td>
</tr>
<tr>
<td></td>
<td>Prof. J. McCoy</td>
</tr>
<tr>
<td></td>
<td>Washington, DC 20017</td>
</tr>
<tr>
<td>1</td>
<td>New York University</td>
</tr>
<tr>
<td></td>
<td>Department of Mathematics</td>
</tr>
<tr>
<td></td>
<td>ATTN: Dr. J. Keller</td>
</tr>
<tr>
<td></td>
<td>University Heights</td>
</tr>
<tr>
<td></td>
<td>New York, NY 10053</td>
</tr>
</tbody>
</table>
DISTRIBUTION LIST

No. of Copies | Organization
--- | ---
1 | North Carolina State University
Department of Civil Engineering
ATTN: Prof. Y. Horie
Raleigh, NC 27607

1 | Pennsylvania State University
Engineering Mechanical Department
ATTN: Prof. N. Davids
University Park, PA 16502

2 | Rice University
ATTN: Dr. R. Bowen
Dr. C. C. Wang
P. O. Box 1892
Houston, TX 77001

1 | Southern Methodist University
Solid Mechanics Division
ATTN: Prof. H. Watson
Dallas, TX 75221

1 | Temple University
College of Engineering Technology
ATTN: Dr. R. Haythornthwaite, Dean
Philadelphia, PA 19122

4 | The Johns Hopkins University
ATTN: Prof. R. B. Pond, Sr.
Prof. R. Green
Prof. W. Sharpe
Prof. J. Bell
34th and Charles Streets
Baltimore, MD 21218

1 | Tulane University
Department of Mechanical Engineering
ATTN: Dr. S. Cowin
New Orleans, LA 70112

3 | University of California
ATTN: Dr. M. Carroll
Dr. W. Goldsmith
Dr. P. Naghdi
Berkeley, CA 94704

1 | University of California
Department of Aerospace and Mechanical Engineering Science
ATTN: Dr. Y. C. Fung
P. O. Box 109
La Jolla, CA 92037

1 | University of California
Department of Mechanics
ATTN: Dr. R. Stern
504 Hilgard Avenue
Los Angeles, CA 90024

1 | University of California at Santa Barbara
Department of Mechanical Engineering
ATTN: Prof. T. P. Mitchel
Santa Barbara, CA 93106

1 | University of Delaware
Department of Mechanical Engineering
ATTN: Prof. J. Vinson
Newark, DE 19711

3 | University of Florida
Department of Engineering Science and Mechanics
ATTN: Dr. C. A. Sciammarilla
Dr. L. Malvern
Dr. E. Walsh
Gainesville, FL 23601

2 | University of Houston
Department of Mechanical Engineering
ATTN: Dr. T. Wheeler
Dr. R. Nachlinger
Houston, TX 77004
<table>
<thead>
<tr>
<th>No. of Copies</th>
<th>Organization</th>
</tr>
</thead>
</table>
| 1            | University of Illinois  
Department of Theoretical and Applied Mechanics  
ATTN: Dr. D. Carlson  
Urbana, IL 61801 |
| 1            | University of Illinois  
ATTN: Dean D. Drucker  
Urbana, IL 61801 |
| 1            | University of Illinois at Chicago Circle  
College of Engineering  
Department of Materials Engineering  
ATTN: Dr. T. C. T. Ting  
P. O. Box 4348  
Chicago, IL 60680 |
| 2            | University of Kentucky  
Department of Engineering Mechanics  
ATTN: Dr. M. Beatty  
Prof. O. Dillon, Jr.  
Lexington, KY 40506 |
| 1            | University of Maryland  
Department of Mathematics  
ATTN: Prof. S. Antman  
College Park, MD 20742 |
| 1            | University of Minnesota  
Department of Aerospace Engineering and Mechanics  
ATTN: Prof. J. L. Erickson  
107 Akerman Hall  
Minneapolis, MN 55455 |
| 1            | University of Pennsylvania  
Towne School of Civil and Mechanical Engineering  
ATTN: Prof. Z. Hashin  
Philadelphia, PA 19105 |
| 4            | University of Texas  
Department of Engineering Mechanics  
ATTN: Dr. M. Stern  
Dr. M. Bedford  
Prof. Ripperger  
Dr. J. T. Oden  
Austin, TX 78712 |
| 1            | University of Washington  
Department of Aeronautics and Astronautics  
ATTN: Dr. Ian M. Fyfe  
206 Guggenheim Hall  
Seattle, WA 98195 |
| 3            | Washington State University  
Department of Physics  
ATTN: Dr. R. Fowles  
Dr. G. Duvall  
Dr. Y. Gupta  
Pullman, WA 99163 |
| 2            | Yale University  
ATTN: Dr. B. T. Chu  
Dr. E. Onat  
400 Temple Street  
New Haven, CT 96520 |

**Aberdeen Proving Ground**

Dir, USAMSAA  
ATTN: AMXSY-D  
AMXSY-MP, H. Cohen  
Cdr, USATECOM  
ATTN: AMSTE-SI-F  
Cdr, CRDC, AMCCOM  
ATTN: SMCCR-RSP-A  
SMCCR-MU  
SMCCR-SPS-IL
USER EVALUATION SHEET/CHANGE OF ADDRESS

This Laboratory undertakes a continuing effort to improve the quality of the reports it publishes. Your comments/answers to the items/questions below will aid us in our efforts.

1. BRL Report Number __________________________ Date of Report __________

2. Date Report Received __________________________

3. Does this report satisfy a need? (Comment on purpose, related project, or other area of interest for which the report will be used.) __________________________

4. How specifically, is the report being used? (Information source, design data, procedure, source of ideas, etc.) __________________________

5. Has the information in this report led to any quantitative savings as far as man-hours or dollars saved, operating costs avoided or efficiencies achieved, etc? If so, please elaborate. __________________________

6. General Comments. What do you think should be changed to improve future reports? (Indicate changes to organization, technical content, format, etc.) __________________________

CURRENT ADDRESS

Name __________________________

Organization __________________________

Address __________________________

City, State, Zip __________________________

7. If indicating a Change of Address or Address Correction, please provide the New or Correct Address in Block 6 above and the Old or Incorrect address below.

OLD ADDRESS

Name __________________________

Organization __________________________

Address __________________________

City, State, Zip __________________________

(Remove this sheet along the perforation, fold as indicated, staple or tape closed, and mail.)