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DEMONSTRATION OF THE INTEGRITY OF TUNGSTEN LINED LAUNCH TUBES FOR USE ON A HYBRID LAUNCHER

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31 July 1980

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report summarizes developments to date concerning tungsten thermal protection for application to a hybrid hypervelocity launcher. Two complete tungsten coating processes are developed to provide good bonding of the coating and appropriate mechanical properties of the substrate. Three launch tubes were fabricated for exposure to severe internal ballistic environments.

Internal ballistic exposures were provided to two of the tubes in three successive firings using 1/8 scale injection hardware developed under the

20. ABSTRACT (Continued)

hybrid launcher program. Modifications to the explosive driver designs are shown to provide very simple refurbishment of the launcher injection block between tests. Details are presented concerning driver and internal ballistic performance, instrumentation for the 1/4 scale demonstrator, and tungsten coating characteristics. A medium temperature tungsten coating process is demonstrated to provide high quality tungsten liners that are well bonded to a steel substrate having appropriate mechanical properties, and that survive severe internal ballistic environments.

PREFACE

The author appreciates the helpful contributions of a number of people and organizations to the effort reported herein. The helpful assistance of Mr. John Watson, Artec Associates, who performed the calculations of the injection test system internal ballistics and helped with the test plans is worthy of note. Messrs. Kurt Suchsland and Jacques Hull of Acurex Corporation provided general consultation and assistance during the current effort. The cooperation of Mr. Richard Kaplan, Ultramet, has been key to the successful development of tungsten coating for protecting critical launcher components. The participation of Physics International in carrying out the injection tests is gratefully acknowledged.

The high caliber assistance of Mr. Robert Huici, Payne, Inc., in preparing the hardware for the injection tests and general assistance on the program is of special note. Finally, the continuing participation of the DNA project monitor, Capt. Arthur T. Hopkins, has added significantly to the quality of the program experience.

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INTRODUCTION

The launch kinetic energy of a projectile fired from a two stage light gas gun of a given bore diameter is limited by the peak pressures and temperatures of the second stage propellant, usually hydrogen. In a conventional light gas gun, these parameters are related almost uniquely by the thermodynamic state of the gases prior to second stage compression. For a given design, higher peak pressures cause higher peak temperatures. In the hybrid launcher concept under development under contract DNA-001-76-C-0407 and the current contract, a level of independent control of pressures and temperatures is afforded by injecting shock-heated gas into the pump tube at the beginning of the second stage compression process. As a consequence, higher launch kinetic energies are possible within conventional pressure limits because of the higher gas temperatures.

Improved thermal protection is important, regardless of the means to attain higher temperature. The hybrid launcher concept includes tungsten lining of critical components to provide sufficient heat sink to avoid melting during the ballistic event.

A recently established requirement to perform hypervelocity impact testing at velocities up to 50,000 feet per second has added urgency to efforts to develop thermal protection methods to increase the performance of existing launchers. Work is underway to test liners made of tantalum, which may be easier to work with than tungsten, but will tolerate lesser ballistic performance.

A launcher of 5-inch bore, such as envisioned for a future Air Force test facility, will be able to launch full-size reentry nosetips to reentry velocities, and test their thermal, erosion and aerodynamic behavior, both in virgin and nuclear-damaged conditions. Erosive environments representative of natural hydrometeors or dust and ice associated with nuclear clouds can be provided. A high performance launcher is essential for such a facility, since the models must have a large mass (ballistic coefficient) to maintain a high velocity down a test range 1 to 3 miles in length. The hybrid launcher will be capable of launching models approximately three times the mass attainable by a conventional two-stage launcher.

In addition to testing reentry vehicle nosetips, such a facility would be used to test the aerodynamic, ablation and thermal performance of replica decoys and maneuvering reentry vehicle control surfaces. The replica decoy is of particular interest in that a complete full scale decoy of a type contemplated by the Air Force could be tested. This is the only way potentially available to ground test the effectiveness of boundary layer trips required for this kind of decoy. Furthermore, decoy discrimination during reentry could result from exposure to X-rays from an exo-atmospheric nuclear burst. Such a test facility would permit direct observation of the aerodynamic consequences of a nuclear encounter.

The objective of the work reported herein is to demonstrate the integrity of tungsten liners that are fabricated according to the new processes developed under the hybrid launcher program. Background on the program is provided in the following section. Following that, the liner development effort will be reviewed, culminating in the selection of the lining processes used under the current contract. Results of a firing program to demonstrate the integrity of the liners are presented in Section 4, followed by conclusions in Section 5.

SECTION 2

BACKGROUND

For a given heat flux level, the combination of tungsten's high melt temperature and thermophysical properties provides the longest time to achieve melt temperature among known materials. The hybrid launcher internal ballistic cycle has been designed so as to avoid melting tungsten by a small margin approximately midway in the propulsion event. That is, the thermal load inherent in the design is the maximum possible that can be sustained without melting tungsten. Any other material will melt under nominal cycle conditions or ablate due to chemical attack.* Obviously, it is not desirable to maximize the design thermal loads, but they are a natural consequence of achieving the maximum hydrogen temperature that can be contained, which is desirable.

During the hybrid launcher feasibility study (Reference 1), scoping calculations of convective heat transfer were carried out as a prelude to the design study (the analytical technique that was used and certain of the results are also reported in Reference 2). During the design study (Reference 3), detailed heat transfer calculations were made in conjunction with internal ballistic calculations to arrive at an optimum cycle. It is shown in Reference 3 that thermal protection capability of tungsten can be enhanced by using a very thin layer of tantalum carbide as an insulator over the tungsten. The composite then allows selection of conditions that enable somewhat superior internal ballistic performance compared to using tungsten alone, and considerably superior performance to using tantalum carbide alone. However, the present design point condition

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*Melting or significant ablation cannot be tolerated since contaminants and particulate flow degrade internal ballistic performance.

has been eased slightly to avoid the composite development effort, at least temporarily.

Estimates are made in Reference 4 of the relative launch mass capabilities of optimized hybrid launchers for conditions that are chosen to be compatible with the melt limits of various candidate materials. On this basis, tungsten allows a launch mass that is about three times greater than steel. Tantalum would allow a factor of two increase over steel. The closest contenders to tungsten are rhenium and tantalum carbide, but tungsten leads these candidates by about 30 percent in launch mass. Thus, development of a method for tungsten lining is a critical element of the successful demonstration of the hybrid launcher.

SECTION 3

REVIEW OF LINER DEVELOPMENT

Several options that were considered to make tungsten liners are discussed in Reference 4. The approach selected includes plating nickel within the bores of the appropriate components and applying the tungsten to the nickel by the chemical vapor deposition (CVD) process. The procedure is complicated by the need to have processes with thermal cycles consistent with the heat treat requirements of the steel substrate. Several components have been successfully coated with tungsten, but until the present effort none of the liners adequately survived representative internal ballistic loads -- invariably the tungsten debonded from the nickel. This experience is described in some detail in Subsection 4.2 of Reference 4.

Recently, a section of the 8 foot tube that was successfully lined with tungsten was machined to prepare a "tubular bend test" sample, to be described later. During the process, after the sample was sectioned longitudinally, a portion of the tungsten shell separated completely from the substrate -- a further demonstration of the inadequacy of the bonding using early processes.

3.1 REVIEW OF THE BONDING DEVELOPMENT STUDY

A bonding development program was carried out in Reference 4, considering various thicknesses and kinds of nickel (electroless and electrolytic) and various thermal cycles for the tungsten CVD. Flat samples prepared the same way as components that were subjected to internal ballistic environments were shown to provide poor bonding. Based on the bonding development study and other experiences, the following conclusions were derived.

1. Thin tungsten liners can be formed successfully by the CVD process in high L/D tubes.
2. A thin, high quality tungsten liner will not survive representative internal ballistic loads when it is not well bonded to the launch tube.
3. Nickel forms a good diffusion bond with steel.
4. Tungsten that is deposited at temperatures below 600°C does not form reliable bonds with nickel.
5. Tungsten that is deposited at temperatures greater than 800°C forms nodules that are unacceptable.
6. Bond reliability improves by increasing the thickness of the nickel that is plated on the steel substrate.
7. Electroless nickel does not form a good bond with tungsten, at least for the thicknesses considered under this program.
8. CVD of tungsten on electrolytic nickel forms reliable bonds and a high quality tungsten liner, if the CVD process starts at high temperature but obtains most of its thickness by deposition below 600°C.
9. Hairline cracks are formed in the tungsten layer if CVD starts at high temperature and is completed below 600°C.
10. The failures that have been experienced under this program using tungsten lined launch tubes are attributed to a nickel layer that was too thin, CVD at temperatures that were too low, and possibly a poor choice of nickel type.
11. The probability of a tungsten liner surviving the hybrid launcher internal ballistic loads is very high based on the bonding development results.

Four flat samples were left without tungsten plating at completion of the work of Reference 4. Three of these samples had been electroplated with 2.5 microns (0.0001 inch) of nickel (samples 5, 6 and 8) and one was plated to 25 microns thickness of nickel (sample 26). For reasons that will be identified below, these samples were subsequently plated with tungsten according to the following procedure:

1. After cleaning, raise samples to 820°C and deposit tungsten for about 1 minute.

2. Hold sample at 820^{o}C for about 1 hour to allow tungsten/nickel diffusion.
3. Cool sample to room temperature and hold at this temperature for a minimum of 0.5 hour.
4. Raise sample temperatures to 500^{o}C and deposit a minimum of 0.64 mm (0.025 inches) of tungsten.

The three samples with the thin nickel debonded during later bend tests, but the sample with the thicker nickel was excellent (as defined in Reference 4) after the bend test. Although this was a modification to certain of the successful processes of Reference 4 (500^{o}C versus 590^{o}C final plating temperature and a quench to room temperature before final plating), it constitutes a third apparently successful plating technique (two were identified in Reference 4).

3.2 REVIEW OF THE LAUNCH TUBE STRUCTURAL REQUIREMENTS, MATERIAL PROPERTIES

Peak pressures in the hybrid launcher launch tube are estimated at 6.5 kbar (650 MPa) toward the breech end (5 kbar at the projectile base). The nominal material selected for the launch tubes is 17-4 PH stainless steel. This selection was based on the combination of high yield strength (185 ksi, 1275 MPa) after proper precipitation hardening, and quenchability in air. This latter factor is desirable in order to provide heat treatment simultaneously with the CVD processing.

Based on AEDC's need for improved performance with conventional launchers, a short section of tungsten lined launch tube was fabricated under this program for use in Range S1.* Peak pressures there are expected to be in excess of 10 kbar (1000 MPa). The yield strength of 17-4 PH is much too low for this application. Thus, maraging 300 stainless steel was selected for the AEDC tube. This material is also air quenchable (and also more costly, by about a factor of 6). Heat treatment temperatures and yield and tensile strengths for maraging 300 steel (Reference 5) are compared with 17-4 PH (Reference 6) in Table 1.

High performance gun tubes are conventionally designed (Reference 7) by considering the Von Mises-Hencky yield theory for triaxial principal

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*Tungsten lined launch tubes that were provided earlier under separate contract from AEDC failed in Range S1, as described in Reference 4.

Table 1. Heat treatment temperatures for two candidate launch tube steels.

		Maraging 300	17-4 PH
Solution anneal temperature	($^{o}F/^{o}C$)	1500/815	1900/1038
Aging temperature	($^{o}F/^{o}C$)	900/482	900/482*
Yield strength -0.2% offset	(ksi/MPa)	275/1896	185/1275

*Condition H 900

stresses. For gun tubes where the axial stresses are small (i.e., due only to axial loads imparted by projectile shear), the theory produces a relation for the equivalent yield stress based on radial and tangential stresses

$$\sigma_e^2 = \sigma_t^3 - \sigma_t \sigma_r + \sigma_r^2 \qquad (1)$$

where, at the bore surface

$$\sigma_t = \text{tangential stress} = \frac{W^2 + 1}{W^2 - 1} p, \ W = \text{ratio of outer to inner diameter}$$

$$= d_o/d_i; \ \sigma_r = \text{radial stress} = -p \qquad (2)$$

The pressures computed from Equations (1) and (2) that produce yielding based on the nominal material properties and design dimensions for the 1¼" hybrid launcher and AEDC launch tube are presented in Table 2. This table shows minor yielding of 17-4 PH for the projected hybrid launch tube peak pressure (i.e., pressure at yield is less than the expected pressure). This is not serious if 17-4 PH achieves the advertised properties since the yield surface is far from the O.D. and appropriate autofrettage is anticipated.

The CVD process outlined in the previous subsection is compatible with the heat treatment of maraging 300. That is, the substrate is

Table 2. Yield pressures based on nominal dimensions and materials.

		Hybrid Launcher (¼ Scale)	AEDC
Outside diameter	(inch/cm)	3.25/8.26	3.00/7.62
Inside diameter*	(inch/cm)	1.30/3.30	0.68/1.73
W		2.5	4.44
σ_e/p_y		2.071	1.825
Nominal material		17-4 PH	maraging 300
σ_e, uniaxial yield strength	(ksi/MPa)	185/1275	275/1896
p_y	(ksi/MPa/kbar)	89.3/616/6.16	150.7/1039/10.39

*Assumes 0.025 inch (0.64 mm) tungsten liner that supports zero tensile load.

elevated to the solution annealing temperature during the initial tungsten deposition and the tungsten/nickel/steel diffusion development period. It is then quenched in preparation for aging, and then aged while most of the tungsten layer is deposited. The experience with the flat 17-4 PH sample described earlier suggests the likelihood of successful bonding and heat treating with a gun tube using maraging 300 steel, as required for the AEDC application.

3.3 POST-CVD HEAT TREATMENT

In order to explore further the characteristics of tungsten plated 17-4 PH, two of the flat tungsten plated samples of Reference 4 were not subjected to bend tests, but preserved for further processing (Samples 23 and 24). The samples were subsequently cut up (Samples 23 A, B, C, etc.), subjected to two kinds of heat treatments, and then tested for hardness and tensile strength, and observed relative to bond integrity. The heat treatment conditions and results are presented in Table 3.

The processing in Reference 4 was restricted primarily to finding those conditions that provided a high quality tungsten layer with acceptable bonding, and this was achieved. The original plan with 17-4 PH steel was to deposit the tungsten in one step at the precipitation hardening temperature. Since the steel is received in the annealed state, the end product should have the appropriate structural properties, providing it is not over-aged. We found that the nominal tungsten

Table 3. Results from post-CVD heat treatment; physical properties of 17-4 PH samples.

Sample	CVD Process Temperatures (°C)	Heat Treatment Temperatures (°C)	Yield Strength (ksi/MPa)	Tensile Strength (ksi/MPa)	Elongation (%)	Reduction in Area (%)	Hardness (R_c)
23A	1040-590	1040-20-510	173/1191	185/1276	15.6	68	39
23B	↓	820-20-510	156/1072	160/1100	15.6	70	37
23C	↓	None	180/1238	190/1307	17.8	66	34
24A	820-590	1040-20-510	132/907	170/1172	13.3	71	40
24B	↓	820-20-510	141/972	151/1038	22.2	72	38
24C	↓	None	128/883	150/1034	22.0	74	37

deposition process did not yield reliable tungsten bonds. The high temperatures and times necessary for good bonding were expected to lead to over-aging and inadequate structural properties. The concept was then changed to consider a two-temperature deposition, and this was successful. Peak temperatures that were examined included the solution-annealing temperatures for both 17-4 PH and maraging 300. However, proper heat treating requires that the samples be cooled to room temperature after annealing but before the aging process. This was not done in Reference 4 (quenching was done, as described in the last subsection, for the nominal maraging steel heat treatment).

Considering the possibility of performing the heat treatment after the tungsten deposition is complete, sample 23A was subjected to the nominal heat treatment process for 17-4 PH. The post-heat-treat strength properties (Table 3) are fairly good, but somewhat less than advertised. Sample 23C was not heat treated after plating, and its properties are roughly comparable to Sample 23A. That is, apparently the initial high temperature during the CVD process was not held long enough to provide substantial over-aging. However, the tensile strength data for sample 23C seem to be in conflict with the hardness data, obviating a firm conclusion here.

Sample 23B was heat treated according to nominal specifications for maraging 300 steel. As expected, the structural properties are inferior to 17-4 PH that is properly treated. However, the sample survived the heat treatment without debonding, which was the primary purpose of this particular exercise.

As noted in Table 3, the initial CVD process temperature for sample 23 was the solution-anneal temperature for 17-4 PH. The noticeable surface cracks that are shown in Figure 35 of Reference 4 for this process become very much more evident after heat treatment. In addition, the heat treatment was done in air, resulting in formation of both WC (probably from organic contaminants in the oven) and WO_3, based on the colors of the formations. The WO_3 was in powder form and was removed easily from the samples.

Sample number 24 also showed oxidation and carbide formation, and the hairline surface cracks after CVD were augmented somewhat by heat treatment. It is surprising that the post heat-treatment properties of sample 24 using the nominal 17-4PH heat treatment are so poor, sample 24A.

However, these tensile data are also in conflict with the hardness data. Samples 24B and 24C show clearly that, at least, the solution-anneal temperature and subsequent quench are definitely necessary for adequate treatment after the CVD process of Sample 24. However, these conditions might not be sufficient, based on the results of Sample 24A. On the other hand, the generally good appearance of sample 24B after heat treatment suggests that maraging 300 can be heat treated after tungsten plating, if it is necessary, and preferably in an inert environment.

3.4 SELECTION OF CVD AND HEAT TREATMENT PROCESSES

The processes outlined in Subsection 3.1 were subsequently used to coat the AEDC launch tube and one of two 17-4 PH tubes that were subsequently tested using injection test hardware (see Section 4). The second 17-4 PH tube was processed in the same way, but with the initial CVD at 1040°C for treatment of 17-4 PH, rather than 820°C. The maraging steel process is subsequently referred to as the "medium temperature process," and the 17-4 PH process is referred to as the "high temperature process."

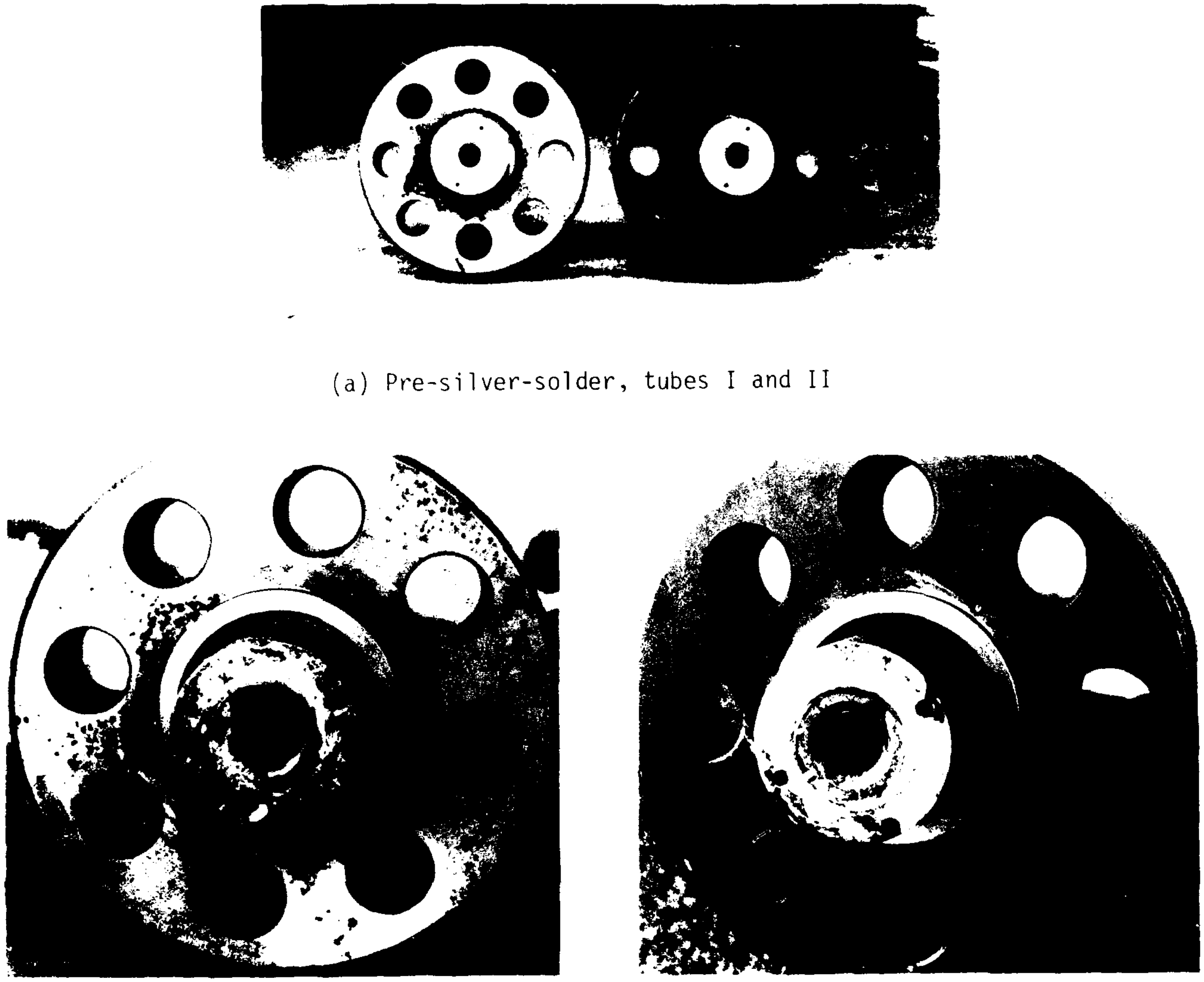
It is important to point out that it is unconventional to electropolate the insides of tubes with nickel, and special tooling was developed to do this. This is an essential part of the overall process. Typically, the electroless nickel process is used for internal plating, and our experience shows poor tungsten bonding with electroless nickel.

3.5 RESULTS OF TUNGSTEN COATING ACCORDING TO SELECTED PROCESSES

Two launch tubes were lined with tungsten using the medium temperature process, with good success. One tube is maraging steel, for AEDC, and the other tube is 17-4 PH, defined here as Tube I. Samples were prepared for bend tests by turning down the outside of a short length of tungsten coated tube, reducing the wall thickness to about 1/8 inch ($\approx$ 3 mm). This thin tube was then cut in half longitudinally. The resulting "arch" was then collapsed in a vice to provide a bend test for tubular samples. The results compare very well with those for flat sample number 26, showing cohesive failure of both the tungsten and steel, but no bond failures.

The launch tubes were designed with bell-mouth inlets, and the inlets were plated along with the bore. A number of small cracks were quite evident in the entry region for the medium temperature process, but no apparent bond failure. In addition, both tubes processed at medium temperatures ended up with thinner liners than desired. Consequently, these liners were not fully honed, and a few small bumps of tungsten remained on the liner of the 17-4 PH tube near the entrance after honing.

One 17-4 PH launch tube was lined using the high temperature process, Tube II. In preparing to dismantle the tube from the tungsten plating setup the tube was found to be bent, apparently having yielded while at the peak temperature. The tube was reheated to straighten it and, based on the success of our post-CVD heat treatment experience, put through a complete 17-4 PH heat treatment after completing the tungsten CVD. Post treatment examination showed a segment of tungsten debonded from the entry region as well as a number of hairline cracks. The debonded region is shown in Figures 1(a) (Tube II) and 1(c). The causes of the bond failure are not known. A tubular bend test using a sample from the opposite end of the tube showed excellent bond retention, as in Tube I. Our experience suggests that the nickel plating might have been too thin in the entrance end of the tube. The appearance of the surface in the debonded region is similar to those cases where the nickel was known to be too thin. However, note that the post-CVD heat treatment presents very severe shear stresses in the entry region bonding interface because of differential expansion. This treatment at least increases the probability of debonding.



(a) Pre-silver-solder, tubes I and II

(b) Post-silver solder, tube I

(c) Post-silver-solder, tube II

Figure 1. Pretest photos of entrances to launch tubes.

SECTION 4
DEMONSTRATION OF LINER INTEGRITY

Considering the temperatures involved in the CVD process and the large differences of coefficients of expansion between steel and tungsten, the shear at the bondline of a flat sample is probably significantly greater than will be experienced during an internal ballistic exposure. In addition, the bend tests are also very severe in terms of bondline shear loads. Thus, it is reasonably certain that launch tubes processed in the same way as flat samples will show excellent bond retention if the flat samples do. Predicted compressive loads on the liner within a launch tube are quite high (see Figure 28 of Reference 4), even under moderately high pressure conditions, and the compressive stresses are augmented because of heat transfer to the liner. And the dynamic nature of a gun firing suggested the need for proof testing the liners under representative environments before completing the subscale launcher hardware.

4.1 DEFINITION OF THE TESTING APPROACH

Range S1 at AEDC under high performance conditions represents more severe pressure loading than in the hybrid launcher, but less severe heat transfer because of the inherent lower hydrogen temperatures. Much higher temperatures are achieved by dumping shock compressed gases into a chamber, using the nominal hybrid launcher demonstration driver design. Neither Range S1 nor the products of an injection experiment provide heat loads as high as expected in the hybrid launcher. But the conditions they represent are the most severe available, and the hardware provides reasonable test beds for evaluating tungsten liner integrity.

The tungsten lined section of a maraging steel launch tube has been sent to AEDC for testing.

Integrity tests have been performed using some of the 1/8 scale injection hardware that was used in Reference 4. Figure 2 shows the injection block clamped to a load stand; two drivers in an arrangement akin to the 1/4 scale demonstrator design (i.e., the drivers are not directly across from each other); and two launch tubes, one in each injection block end flange. Blast shields to protect the range instrumentation are shown installed in Figure 2(b).

4.2 PREPARATIONS FOR TESTING AND DESCRIPTION OF THE HARDWARE

The test plan called for three firings over a 2-day period, providing three exposures of both launch tubes, and providing information concerning refurbishment of injection hardware pertinent to the 1/4 scale launcher. The shots were designated I-6, I-7, and I-8 following the five previous injection tests, and representing the third through fifth use of the 1/8 scale injection block.

Because of some melting at the driver/injection block interface during the I-4 experiment, the driver seals had been "welded" to the block and had to be machined out. The interface was also milled slightly to "clean up" the surface. The driver coupling rings that were used in I-3 and I-4 were turned on a lathe to clean them for use on I-8. Four new driver coupling rings were fabricated, two each being used on I-6 and I-7.*

The driver designs for I-6 through I-8 were modified from those on I-3 and I-4 to provide better seating between the driver termination and the coupling ring, and to provide better sealing, with the objective of eliminating melting in the vicinity of the driver/block interface. In addition, a heavier tamper was included on the I-8 drivers near the termination in an attempt to eliminate leakage out of the closure center after driver termination. As in I-3 through I-5, mylar diaphragms were used to separate the high pressure hydrogen from the chamber prior to injection.

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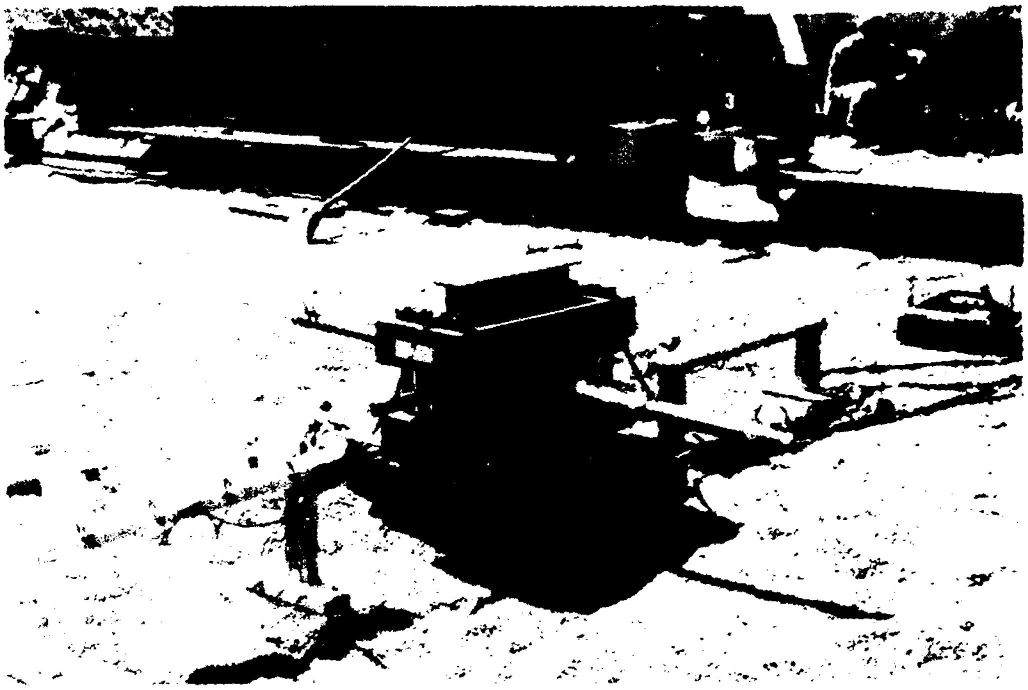
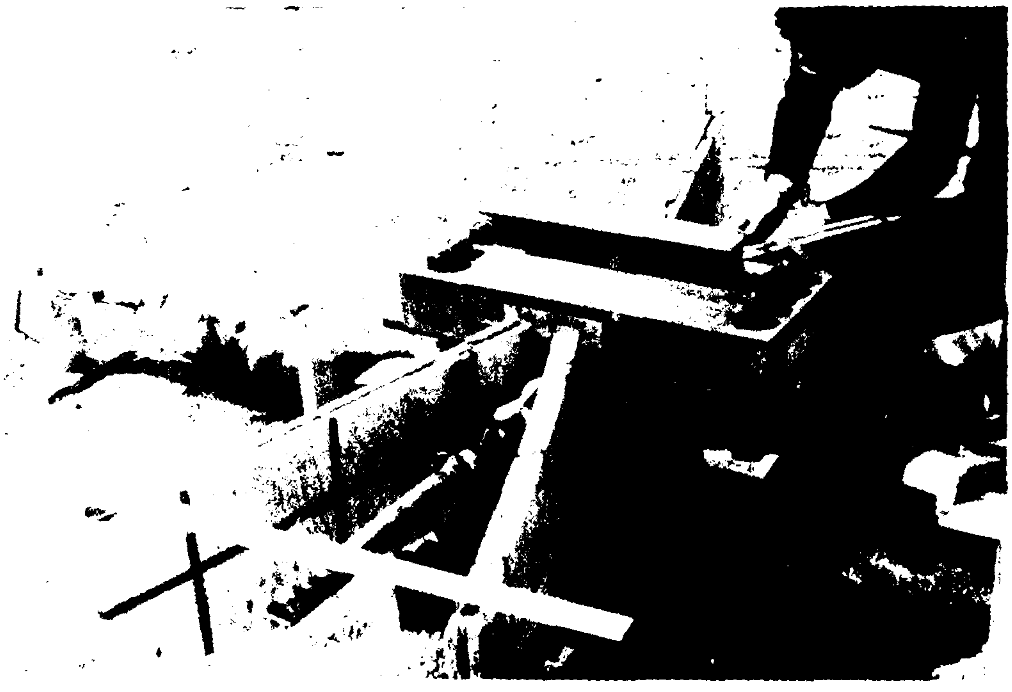
*Following driver operation, the driver terminations need to be machined before they can be removed from the coupling rings because of the plastic flow of the termination. Since three shots were planned over a 2-day period, enough coupling rings were made to obviate this refurbishment between shots.



(a) Before blast shields



(b) After blast shields are installed

Figure 2. Pre-I-6 photos of assembled injection block.

The launch tubes were threaded all of the way through the end flanges to enable exposure of the plated bell-mouth inlets (Figure 1(a)). The peripheries of the ends of the launch tubes were silver-soldered to the end flanges to eliminate leakage there (see Figures 1(b) and 1(c)), and the tubes were also welded to the outer surfaces of the flanges. The end flanges were machined so as to mount a pressure transducer in each flange, and to provide a chamber filling or venting port for pretest purging of the chamber with hydrogen (the two ports can be seen on the flange hubs in each of the end flanges in Figure 1).

Instrumentation included the pressure transducers located as described previously; four ion gages per driver to detect the nitromethane detonation fronts; four cap pins per driver to detect driver shock fronts; and range switches to determine projectile velocities. The range switches can be seen in Figure 2, and a few of the cap pins and ion pins can be seen on driver B in Figure 2(b). Teflon projectiles weighing 13.6 gm were inserted into each of the launch tubes before the end flanges were bolted to the injection block before each firing.

4.3 TEST RESULTS

Injection tests I-6 and I-7 were executed March 20, 1980 at the Physics International test site in Tracy, California. Injection test I-8 was executed the next day. The following subsections present the results of the tests.

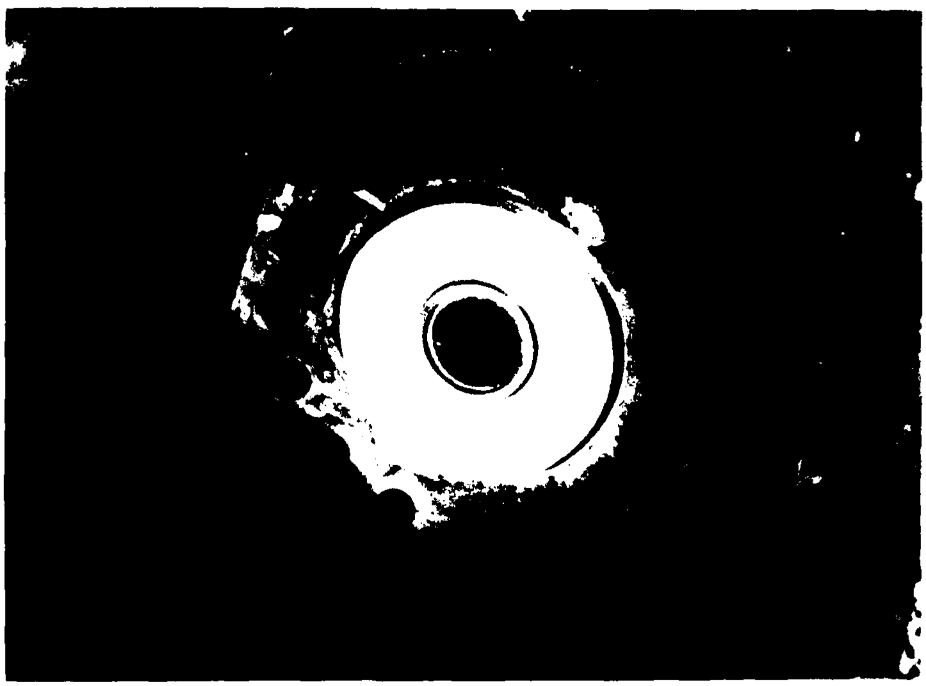
4.3.1 General Results

A typical post-test photo of the injection block assembly is presented in Figure 3(a), showing one of the expended drivers. Figure 3(b) shows the injection-block-driver interface surface prepared for accepting a new driver for the last test, I-8. The driver interface redesign has eliminated melting at the interface (note the undercutting inside the bolt circle that occurred during I-4).

The driver remnants and coupling rings from I-6 are shown in Figure 4. Figure 4(a) shows a driver sealing ring that is worked into an octagonal shape on the driver side, while retaining its circular shape on the injection block side. The seals are easily removed from the injection block if they are left behind on removal of the terminated driver.

Figure 4(b) shows the I-6 driver terminations. All but one of the terminations were completely closed at their centers post-test, showing

(a) Injection block assembly, post-I-8



(b) Injection block side of driver interface surfaces, post-I-7

Figure 3. Post-test photos of test hardware.

(a) Driver-injection-block interface surfaces

(b) Closures

Figure 4. Post-I-6 photos of driver terminations.

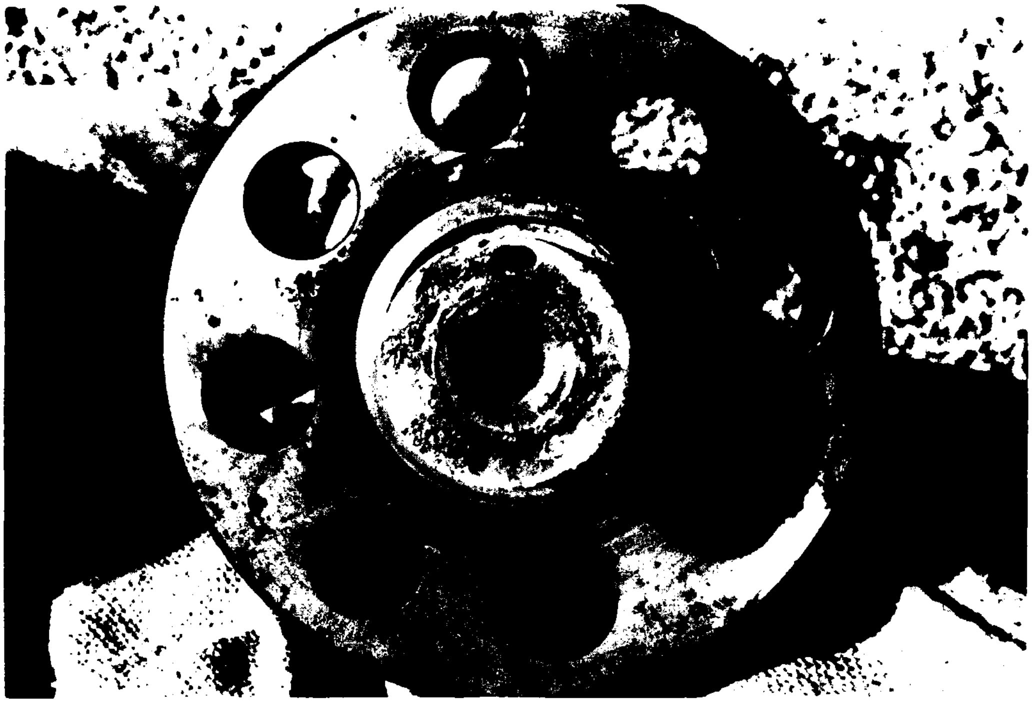
that the additional tamper used on I-8 was not necessary (the one termination not completely closed is driver B of I-8 which had added tamper -- this could be attributed to an excessive tamper causing a rebound of the closure). Past drivers have been characteristically slightly open post-test. Although the driver design modifications were not addressed to this issue (except for the added tamper on I-8), the changes seem to have improved this aspect of the termination, for reasons that are not apparent.

A number of dents were developed across from the ports on I-3 and I-4 because of solid matter ejected from the drivers. No additional dents were developed on I-6 through I-8. Rather, the edges of the dents were made more rounded due to local melting. As In I-5, graphite cloth was bonded across from the ports to minimize melting there, which it did. Some melt globules were found post-test in the injection block cavity and within the driver terminations (e.g., see Figure 4(a)). The melt material was analyzed and found to contain constituents characteristic of 4340 steel. Thus, the melt seems to have come from the injection block, and probably across from the ports. The amount of melt is minimal.

Post-test photos of the entrances of the launch tubes are presented in Figure 5. The figure also shows the excellent condition of the end flange seals -- they can be reused. The excellent condition of the entrance to Tube I in Figure 5 is notable, as is the loss of additional tungsten liner at the entrance of Tube II during I-6.

It was intended that, except for tamper modifications to I-8, the last two shots were to be repeats of I-6. However, the undetected premature expulsion of the projectile in launch Tube II on I-6 during the purging process caused a certain amount of atmospheric air to diffuse into the injection block before the firing. Consequently, the gas stagnation temperatures were somewhat higher than planned during the early part of the ballistic event. The projectiles for the last two shots were expelled as originally planned.

After completing I-7, Launch Tube I was drilled and plugged to simulate a pressure port, with the objective of noting the port integrity for possible pressure instrumentation for the 1/4 scale demonstration. All other aspects of the experiments were the same from shot to shot.



(a) Tube I

(b) Tube II

Figure 5. Post-I-6 photos of entrances to launch tubes.

Refurbishment between shots consisted of:

1. Replacing end flange seals
2. Removing driver seals, replacing them, wiping the interfaces clean and bolting on the new drivers (already instrumented, and including diaphragms) using new driver cap screws
3. Knocking melt globules from the I.D. of the injection block using a chisel or crowbar
4. Installing a new projectile in each barrel, and bolting the barrel assemblies to the injection block

Additional preparations included the connection and checkout of the instrumentation, and, of course, the loading of the drivers with hydrogen and nitromethane, purging the chamber with hydrogen, and installing the driver detonators. These were all accomplished without difficulty.

4.3.2 Driver and Internal Ballistic Performance

Driver and projectile velocity data from all shots are summarized in Table 4. Timing data are presented in Table 5.

Driver shock velocity data are on the high side compared to earlier experience, and show a little more scatter. However, the scatter is influenced by the short space available for instrumenting 1/8 scale drivers. The "jitter" in cap pin signal relative to shock passage becomes a larger fraction of the time interval between pins at smaller scale (time intervals between first and last cap pins is about 40 μsec for these tests). The current shock velocity data agree with former data within the jitter in the cap pin signals in Table 5. This conclusion is supported by the projectile velocity data that are repeatable within about 2 percent. That is, the repeatability of projectile velocities suggests higher repeatability of driver performance than implied by the shock data.

Internal ballistic predictions included the complete specification of driver detonation and performance, injection into the injection block, and expansion of the injection "fireballs" and their subsequent actions on the projectiles. The calculated results after fireball formation were obtained from Reference 8 using an adaptation of the STEALTH code, Reference 9. Because of the symmetry of the injection block, the calculation was carried out considering only one-half of the system including one driver and one launch tube, and a zero crossflow plane at the longitudinal center of the injection block. A "shot start" condition

Table 4. Velocity data.

Shot	Shock or Projectile Velocity (km/sec)			
	Driver A	Driver B	Launch Tube 1[1]	Launch Tube 2[2]
I-6	9.3	9.8	0.86	--[4]
I-7	10.5	9.0	0.87	1.00
I-8	9.2	9.5	0.87	1.02
Predicted	9.0[3]		0.98[2]	

[1]In-barrel travel ≈ 33 cm (13 in.)
[2]In-barrel travel ≈ 35.6 cm (14 in.)
[3]Based on detonation velocity = 6.7 km/sec
[4]Projectile expelled during purging operation

Table 5. Timing data.

Shot	Time at First Cap Pin (μsec)[1]		Time at Nominal Launch Tube Muzzle (μsec)[2]	
	Driver A	Driver B	Launch Tube I	Launch Tube II
I-6	65.0	62.4	735	--[3]
I-7	60.6	58.1	710	720
I-8	62.0	65.5	725	690
Predicted	61.0		735	

[1]First cap pin located 32.4 cm from detonator
[2]Nominal muzzle is 38.1 cm from launch tube entrance
[3]Projectile expelled during purging operation

(to be defined) was not considered in the calculation, making the actual performance very sensitive to the early-time pressure rise at the projectile base.

The projectiles from launch Tube II attained velocities 2 to 4 percent higher than predicted. Projectiles from Launch Tube I were consistently slower than expected. They were expected to be about 4 percent slower than the nominal prediction due to a shorter travel, but averaged about 11.8 percent below the nominal prediction, for a net shortfall of about 8 percent. It is significant that the projectile in Launch Tube II needed to be forced into the entrance of the tube for tests I-7 and I-8. This was required because of the local steel melting and melt accumulation in the launch tube entrance because of the loss of part of the liner upstream (see Figures 1(c) and 5(b)). As a consequence, a "shot start" condition existed in Tube II, and the actual velocity is somewhat higher than predicted, which is reasonable. That is, constraining the projectile from moving until the projectile base pressure builds up (shot start) enables greater acceleration over a longer distance, and higher muzzle velocity. On the other hand, if the projectile is not constrained and the pressure buildup is slightly slower than predicted, muzzle velocity will be lower than expected, especially for a short barrel such as in these experiments. The projectile in Tube I was in fact rather loose in the barrel, although fairly tightly sealed at the base with the base flare designed into the projectile. The lower projectile velocities from this launch tube are probably a result of the loosely fitting projectile and a slight delay in the early time pressure buildup.

The timing data agree quite well with the predicted timing, the driver shocks passing the first cap pins within 4.5 μsec of the predicted time, and projectiles passing the nominal muzzle location within 45 μsec of the predicted time, averaging 19 μsec early. These variances from predicted timing are very acceptable relative to operation of the 1/4 scale demonstrator, and show again that adequate driver gases are being injected into the injection block in the appropriate state well within the 1/4 scale demonstrator timing requirements.

4.3.3 Liner Performance

Post I-6 photos of the launch tube entrances in Figure 5 show the excellent post-test condition of Tube I, and the loss of some additional tungsten at the entrance of Tube II. Tube I appeared to be in excellent condition along the entire bore, with a very thin layer of molten steel and silver solder deposited on top of the tungsten because of upstream melting of unprotected areas. The bore of launch Tube II appeared to be in good shape, with somewhat heavier melt deposits in the upstream region because of melting of entrance steel from the loss of the tungsten coating there.

The post-test I-7 condition of the tubes was substantially unchanged, with the exception of greater accumulations of upstream melt. The same results apply also to I-8. At the completion of the three firings, both bores appeared to be in excellent shape, with the only problem being the entrance region debonding of Tube II, in an apparent progression of the pretest bonding failure.

The tube/flange welds were undercut and Tube II was heated to melt the silver solder to allow unscrewing of the tube from the flange before sectioning. This was unsuccessful, so the entire launch tube/flange assemblies were sectioned. Tube II was sectioned first on a trial basis, finally requiring flame cutting to finish the job. The results are shown in Figure 6. The three firings, plus the heating to attempt to remove the tube from the flange, plus the flame cutting in the final stage of sectioning the tube resulted in debonding of the liner of Tube II over portions of the first 10 to 15 cm of the tube. (Recall this tube was also put through a complete 17-4 PH heat treatment after completion of CVD.) The downstream 23 to 28 cm of the liner was found in excellent condition after sectioning.*

A longitudinal section of Tube I is shown in Figure 7. Blemishes in the appearance of the liner include:

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*The most downstream 10 cm of the tubes were cut off after sectioning to provide tensile specimens. Thus, the downstream ends of the tubes are not shown in Figures 6 and 7.

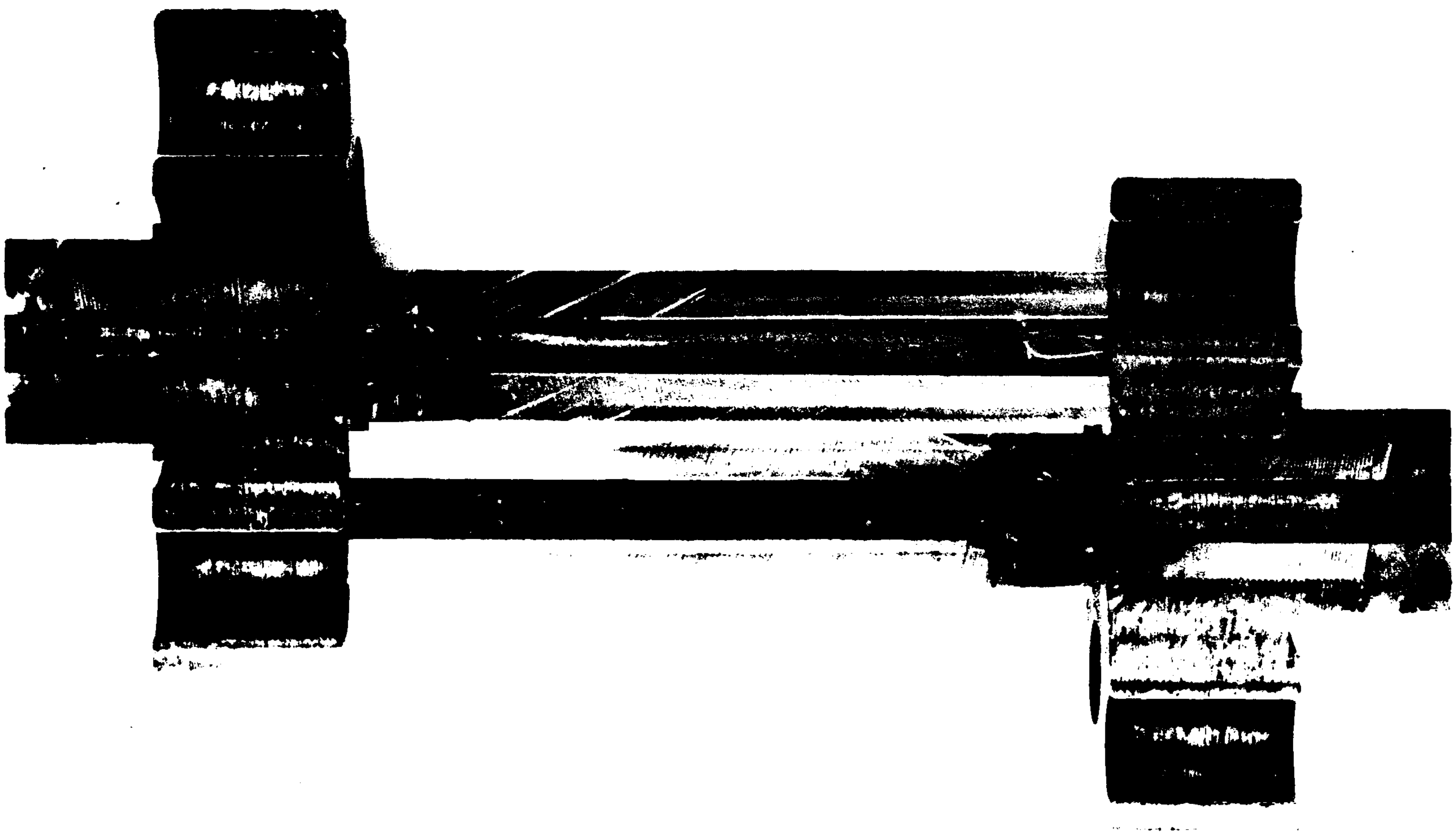

Figure 6. Section of Launch Tube II after three ballistic events.

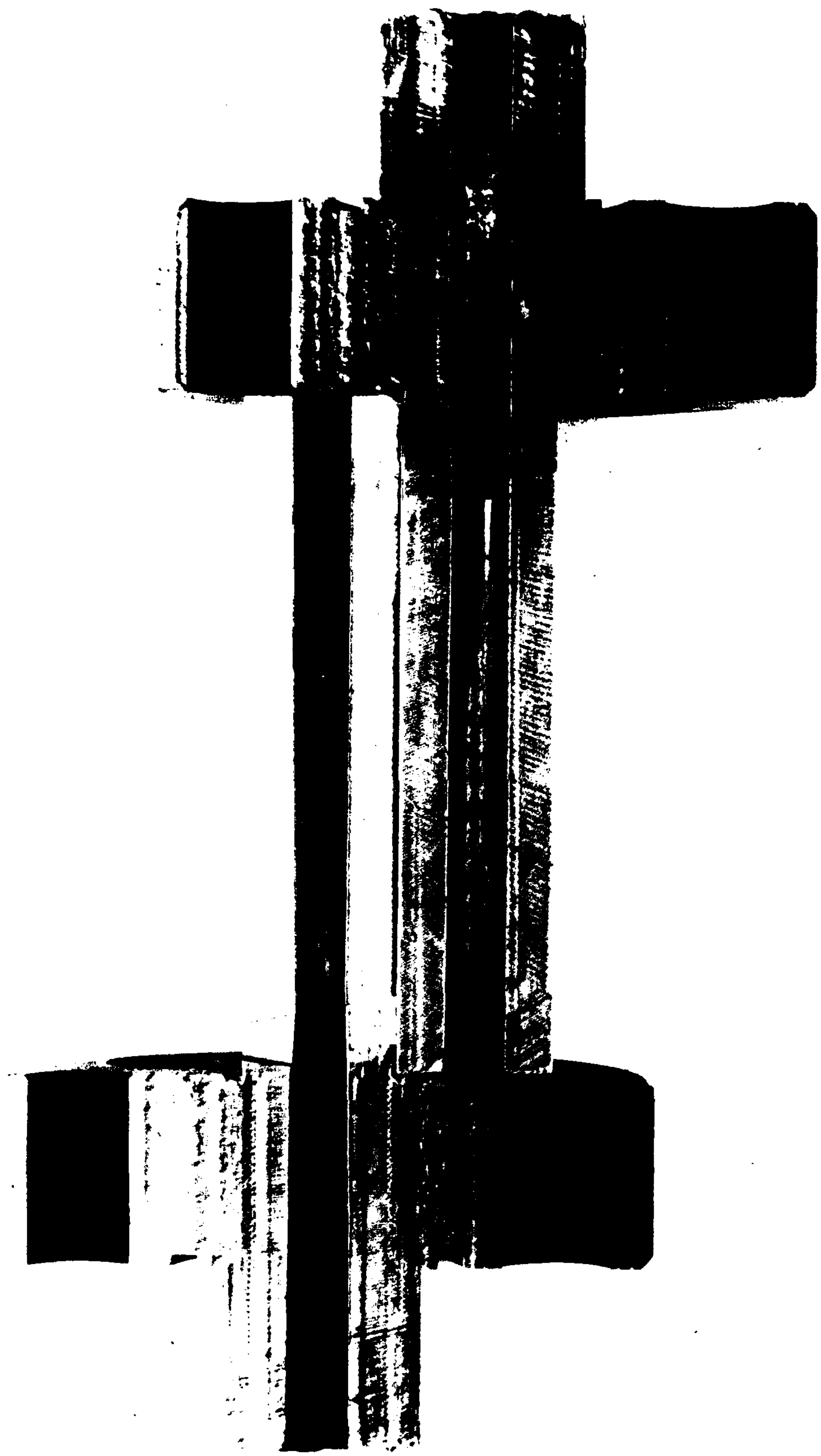

Figure 7. Section of Launch Tube I after three ballistic events.

- Deposition of steel melt on top of the tungsten coating in the first 8 to 12 cm of the tube because of upstream melting of unprotected steel
- A pit in the liner, probably caused by removal of the remnants of a tungsten nodule by the projectile (this can be seen on the lower half of the sectioned tube in Figure 7 approximately midway between the two surfaces of the end flange -- recall that the nodules were not completely honed here because the tungsten liner was thinner than desired). The pit appears to be roughly one-half of the thickness of the liner.
- An "etched" region starting from the simulated pressure port and extending downstream about 15 cm. The port is shown in the lower half of Figure 7, approximately 3 cm downstream of the end flange (for reference, the bore is 1.59 cm in diameter).

Typically, pressure ports are filled with oil or grease to protect the pressure transducers from thermal loads and to minimize the effects of transient filling of the port. Accordingly, the simulated port was filled with Vaseline prior to plugging the outer end of the port with a pipe plug. Apparently, some constituent in Vaseline reacts with tungsten. The tungsten was etched to a depth of perhaps 50 microns (0.002 inches) because of this reaction during the course of only one firing (I-8).

The test results for Tube I are considered excellent. The hairline cracks in the tungsten in the entry region that were noted before testing caused no difficulty during the tests -- the "tiles" were held in place, as desired. The only undesirable feature of the liner of Tube I is the pit mentioned earlier. This can probably be resolved with more complete honing of the tube.

Post-test yield strengths of both tubes are about 128 ksi (882 MPa), with ultimate tensile strengths of 165 ksi (1138 MPa) and 172 ksi (1186 MPa) for Tubes I and II, respectively. Tube I is over-aged, as expected, but Tube II should have shown a higher yield strength based on the post-CVD heat treatment. However, based on the poor bond integrity demonstrated with Tube II that was processed according to nominal 17-4 PH heat treatment specifications, it is clear that 17-4 PH steel is not the best choice for the 1/4 scale demonstrator launch tubes. On the other hand, Tube I was processed according to the nominal maraging steel heat treatment, and the bond integrity using this processing has been demonstrated.

SECTION 5

SUMMARY AND CONCLUSIONS

Tungsten liner developments under the hybrid launcher program have been reviewed and extended to provide both good bonding of liners and the necessary structural properties of the substrate. Certain structural requirements for the hybrid launcher are reviewed, showing that the selection of 17-4 PH for the 1/4 scale demonstrator launch tubes is adequate if the advertised properties can be achieved. The necessary conditions for achieving appropriate properties by heat treating after completing the tungsten CVD processes have been explored.

Two complete tungsten lining processes were developed for application to the 1/4 scale demonstration of the hybrid launcher concept. One technique is designed for 17-4 PH steel (high temperature process), the other for a maraging steel substrate (medium temperature process). The concepts include:

- Electrolytic deposition according to the Watts process of at least 25 microns of nickel on the surface that is to be lined with tungsten
- Raising the component to its solution-anneal temperature, depositing a thin layer of tungsten, and holding the component at the elevated temperature sufficiently long to assure annealing of the substrate and to provide good tungsten/nickel diffusion
- Quenching the component to room temperature as a prelude to the aging process
- Raising the component to the appropriate aging temperature, and depositing the desired thickness of tungsten during the substrate aging process

Three launch tubes were coated internally according to the developed processes, two (using both processes) for testing using hybrid launcher injection test hardware, and one (using the medium temperature process) for testing at AEDC. Three tests were executed using the hybrid injection hardware to provide data on driver design improvements, refurbishment of the 1/4 scale demonstrator, and driver and internal ballistic performance, and to demonstrate the integrity of the tungsten liners.

Conclusions derived from the current study include:

- Minor modifications to the driver design have been successful in that no melting occurs at the driver/injection block interface, the driver terminations are completely closed with high reliability, and refurbishment of the injection block to accommodate replacement drivers has been reduced to a trivial task
- Driver and internal ballistic performances of the driver-injection test system are well within acceptable ranges, and the timing of events is highly predictable. Consequently, the fluidynamic, thermodynamic, and structural dynamic aspects of the injection process that are fundamental to the hybrid concept have been proven.
- Minor melting occurs inside the injection block. This probably occurs directly opposite the injection ports, is not of concern for the 1/4 scale hybrid demonstration, and can be eliminated for a full scale design. The 1/8 scale injection block has survived five injection experiments, and can be reused many more times. Thus, the reusability of the injection block for the hybrid launcher has been demonstrated.
- The eventual inclusion of pressure ports through a tungsten liner depends on the availability of an oil or grease that is inert to tungsten in a hydrogen atmosphere at high temperatures. Pressure ports are not recommended for the tungsten lined components of the hybrid demonstrator.
- The characteristics of the tungsten coating vary over the length of the launch tube. Cracks are noticed in the coating in the entry region, but not in the downstream ends of the

tubes. Bend tests on downstream samples show excellent bonding, but one tube processed at high temperature showed debonding in the entry region. Variations in the thickness of nickel are suspected, and should be investigated.

- The high temperature coating process is apparently not reliable. The process is based on the heat treatment requirements of 17-4 PH steel. The advertised properties of 17-4 PH steel have not been obtained reliably using the techniques of this program.
- The high temperature coating process is not necessary in that the medium temperature process appears to yield reliable results and is completely compatible with the heat treatment of maraging steel. The integrity of tungsten lined tubes using this process has been demonstrated under severe internal ballistic loads.
- The feasibility of heat treating tungsten coated components after completion of the coating has been established for applications using maraging steel as the substrate. However, post process heat treating is risky, should be done in a hydrogen or inert (e.g., argon) environment, and should be avoided if possible.

SECTION 6

REFERENCES

1. Cohen, et al., "Feasibility of a Hybrid Hypervelocity Launcher," DNA 4226F, January 1977.

2. Anderson, A. D. and Dahm, T. J., "Boundary Layer Closure and Heat Transfer in Constant Base Pressure and Simple Wave Guns," Transactions of the ASME, Journal of Heat Transfer, Volume 100, No. 4, November 1978.

3. Dahm, T. J. and Watson, J. D., "Analysis and Design of a Two-Stage Hybrid Launcher," DNA 4334F, May 1977.

4. Suchsland, K., et al., "Development and Testing of a Two-Stage Hybrid Launcher," DNA 5074F, October 1979.

5. Hall, A. M. and Slunder, C. J., "The Metallurgy, Behavior, and Application of the 18-Percent Nickel Maraging Steels," NASA SP-5051, 1968.

6. Anon, "Armco 17-4 PH Precipitation-Hardening Stainless Steel Bar and Wire," Product Data Bulletin 5-6C, Armco Steel Corporation, Baltimore, Maryland.

7. Anon, "Research and Development of Materiel, Engineering Design Handbook, Gun Series, Gun Tubes," Headquarters, U.S. Army Materiel Command, AMCP-706-252, February 1964.

8. Personal communication with Mr. John D. Watson, Artec Associates, Hayward, California, January 1980.

9. Hofmann, R., "STEALTH: A Lagrange Explicit Finite Difference Code for Solids, Structural and Thermohydraulic Analysis," EPRI Technical Report NP-176, Project 307, June 1976.

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