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Explosive Bonding of Refractory Metal Liners

by William S. de Rosset

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14. ABSTRACT

TPL, Inc. has successfully bonded a pure tantalum liner to the inside of an M242 Bushmaster barrel using a low-detonation-velocity explosive. This report examines the governing equations of the explosive bonding process as they apply to this particular situation. The relevant properties of other higher strength tantalum alloys are examined to see if they are suitable for explosive bonding, with the expectation that they would be better able to resist the wear forces at the rifled bore surface. For all candidate materials, attention is paid to the values of critical impact pressure, the critical flow transition velocity, the critical angle for jet formation, and maximum flyer plate velocity. Example plots are provided to indicate the bounds of explosive welding parameters that will result in a good bond.

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explosive bonding, gun tube liners, refractory metals, wear and erosion, Bushmaster

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Contents

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List of Figures

List of Tables

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1. Introduction

Gun barrel wear and erosion has been a major determinant in the useful life of most Army guns. It is a problem that has been addressed with propellant additives, barrel coatings, and reduced flame-temperature propellants. The problem has become more of an issue with the push to use higher-performance, higher flame-temperature propellants. Thus, the need to reduce barrel wear and erosion is established on prolonging the life of current gun barrels as well as providing the opportunity to introduce new propellants into future gun systems.

As part of a Small Business Innovative Research (SBIR) Phase 2 program, TPL, Inc. has demonstrated its ability to line the inside of both a rifled and smooth-bore (honed out) M242 Bushmaster 25-mm gun barrel with pure tantalum (Lowey, 2002) using an explosive bonding process. Initial firing tests at the U.S. Army Aberdeen Test Center showed that the tantalum-lined barrels have a remarkable resistance to wear and the explosive bonding process produced an extremely strong bond between the tantalum and gun steel. Most of the work was conducted with a smooth-bore gun, and the question of wear on a rifled surface was still an issue.

This successful effort has prompted continuance of the work through a Manufacturing Technology (Mantech) program. The goal of the program is to reduce wear and erosion of the M242 25-mm Bushmaster gun tube. One of the tasks of this program is to examine the choice of liner materials to see if another candidate material is more suitable. It may be that pure tantalum is too soft to withstand the forces exerted on the lands and grooves of rifled guns. Tantalum is also considered an expensive material, and since cost avoidance is one of the principal tenets of the Mantech program, high material cost is an issue.

One criterion for choice of a liner material is its cladability. This report investigates the material properties that make materials amenable to being explosively bonded to gun steel. In the next section, the work that TPL did to bond the tantalum liner to the M242 will be reviewed. Particular attention will be paid to the characteristics of the explosive and the geometry of the tantalum cylinder used in the TPL work. The governing equations used in explosive bonding are presented in section 3. These equations indicate what material parameters are important for the process to be successful. (Note that other important characteristics of the liner, such as hardness, resistance to chemical attack, and machinability, are not addressed in this particular task.) Section 4 takes the values of those material parameters for tantalum and several of its alloys to calculate the collision angle and collision velocity that give a good explosive bond. Results are also presented for niobium. The final section discusses the suitability of these metals and the implications for the choice of explosive.

2. Background

There is a certain amount of trial and error in establishing the operating parameters used in explosive bonding. This is evident in the number of different explosive formulation variations used by TPL in its work with the M242 Bushmaster gun barrel (Lowey, 2002). The final report for the Phase 2 effort omitted several important details; therefore, some suppositions about this work will be made for the remainder of this report. For instance, the actual formulation used to clad the three M242s was not explicitly specified in the final report; however, it can be inferred from the report that the explosive had a detonation velocity between 1.7 and 2.2 km/s.

The characteristic velocity, known as the Gurney velocity, $\sqrt{2E}$, can be estimated from the following:

$$\sqrt{2E} = D/2.97, \tag{1}$$

where D is the detonation velocity (Cooper, 1996). For this specific case, $\sqrt{2E}$ is calculated to be 0.74 km/s, using the upper limit of D (2.2 km/s). Values of the Gurney velocity for standard military explosives generally fall between 2 and 3 km/s (Zukas and Walters, 1998).

There were many steps needed to process the M242 gun tube. The parts dealing primarily with the explosive bonding process itself were filling a tantalum donor tube with explosive, inserting the donor tube into the gun tube, centering the donor tube so that it was concentric with the gun tube, evacuating the gun tube, and detonating the explosive. The gun tube had been bored out to an inner diameter of 1.064 in (27.03 mm) to accommodate the liner thickness. (The diameter reported in Lowey [2002] was given as 1.0547 in. This is a typographical error [Lowey, 2004b].) The original dimensions of the tantalum donor tube were 0.75 in (19.05 mm) for the diameter and 0.065 in (1.651 mm) for the wall thickness. Given the density of the explosive as 0.66 g/cm^3 (Lowey, 2004a) and the density of tantalum as 16.65 g/cm^3, the charge-to-mass ratio (C/M) can be calculated as 0.0856. Using the Gurney equation for the metal velocity V of the expanding cylindrical wall, we get the following:

$$V = \sqrt{2E}\ (M/C + ½)^{-1/2} = 0.212 \text{ km/s}. \tag{2}$$

The tantalum donor tube used in the explosive bonding to the M242 gun tube underwent a large amount of plastic strain. The radial component of strain ε on the outer surface of the cylinder can be found using the values of the following initial and final cylinder outer diameters:

$$\begin{aligned} \varepsilon &= \ln \text{(final cylinder diameter/initial cylinder diameter)} \\ &= \ln (1.064/0.75) = 35\%. \end{aligned} \tag{3}$$

There is a certain amount of plastic strain associated with the explosive bond itself. Consequently, an important material characteristic for explosive bonding is material ductility. However, in this particular instance, the need for material ductility is increased due to the fact that the tantalum donor tube has to expand and stay together within the gun tube. TPL made an attempt to use tantalum-10% tungsten (Ta-10W) as the liner material (Lowey, 2002). No successful bonds were ever achieved. One possible cause cited for this failure was that the Ta-10W might have had too many interstitial impurities. Also, the starting material may have been too strain-hardened. Mulligan et al. (2002) point out that "… commercially pure electron beam melted tantalum has an elongation of ~30 to 40% and a yield strength of ~5 ksi at 1000 °C, while Ta-10W has an elongation of ~25% (within limits of explosive bonding)…" If the same initial donor tube dimensions were used for Ta-10W as were used for the pure tantalum, the allowable elongation limit may have been exceeded.

The need to have liner ductility in excess of 30% elongation may be reduced if the initial donor tube diameter is increased. (The tantalum tubes used by TPL, Inc. were purchased as off-the-shelf items and therefore came in a standard size.) However, there is a limit to the diameter size of the donor tubes. This is due to the standoff (initial distance between the outer donor tube wall and the inner gun wall) needed in the explosive bonding process. A rough "rule of thumb" is that the standoff should be between 1/2 and 1× the flyer plate thickness (Wylie et al., 1970). In any event, the cylinder wall thickness can be calculated as a function of the outer radius of the cylinder, assuming that the M242 is honed to the same dimensions (1.064-in inner diameter) and that the same final liner thickness (0.044 in) is achieved. This relation is shown in figure 1.

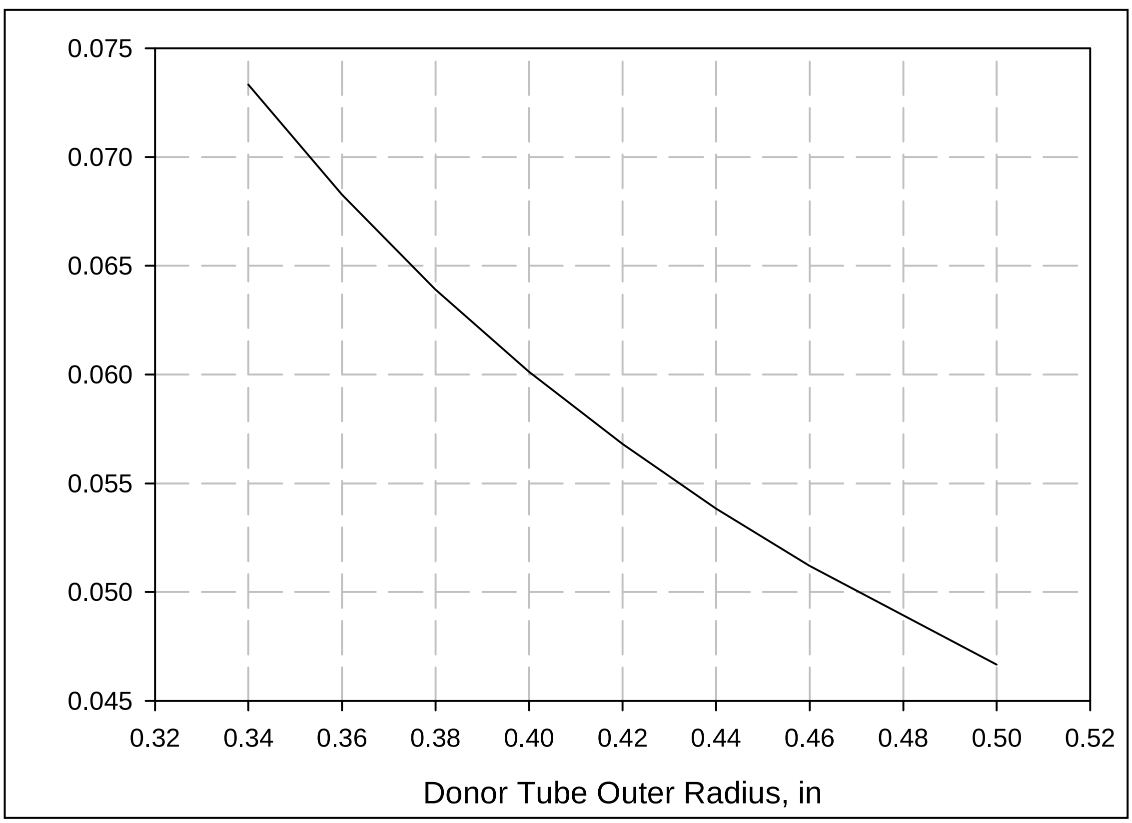

Figure 1. Donor tube wall thickness as a function of the donor tube outer radius for a fixed final liner thickness.

As the donor tube outer radius changes, the standoff (distance from the outer diameter of the donor tube to the inner diameter of the gun tube) normalized to the donor tube wall thickness changes. This is shown in figure 2. Finally, the amount of strain imparted to the donor tube can be calculated as a function of the donor tube outer radius. This is shown in figure 3.

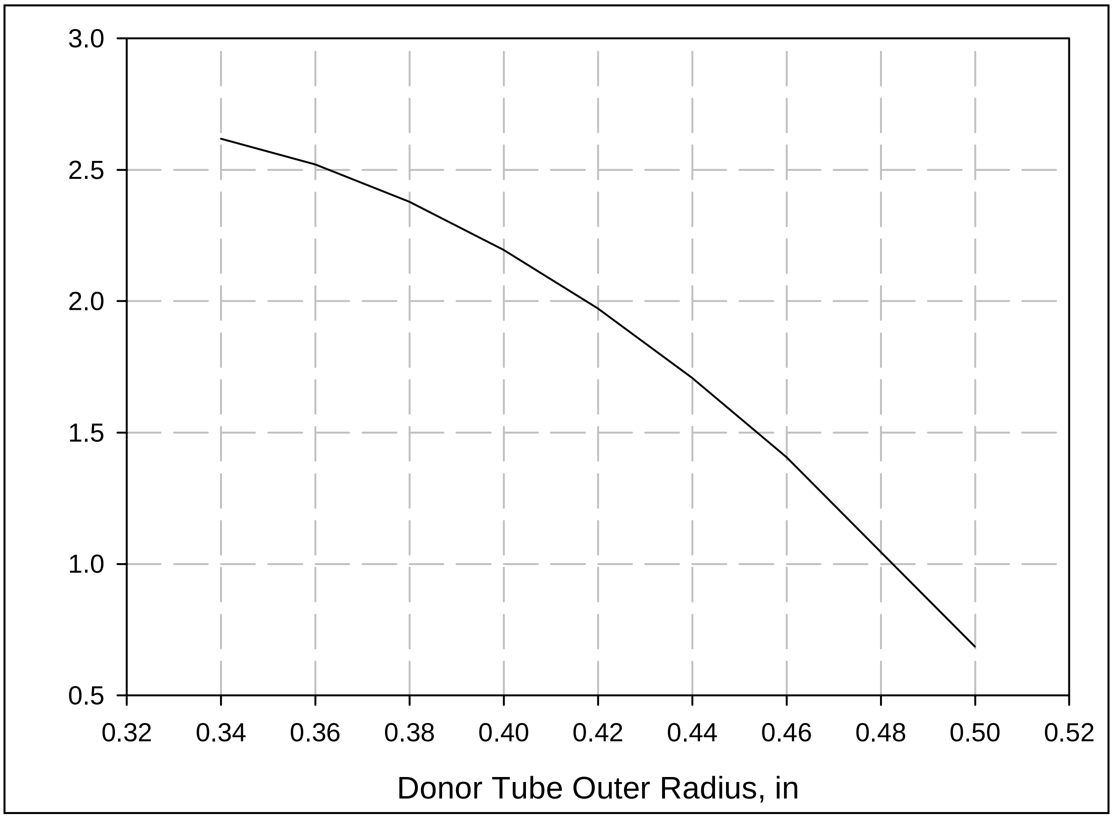

Figure 2. Standoff normalized to donor tube wall thickness as a function of donor tube outer radius.

These figures indicate that there is a range of possible initial conditions. The exact choice of these parameters will depend upon many other factors, including type of explosive used, availability of liner material with specified dimensions, and allowable elongation of the liner material. Similar plots can be made for other gun systems or for different choices of final liner thickness or initial gun tube diameter. The main point of these three figures is that if a normalized standoff less than 2 can be used, a lower elongation requirement can be met. For instance, a normalized standoff of 1.5 will result in a final elongation of less than 20%.

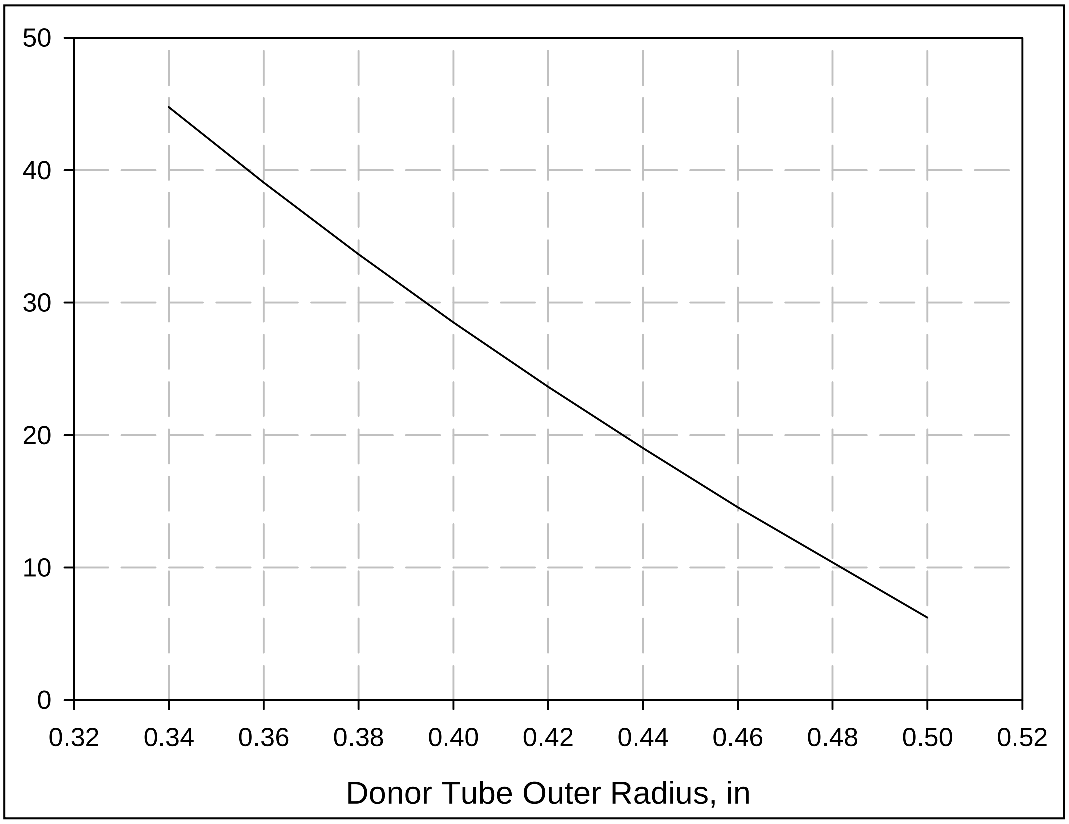

Figure 3. Strain imparted to cylinder as a function of donor tube outer radius.

3. Governing Equations

Explosion bonding has been used commercially for over 40 years to weld dissimilar metals that are otherwise difficult to join. The technology is relatively mature, and the governing equations have been documented in many publications. Carpenter and Wittman (1975) provide an excellent review of the technology, and most of what is presented in this section is taken from their work. (See this reference for a more thorough discussion of the equations.) In particular, they present four boundary conditions necessary to provide optimum explosion bonding characteristics. These are the critical angles for jet formation, the critical impact pressure, the critical flow transition velocity, and a maximum impact velocity.

Figure 4 briefly describes these governing equations and their rationale and shows the geometry of the explosive bonding setup. A constant standoff geometry is used for bonding the metal liner to the gun tube wall. (We distinguish between the initial liner configuration, called the donor tube, and the gun barrel.) In this figure, V is the flyer plate velocity, D is the velocity of detonation of the explosive, V_c is the collision point velocity, and α is the angle between the donor tube and the gun barrel at the collision point.

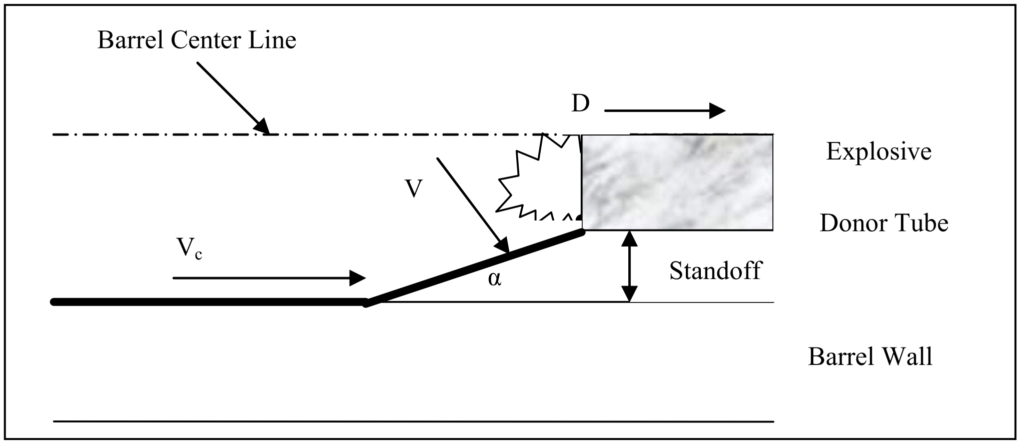

Figure 4. Geometry of explosive bonding setup.

In general,

$$V_c = D, \tag{4}$$

and

$$V = 2D \sin\alpha/2. \tag{5}$$

For small values of α,

$$V = D \sin\alpha. \tag{6}$$

The first consideration is the minimum impact pressure needed to make the explosive bonding process work. Carpenter and Wittman (1975) provide an empirically-successful relation between the minimum donor tube impact velocity V_{min} and the ultimate tensile strength σ_{ts} as follows:

$$V_{min} = (\sigma_{ts} / \rho)^{1/2}, \tag{7}$$

where ρ is the donor tube density. It is presumed that the ultimate tensile strength is that strength measured at room temperature. However, it is expected that the donor tube will be heated during plastic deformation, lowering its strength. Consequently, the V_{min} calculated may overestimate the actual value of V_{min}. Note also that these same authors acknowledge that it would be better to use the Hugoniot elastic limit (HEL) to calculate V_{min} (in another formula). However, the value of HEL for many alloys is not always available. Consequently, for sake of comparison among the alloys examined in this report, the ultimate tensile strength will be used in the calculations.

The second consideration is the existence of a specific collision velocity below, where researchers have found the bond line to be flat, and above, where they found it to be wavy. A wavy bond line is indicative of a good bond, implying that there is a lower limit to the collision velocity for a good bond. This transition velocity will be designated as V_T. Cowan et al. (1971) relate V_T to the density of the donor tube, ρ to the density of the gun barrel ρ_b, and H_F and H_B to the diamond pyramid hardness of the donor tube and gun barrel, respectively, given a consistent set of units, in the following way:

$$V_T = \sqrt{2R_T(H_F + H_B)/(\rho + \rho_b)}\ . \tag{8}$$

R_T is an empirically determined parameter that, for a wide range of metals, averages to 10.6 (no units). This is the value that will be used for calculations in this report.

Wittman (1973) derived a formula for the maximum donor tube velocity that would not result in melt-induced defects destroying the bond strength. This maximum velocity, V_{max}, can be calculated from the following equation:

$$V_{max} = \frac{(T_{MP}\ C_B)^{1/2}\ (KCC_B)^{1/4}}{N\ V_c\ (\rho h)^{1/4}}\ . \tag{9}$$

The material characteristics associated with the flyer plate are as follows:

- T_{MP}, the melting point in °C;
- C_B, the bulk sound speed;
- K, the thermal conductivity;
- C, the specific heat;
- h, the flyer plate thickness; and
- ρ, the flyer plate density.

N is a constant that is not explicitly provided in the Carpenter and Wittman reference (1975). However, it can be derived from the table of material properties provided in this reference. First, calculate the value of V_{min} using the values of ρ and σ_{ts} with equation 7. Next, determine NV_{max} from the other parameters provided in Carpenter and Wittman (1975) and equation 9. The value of N can then be determined from the ratio of V_{max} to V_{min} provided in this reference. For the 12 metals listed, the average value of N is 0.11, with a mean deviation of 0.009. N will be taken as 0.11 (using cgs units) for calculations in this report.

There is experimental evidence that a jet is formed at the intersection of colliding surfaces during the explosive bonding process (Bergmann et al., 1966). It is generally accepted that this jet rids the colliding surfaces of any oxides and promotes a metallurgical bond. However, not all collisions result in a jet. Walsh et al. (1953) first proposed the concept of a critical collision angle for jet formation. This is the minimum angle at a specified collision velocity that is required for jet formation. Cowan et al. (1971) extended this work to asymmetric collisions. They give the angle α in terms of the shock parameters and V_c:

$$\tan\alpha = U_p(V_c^2 - U_s^2)^{1/2}/(V_c^2 - U_pU_s). \tag{10}$$

At the critical collision angle, the partial derivative of the pressure with respect to α is zero (fixed V_c) (Walsh et al., 1953). The pressure P is related to the shock velocity U_s and the particle velocity U_p through the following usual equation:

$$P = \rho U_s U_p. \tag{11}$$

The empirically determined relation between U_s and U_p is also required to determine the critical angle. The relation between the shock velocity and V_c is given by the following:

$$U_s = V_c \sin \beta, \tag{12}$$

where β is the angle between the shock front and the material flow vector into the collision point viewed from a frame of reference that is stationary with respect to the collision point. Rather than calculate α explicitly in terms of P and take the partial derivative, it was easier to fix V_c and vary β. This generated values of U_s, U_p, P, and α. A plot of P vs. α showed a distinct maximum, and the critical angle for the given value of V_c was obtained. This was done for enough values of V_c to generate the required information.

4. Application of Governing Equations

Some cautions must be stated before applying the governing equations. First, they are to be applied with the understanding that the equations provide guidelines only. The actual parameters used to obtain the best possible bond will still be determined through a trial and error experimental process. Second, in applying these equations, it is important that a consistent set of units be used. In many instances, material property data are gathered from different sources that use different units. Some care must be exercised in converting all the data so that the units are consistent. Note that in equation 9, the value of N was determined using centimeter-gram-seconds °C as the set of units. Finally, it may not be possible to obtain the exact material properties for all alloys. In these cases, best estimates will be made.

While the use of pure tantalum resulted in a successful cladding of a liner to the M242 Bushmaster barrel, it may be that a higher-strength alloy is needed in a rifled bore configuration. Such alloys as tantalum-3% tungsten (Ta-3W) and Ta-10W are likely candidates. The densities of these two alloys can be found from a rule of mixtures, where the density of tantalum is taken to be 16.65 g/cm^3 and the density of tungsten is taken to be 19.3 g/cm^3. The ultimate tensile strength of tantalum varies as a function of temperature. A value of 250 MPa = 36 ksi is used for the room temperature value of σ_{ts} (American Society for Metals, 1979). The values of σ_{ts} for Ta-3W and Ta-10W are 60 ksi and 120 ksi, respectively (Aimone, 2004). The calculated values of V_{min} are given in table 1.

Table 1. Tantalum alloy material properties.

Material	Density (kg/m^3)	Ultimate Tensile Strength, (MPa)	V_{min} (km/s)	V_T (km/s)
Tantalum	16.65×10^3	250	0.123	2.05
Ta-3W	16.73×10^3	414	0.157	2.10
Ta-10W	16.92×10^3	828	0.221	2.15

The transition velocity V_T for these materials can be found from equation 8. The Vickers hardness ranges for tantalum and Ta-3W are 90–100 and 110–130 (Aimone, 2004). An estimate of the hardness range for Ta-10W is 140–160 Vickers. Note that the hardness of the tantalum liner (after explosively bonding) was measured by Pepi et al. (2003) to be 140 Vickers. It is likely that the explosive bonding process increased the hardness of the liner above the original hardness. The gun steel hardness reported in Pepi et al. (2003) was 400 Vickers. For purposes here, the lower end of the hardness ranges of tantalum and its alloys before explosive bonding occurs will be used; the value of 400 Vickers will be used for the steel. The calculated values for V_T are also shown in table 1.

It is expected that the critical angle for jet formation and V_{max} will depend on the bulk properties of the material so that a calculation for tantalum will provide close approximations of these values for the Ta-3W and Ta-10W alloys (Furnish et al., 1995). The values of the bulk properties of tantalum used to calculate V_{max} are shown in table 2. The relation between the shock velocity U_s and the particle velocity U_p (Marsh, 1995) is given by the following:

$$U_s = 3.43 \text{ (km/s)} + 1.19\, U_p. \tag{13}$$

In this equation, U_s and U_p are in kilometers per second.

Table 2. Tantalum material properties.

Property	Value	Reference
Bulk sound speed	3.43 km/s	(Marsh, 1980)
Density	16.65×10^3 kg/m^3	(American Society for Metals, 1979)
Melting point	3269° K	(American Society for Metals, 1979)
Thermal conductivity	54.4 w/m K	(American Society for Metals, 1979)
Specific heat	139.1 J/kg K	(American Society for Metals, 1979)

A flyer plate thickness of 0.15 cm (0.059 in) was selected. The table 2 values of input parameters were converted to the cgs system, and equation 9 was used to find V_{max} in terms of V_c.

$$V_{max} = 0.923 \text{x} 10^{10}/V_c, \tag{14}$$

where V_{max} and V_c are now in centimeters per second. We then have the following condition on α at $V=V_{max}$:

$$\alpha = 2\sin^{-1}(V_{max}/2V_c) = 2\sin^{-1}(.923/2V_c^2), \tag{15}$$

with V_{max} and V_c in kilometers per second.

The calculation for the critical angle for jet formation is as follows. First, fix a value of V_c. Then,

$$U_s = V_c \sin\beta. \quad (16)$$

From the relation between U_s and U_p,

$$U_p = (V_c \sin\beta - 3.43)/1.19. \quad (17)$$

Also,

$$P = \rho\,(V_c \sin\beta)(V_c \sin\beta - 3.43)/1.19. \quad (18)$$

Then, from equation 10,

$$\tan\alpha = ((\sin\beta - 3.43/V_c)/1.19)(1 - \sin^2\beta)^{1/2}/(1 - \sin\beta(\sin\beta - 3.43/V_c)/1.19). \quad (19)$$

By varying β, values of P and α can be generated. A plot of P vs. α for the case of $V_c = 5$ is shown in figure 5.

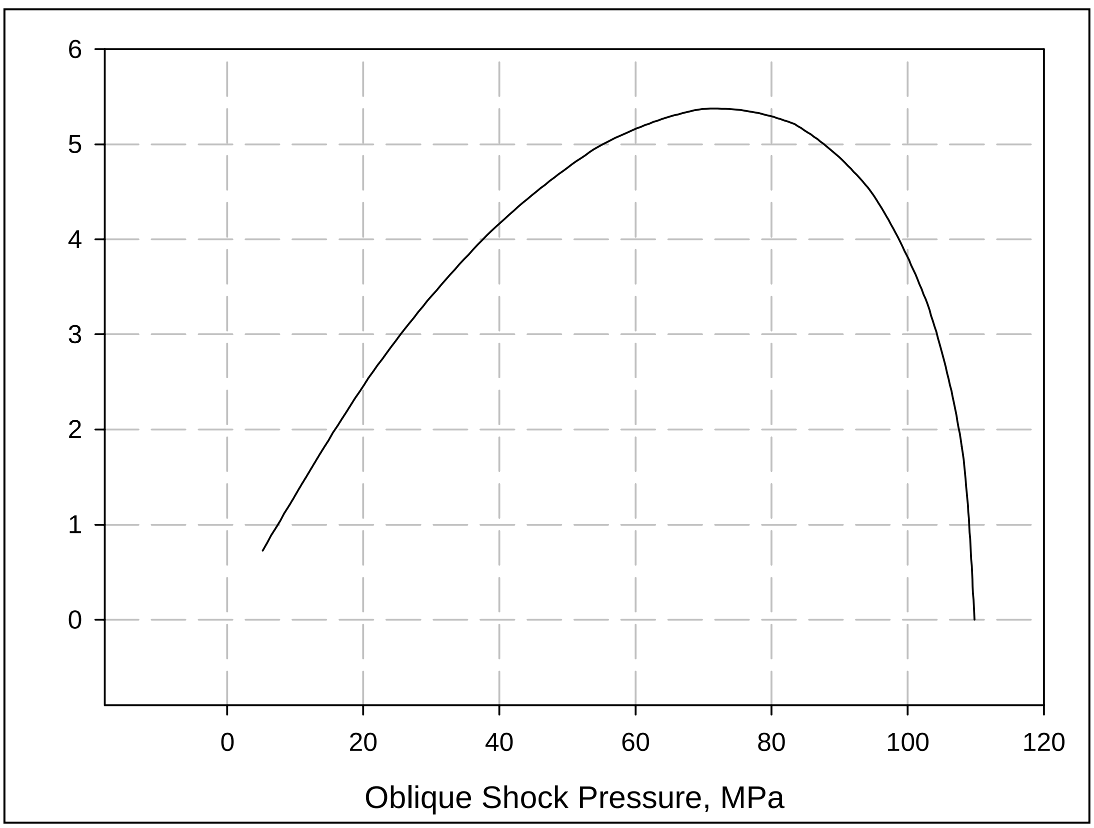

Figure 5. Relation of pressure P in MPa vs. α in degrees for $V_c = 5$ km/s.

It is clear from this figure that the maximum value of α is ~5.4°. Thus, the critical angle for V_c = 5 km/s is 5.4°. The relation between V_c and α can be generated with this approach.

The end result of all these calculations is a plot similar to that shown in Carpenter and Wittman (1975), shown in figure 6. For each metal, there is a central area bounded by four lines that indicate appropriate ranges of parameters. Bounded from below are the plots of V_{min} for each of the metals. On the left, the boundary is V_T. The values for each metal are so close together that V_T is represented by a single thick vertical line. On the right, the area is bounded by the condition for the critical angle for collision. At the top, the area is bounded by V_{max}.

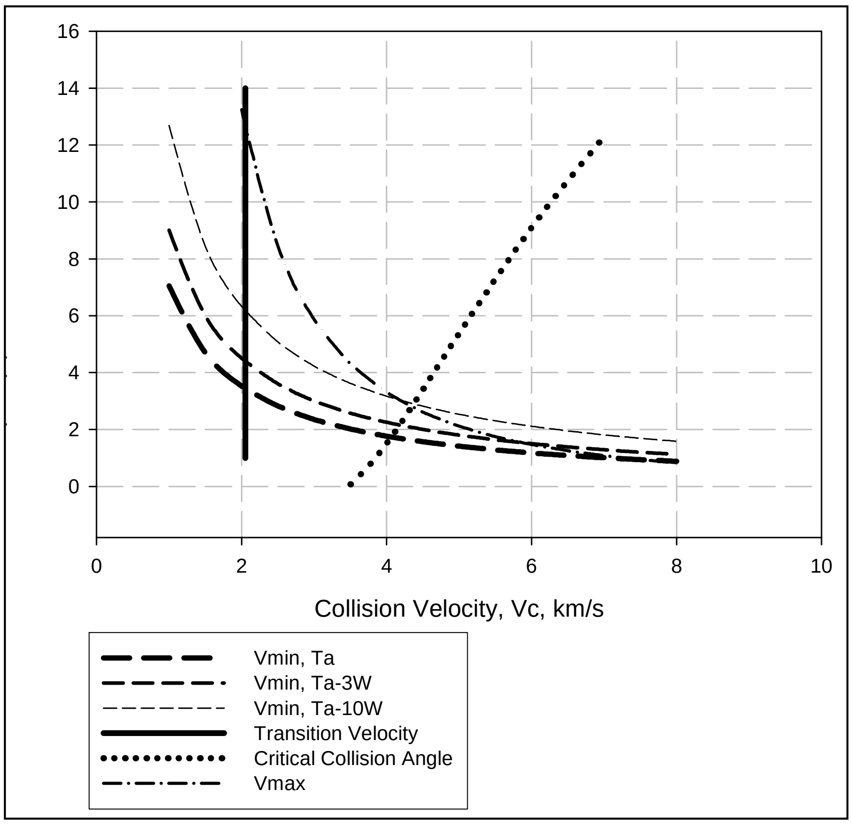

Figure 6. Bounding plots for explosive bonding of tantalum and two alloys.

A similar plot can be made for niobium (annealed). Table 3 lists the properties that were used for the calculations. All values were obtained from the Metals Handbook (American Society for Metals, 1979) except for the bulk sound speed, obtained from Marsh (1980). In addition, the relation

$$U_s = 4.46\ (\text{km/s}) + 1.20U_p \qquad (20)$$

and a value of 0.15 cm for the flyer plate thickness were used to generate the plots in figure 7.

Considering the fact that the material properties for niobium are not too different from those of tantalum and its alloys, it is not surprising that the bounding plots in figure 7 appear similar to those in figure 6.

Table 3. Properties of niobium.

Property	Value
Tensile strength	275 MPa
Density	8.57 g/cm^3
Hardness	80 Vickers
Melting point	2468 °C
Bulk sound speed	4.46 km/s
Specific heat (at 20° C)	270 J/kg K
Thermal conductivity (at 0° C)	52.3 w/m K

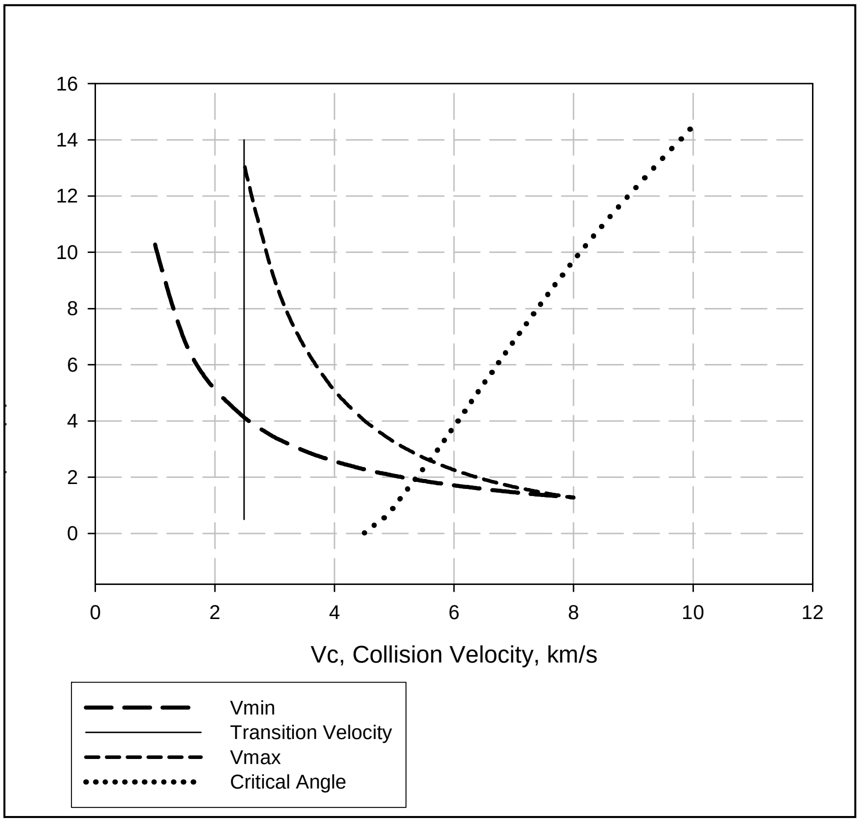

Figure 7. Bounding plots for niobium.

5. Discussion

The governing equations presented in section 3 have been developed as a result of many years of experience in explosive welding. While they are based on a physical understanding of the explosive bonding process, reliance is also placed on fixing certain parameters obtained from averages of a large number of tests. For this reason, the governing equations should be taken as guidelines to establish the approximate operating parameters for a specific case. Note also that the equations were based primarily on experience gained with cladding flat pats on a flat substrate. In the case of explosively bonding a liner to the inside of a gun tube, the geometry is different. The large amount of hoop strain that might occur in bonding liners could affect material properties to the extent that the equations are no longer good approximations. This is especially true if the material properties are highly strain and/or strain rate sensitive.

In any event, the governing equations help to assess the cladability of a material. Perhaps the most important material property is the ultimate tensile strength. As seen in figure 6, as the ultimate tensile strength of the various tantalum alloys increases, the V_c-α operating area decreases. This is because the lower limit (V_{min}) is raised, but the upper limit, being based on bulk properties such as density and sound speed, stays about the same. Consequently, the choice of high explosive is more restrictive as small alloy additions increase a material's strength. Note that if annealing can lower the tensile strength of the Ta-10W, its cladability would improve (Montgomery, 2004).

The choice of explosive will have a great deal to do with the cladability of a material. The explosive used by TPL had an upper limit on the detonation velocity D of 2.2 km/s. Since $D = V_c$, TPL may have been operating at the far left portion of the bounded area for tantalum and the two alloys. V_T for Ta-10W was calculated to be 2.15 km/s, providing another possibility as to why efforts to form a good bond were not successful with this material. For V = 0.212 km/s and D = 2.2 km/s, $\alpha = 5.5°$. This value appears to lie close to the V_{min} line shown in figure 6 and may provide another reason why the use of this particular explosive was not successful in bonding the Ta-10W. However, the explosive should work for the Ta-3W.

The value of α can be varied by changing V where D is fixed (equations 5 or 6). This can be done by changing the charge-to-mass ratio (see equation 2). The possible range of α can be calculated with the following assumptions. First, we expect that the liner will be fully packed with explosive since allowing a hollow portion down the axis of the explosive may result in a dimension less than the failure diameter. Next, consider standoffs between 0.01 and 0.25 in. This will allow the mass of both the metal liner and explosive to vary. Finally, we use the dimensions previously discussed (1.064-in inner diameter of the gun tube and a final liner thickness of 0.044 in).

The relation between α and standoff is shown in figure 8. The larger standoffs reduce the amount of explosive and increase the thickness of the metal liner. Thus, the value of V will decrease for larger standoffs, resulting in a decrease in α. Referring to figure 6, it can be seen that the values of α in the range of 4–8° at V_c = 2.2 km/s are acceptable and may even allow explosive bonding of the higher-strength alloys for the higher values of α (shorter standoff).

A final consideration in choice of explosives is failure diameter. For all explosives, there is a minimum dimension needed to sustain a detonation without confinement. In general, explosives with low detonation velocities such as ammonium nitrate have large failure diameters. For the current application, this minimum dimension must be less than 25 mm, the bore diameter of the M242 gun tube. This condition limits the available choices of explosives for bonding the liner to the gun tube.

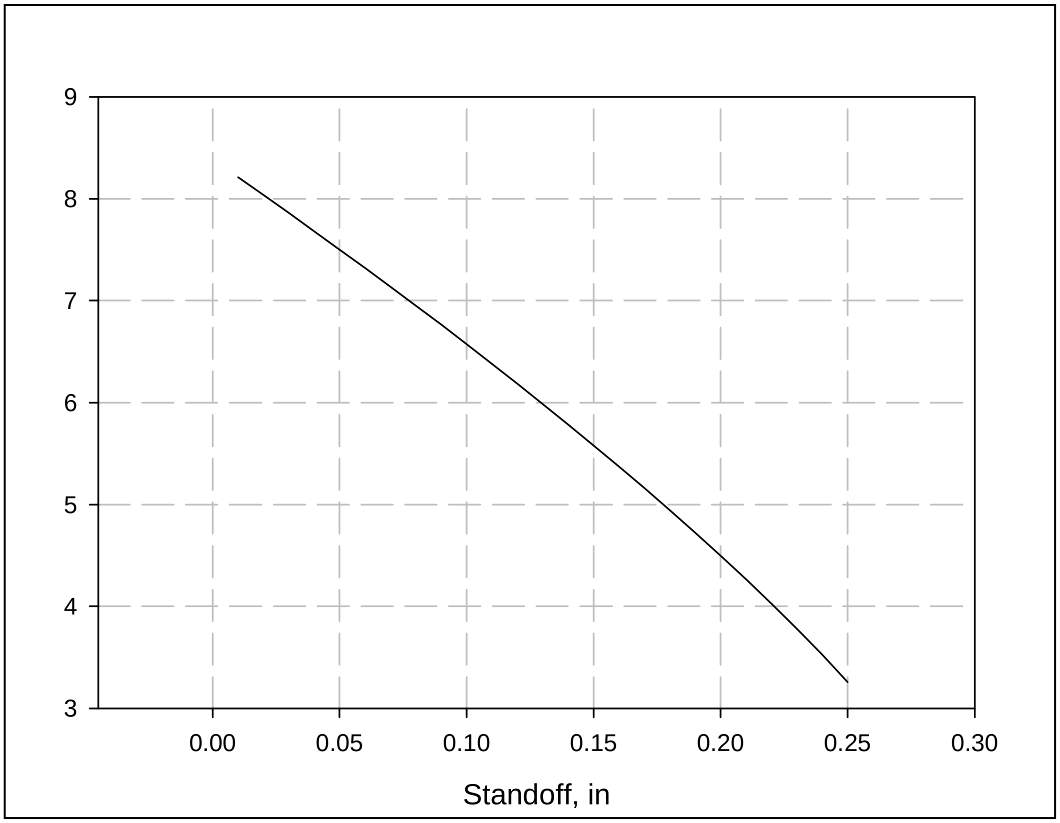

Figure 8. Relation between α (in degrees) and standoff for a specific case.

6. Summary

A pure tantalum liner has been successfully bonded to the inside of an M242 Bushmaster medium-caliber cannon in previous work performed by TPL, Inc. under a Phase 2 SBIR. In expectation that the tantalum will be too soft to resist wear forces at the lands and grooves in the gun barrel, other alloys were examined for suitability for cladding. Semiempirical equations governing explosive bonding were applied to two tantalum alloys and niobium. The equations indicated that for the particular explosive used by TPL, a shorter standoff would facilitate the bonding of higher-strength alloys by increasing the collision angle α and reducing the amount of strain in the liner produced by the explosive bonding process.

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2800 POWDER MILL RD
ADELPHI MD 20783-1197

NO. OF
COPIES ORGANIZATION

ABERDEEN PROVING GROUND

1 US ARMY ATC
CSTE DTC AT AC I
W C FRAZER
400 COLLERAN RD
APG MD 21005-5059

91 DIR USARL
AMSRD ARL CI
AMSRD ARL O AP EG
M ADAMSON
AMSRD ARL SL BA
AMSRD ARL SL BB
D BELY
AMSRD ARL WM
J SMITH
H WALLACE
AMSRD ARL WM B
A HORST
T KOGLER
AMSRD ARL WM BA
D LYON
AMSRD ARL WM BC
J NEWILL
P PLOSTINS
A ZIELINSKI
AMSRD ARL WM BD
P CONROY
B FORCH
M LEADORE
C LEVERITT
R LIEB
R PESCE RODRIGUEZ
B RICE
AMSRD ARL WM BF
S WILKERSON
AMSRD ARL WM M
B FINK
J MCCAULEY
AMSRD ARL WM MA
L GHIORSE
S MCKNIGHT
E WETZEL
AMSRD ARL WM MB
J BENDER
T BOGETTI
L BURTON
R CARTER
K CHO
W DE ROSSET
G DEWING
R DOWDING
W DRYSDALE

NO. OF COPIES | ORGANIZATION

R EMERSON
D HENRY
D HOPKINS
R KASTE
L KECSKES
M MINNICINO
B POWERS
D SNOHA
J SOUTH
M STAKER
J SWAB
J TZENG
AMSRD ARL WM MC
J BEATTY
R BOSSOLI
E CHIN
S CORNELISON
D GRANVILLE
B HART
J LASALVIA
J MONTGOMERY
F PIERCE
E RIGAS
W SPURGEON
AMSRD ARL WM MD
B CHEESEMAN
P DEHMER
R DOOLEY
G GAZONAS
S GHIORSE
C HOPPEL
M KLUSEWITZ
W ROY
J SANDS
D SPAGNUOLO
S WALSH
S WOLF
AMSRD ARL WM RP
J BORNSTEIN
C SHOEMAKER
AMSRD ARL WM T
B BURNS
AMSRD ARL WM TA
W BRUCHEY
M BURKINS
W GILLICH
B GOOCH
T HAVEL
E HORWATH
M NORMANDIA
J RUNYEON
M ZOLTOSKI

NO. OF COPIES | ORGANIZATION

AMSRD ARL WM TB
P BAKER
AMSRD ARL WM TC
R COATES
AMSRD ARL WM TD
D DANDEKAR
T HADUCH
T MOYNIHAN
M RAFTENBERG
S SCHOENFELD
T WEERASOORIYA
AMSRD ARL WM TE
A NIILER
J POWELL

NO. OF COPIES	ORGANIZATION
1	LTD R MARTIN MERL TAMWORTH RD HERTFORD SG13 7DG UK
1	SMC SCOTLAND P W LAY DERA ROSYTH ROSYTH ROYAL DOCKYARD DUNFERMLINE FIFE KY 11 2XR UK
1	CIVIL AVIATION ADMINSTRATION T GOTTESMAN PO BOX 8 BEN GURION INTRNL AIRPORT LOD 70150 ISRAEL
1	AEROSPATIALE S ANDRE A BTE CC RTE MD132 316 ROUTE DE BAYONNE TOULOUSE 31060 FRANCE
1	DRA FORT HALSTEAD P N JONES SEVEN OAKS KENT TN 147BP UK
1	SWISS FEDERAL ARMAMENTS WKS W LANZ ALLMENDSTRASSE 86 3602 THUN SWITZERLAND
1	DYNAMEC RESEARCH LAB AKE PERSSON BOX 201 SE 151 23 SODERTALJE SWEDEN

NO. OF COPIES	ORGANIZATION
1	ISRAEL INST OF TECHLGY S BODNER FACULTY OF MECHANICAL ENGR HAIFA 3200 ISRAEL
1	DSTO WEAPONS SYSTEMS DIVISION N BURMAN RLLWS SALISBURY SOUTH AUSTRALIA 5108 AUSTRALIA
1	DEF RES ESTABLISHMENT VALCARTIER A DUPUIS 2459 BLVD PIE XI NORTH VALCARTIER QUEBEC CANADA PO BOX 8800 COURCELETTE GOA IRO QUEBEC CANADA
1	ECOLE POLYTECH J MANSON DMX LTC CH 1015 LAUSANNE SWITZERLAND
1	TNO DEFENSE RESEARCH R IJSSELSTEIN ACCOUNT DIRECTOR R&D ARMEE PO BOX 6006 2600 JA DELFT THE NETHERLANDS
2	FOA NATL DEFENSE RESEARCH ESTAB DIR DEPT OF WEAPONS & PROTECTION B JANZON R HOLMLIN S 172 90 STOCKHOLM SWEDEN

NO. OF COPIES	ORGANIZATION
2	DEFENSE TECH & PROC AGENCY GROUND I CREWTHER GENERAL HERZOG HAUS 3602 THUN SWITZERLAND
1	MINISTRY OF DEFENCE RAFAEL ARMAMENT DEVELOPMENT AUTH M MAYSELESS PO BOX 2250 HAIFA 31021 ISRAEL
1	TNO DEFENSE RESEARCH I H PASMAN POSTBUS 6006 2600 JA DELFT THE NETHERLANDS
1	B HIRSCH TACHKEMONY ST 6 NETAMUA 42611 ISRAEL
1	DEUTSCHE AEROSPACE AG DYNAMICS SYSTEMS M HELD PO BOX 1340 D 86523 SCHROBENHAUSEN GERMANY

NO. OF
<u>COPIES</u> <u>ORGANIZATION</u>

<u>ABERDEEN PROVING GROUND</u>

15 DIR USARL
AMSRD ARL WM TC
L MAGNESS
AMSRD ARL WM TB
J WATSON
AMSRD ARL WM TD
S SEGLETES
AMSRD ARL WM MB
W DE ROSSET (10 CPS)
AMSRD ARL WM MC
V CHAMPAGNE
AMSRD ARL WM MD
B SCOTT

INTENTIONALLY LEFT BLANK.