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DEVCOM ARMY RESEARCH LABORATORY

# Evaluation of Surrogate 14.5-mm BS41 Armor-Piercing Projectiles

by Donald Little, Matthew Burkins, and Joseph Paras

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# Evaluation of Surrogate 14.5-mm BS41 Armor-Piercing Projectiles

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**14. ABSTRACT**
A qualified surrogate for 14.5-mm armor-piercing incendiary (API) BS41 projectiles was needed for laboratory experiments and armor plate military specification acceptance testing. The US Army Research Laboratory* performed an analysis on the old and new domestic surrogate 14.5-mm API BS41 projectiles to establish the new projectile performance compared to the existing domestically produced surrogate. There was no attempt to compare either surrogate to the actual Soviet WWII BS41 projectile. This report outlines the tasks performed and data collected in support of this effort.

**15. SUBJECT TERMS**
14.5-mm BS41, armor-piercing incendiary, API, rolled homogeneous armor, RHA, steel, high-hardness armor, HHA, penetration, perforation, $V_{50}$, armor

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## 1. Introduction

The 14.5-mm BS41 armor-piercing incendiary (API) projectile has a tungsten carbide (WC) core and was developed in the USSR on the eve of World War II as a tank-killing weapon. The now defunct Frankfort Arsenal of Philadelphia, Pennsylvania, characterized the Soviet rounds, prepared drawings, and produced surrogate projectiles in the 1960s. By the 1980s, supplies of these surrogates had been nearly exhausted.

Since these surrogates were used for ballistic qualification for high-hardness armor (HHA; MIL-A-46100C)[1] and 7039 aluminum armor (MIL-A-46063E),[2] the US Army Combat Systems Test Activity* (CSTA) took the lead in obtaining new surrogates from Brass Extrusion Laboratories, Ltd (BELL) of Bensenville, Illinois, in 1984[3].

By the year 2002, quantities of the BELL surrogate BS41 projectiles had become low and the US Army Research Laboratory† (ARL) took the lead in purchasing a new set of surrogates from New Lenox Ordnance (NLO) of Dwight, Illinois. Since the BS41 is still used for acceptance testing of MIL-DTL-46100E[4] HHA and MIL-DTL-46063H[5] 7039 aluminum, the performance of the BELL and NLO surrogate rounds needed to be compared.

An evaluation plan was developed to compare both surrogate rounds to determine if the performance of the NLO rounds were similar to the BELL rounds. Physical measurements were collected, the cores of both rounds were characterized, and then ballistic evaluations were conducted. At no point were either surrogates compared to the original, Soviet-produced, 14.5-mm BS41 projectiles, as this was outside the scope of this effort.

## 2. Physical Measurements Comparison

Prior to beginning the procurement of the BS41 surrogates, it was determined that new drawings were needed to replace the old Frankford Arsenal surrogate drawings, which were in poor condition. New drawings were produced at ARL that attempted to match the old drawings as closely as possible. These new drawings, provided in Appendix A, were used to establish the measurements and tolerances for the NLO surrogate BS41 projectiles. The requirements for NLO under contract #DAAD17-02-C-0105 are provided in Appendix B.

* As of June 1995, CSTA was renamed the US Army Aberdeen Test Center (ATC).
† As of February 2019, the US Army Research Laboratory was renamed the US Army Combat Capabilities Development Command (DEVCOM) Army Research Laboratory (ARL).

Two lots of BS41 projectile surrogates were analyzed: DAAD05-85-C-4197 produced by BELL in 1985 and DAAD17-02-C-0105 produced by NLO in 2002. This report refers to these lots as BELL-1985 and NLO-2002, respectively. A projectile drawing for the NLO-2002 purchase is provided as Fig. 1.

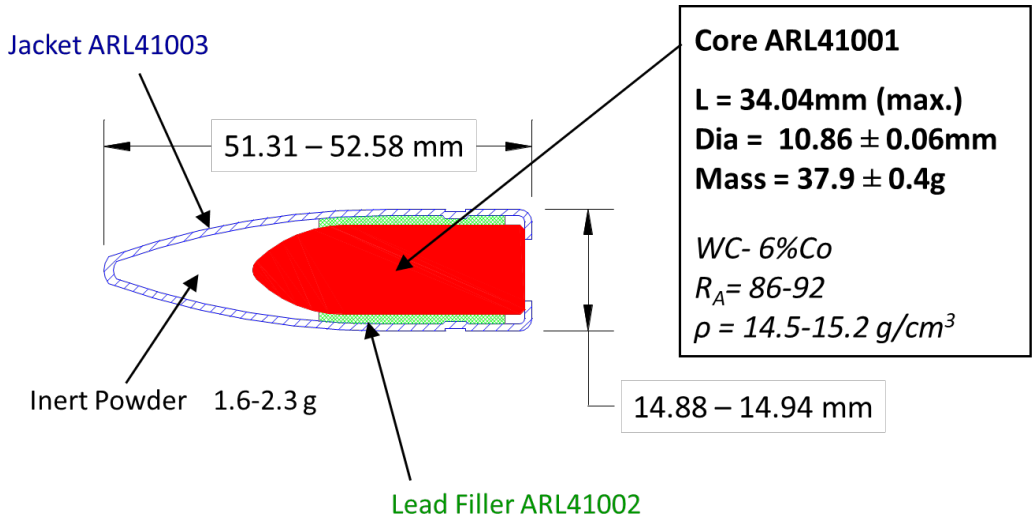



**Fig. 1 Projectile drawing for NLO-2002 contract**

Although the goal was to try to match the existing projectiles as closely as possible, one intentional, major change was to replace the incendiary with inert filler. This change made handling and shipping the projectiles easier without compromising performance for any of the expected applications or uses.

The BELL-1985 and NLO-2002 bullets are shown in Fig. 2. The gray-painted tip on the BELL-1985 bullet indicates the presence of incendiary material. The NLO-2002 inert bullet is not painted and simplifies identifying the two bullets.

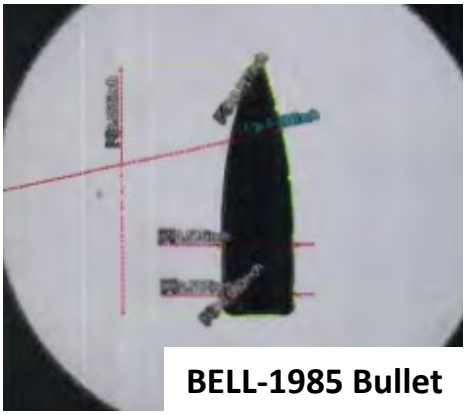
**Fig. 2 BELL-1985 bullet (left) and NLO-2002 bullet (right)**

Physical measurements were required for the NLO-2002 bullets and cores to ensure they conformed to the drawings. Five bullets were selected at random and their length, diameter, and mass were measured. These bullets were then cut open, the WC cores removed, and the core length, diameter, and mass measured. The same process was conducted on the BELL-1985 bullets and cores to provide a comparison for the existing lot. The measurements, as well as average and standard deviation, are provided in Table 1. The NLO-2002 bullets and cores conform to the drawings and the dimensions and masses are similar to the BELL-1985 bullets and cores.

**Table 1 Physical measurements of bullets and cores for BELL-1985 and NLO-2002**

| Source | Sample no. | Intact bullet length (inch) | Intact bullet diameter (inch) | Intact bullet mass (g) | WC core length (inch) | WC core diameter (inch) | WC core mass (g) |
|---|---|---|---|---|---|---|---|
| Drawing requirements | – | 2.020–2.070 | 0.586–0.588 | 62.2–64.2 | 1.340 max | 0.425–0.430 | 37.5–38.3 |
| NLO-2002 | 1 | 2.050 | 0.586 | 64.14 | 1.286 | 0.427 | 37.81 |
| | 2 | 2.059 | 0.586 | 63.72 | 1.282 | 0.427 | 37.74 |
| | 3 | 2.055 | 0.586 | 64.16 | 1.286 | 0.427 | 37.95 |
| | 4 | 2.055 | 0.586 | 64.21 | 1.283 | 0.426 | 37.75 |
| | 5 | 2.060 | 0.586 | 64.04 | 1.284 | 0.427 | 37.82 |
| | *Avg* | *2.056* | *0.586* | *64.05* | *1.284* | *0.427* | *37.81* |
| | *Std Dev* | *0.004* | *0.000* | *0.20* | *0.002* | *0.000* | *0.08* |
| BELL-1985 | 1 | 2.054 | 0.586 | 64.14 | 1.268 | 0.425 | 37.84 |
| | 2 | 2.053 | 0.586 | 63.65 | 1.277 | 0.425 | 37.96 |
| | 3 | 2.054 | 0.586 | 64.42 | 1.283 | 0.428 | 38.63 |
| | 4 | 2.057 | 0.586 | 63.43 | 1.273 | 0.429 | 37.77 |
| | 5 | 2.055 | 0.587 | 63.80 | 1.279 | 0.425 | 37.88 |
| | *Avg* | *2.055* | *0.586* | *63.89* | *1.276* | *0.426* | *38.02* |
| | *Std Dev* | *0.002* | *0.000* | *0.39* | *0.006* | *0.002* | *0.35* |

In addition, this projectile procurement provided an opportunity to test the Keyence Model IM-6225 image dimension measuring system that ARL had recently acquired. Sample 1 for the bullet and core for each lot was placed in the machine, the image captured, and a series of dimensions simultaneously measured (length, diameter, ogive radius, etc.). Figure 3 shows the image and dimensions collected for both bullets and Fig. 4 shows the image and dimensions for both cores. As can be seen by comparing these figures to Table 1, the Keyence machine measurements for Sample 1 were fairly close to the measurements collected with calipers. The largest difference was 0.015 inch for the NLO-2002 bullet length when comparing the two measurement methods.

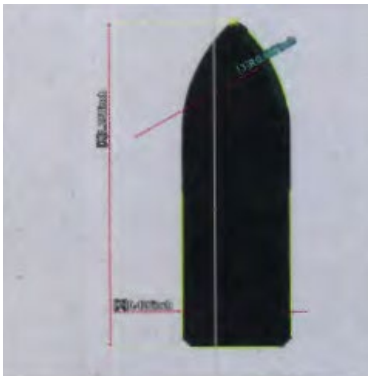


BELL-1985 Bullet

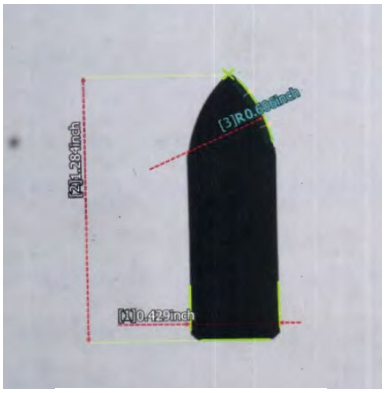
NLO-2002 Bullet

| No. | Feature | Measurement (inch) | No. | Feature | Measurement (inch) |
|---|---|---|---|---|---|
| 1 | Diameter rear | 0.587 | 1 | Diameter rear | 0.586 |
| 2 | Diameter forward | 0.586 | 2 | Diameter forward | 0.586 |
| 3 | Tail fillet | 0.080 | 3 | Tail fillet | 0.105 |
| 4 | Overall length | 2.051 | 4 | Overall length | 2.065 |
| 5 | Nose radius | 0.117 | 5 | Nose radius | 0.107 |
| 6 | Ogive | 4.238 | 6 | Ogive | 4.018 |

**Fig. 3 Keyence measurements for BELL-1985 bullet (left) and NLO-2002 bullet (right)**



BELL-1985 Core



NLO-2002 Core

| No. | Feature | Measurement (inch) | No. | Feature | Measurement (inch) |
|---|---|---|---|---|---|
| 1 | Diameter | 0.426 | 1 | Diameter | 0.429 |
| 2 | Length | 1.268 | 2 | Length | 1.284 |
| 3 | Ogive | 0.607 | 3 | Ogive | 0.606 |

**Fig. 4 Keyence measurements for BELL-1985 core (left) and NLO-2002 core (right)**

While not intended as a rigorous calibration, the quick comparison of lengths and diameters built confidence in the capabilities of the Keyence machine. This was more important for the ogive dimensions, where direct measurement comparison was difficult. The NLO-2002 bullet and core ogives appear to meet the drawing requirements.

## 3. Core Characterization

The two lots of BS41 projectile surrogate cores were analyzed (BELL-1985 and NLO-2002) with the following tests:

- Chemical analysis
- Density
- Microhardness
- Microstructural analysis

### 3.1 Macrostructural Observations

Visual variation exists between the two lots, with BELL-1985 showing signs of aging/corrosion. This can be seen in the color difference between the cores in Fig. 5. Beyond this, the ogives are different between lots. By comparison, the ogive on NLO-2002 is more conical. This difference can be observed in the cross sections of the cores denoted in Fig. 6.

**Fig. 5 BELL-1985 core (left) and NLO-2002 core (right)**

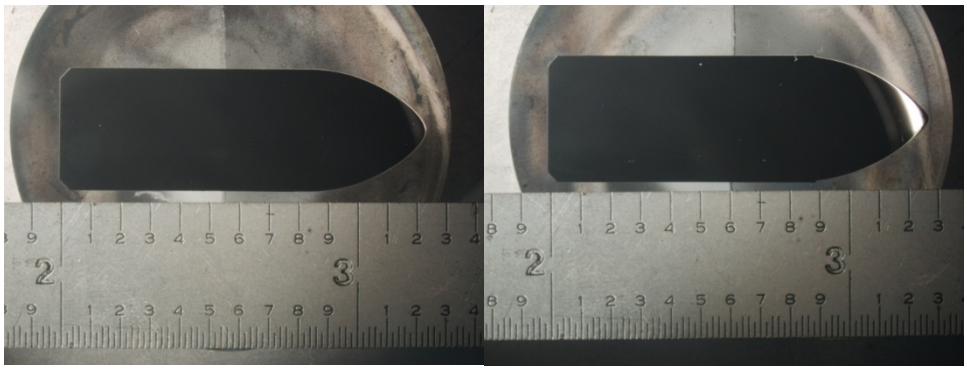


**Fig. 6 Cross sections of BELL-1985 (left) and NLO-2002 (right)**

## 3.2 Chemical Analysis

The chemical composition of the cores was determined using X-ray fluorescence (Rigaku Primus XRF). The data are summarized in Tables 2 and 3. It must be noted that the system calculated the data in semi-quantitative mode.

**Table 2 Chemical composition of BELL-1985 (wt%, semi-quantitative)**

| Mg | Al | S | Ca | Co | Ni | W |
|---|---|---|---|---|---|---|
| 0.0117 | 0.0161 | 0.0888 | 0.0575 | 6.0922 | 0.0261 | 93.7075 |

Note: Abbreviations are detailed in the acronyms list.

**Table 3 Chemical composition of NLO-2002 (wt%, semi-quantitative)**

| Na | K | Ca | Ti | Fe | Co | Ni | Nb | Ta | W |
|---|---|---|---|---|---|---|---|---|---|
| 0.0418 | 0.0411 | 0.0649 | 0.2206 | 0.0861 | 7.4067 | 0.0334 | 0.0807 | 0.2350 | 91.7896 |

Note: Abbreviations are detailed in the acronyms list.

Treating the Mg, Al, S, Ca, and Ni as trace impurities, the composition of BELL-1985 is 94% WC/6% Co. These impurities most likely came from handling of the sample (i.e., dirt, fingerprints, dust, and so on). Similarly, the composition of NLO-2002 is approximately 92% WC/7.5% Co/0.25% titanium carbide (TiC)/0.25% tantalum carbide (TaC). In this case, Ti and Ta are present in significant amounts such that they cannot be treated as trace impurities. It is known that TiC and TaC are used as sintering aids for WC-Co, so it is assumed that the Ti and Ta detected are actually TiC and TaC. Note: The parameters of these measurements did not include a search for carbon.

## 3.3 Density

Given the chemical composition of the cores, the theoretical densities were calculated to assess the relative density. The density of the cores was measured via the Archimedes method, using an alcohol bath. BELL-1985 was measured in an

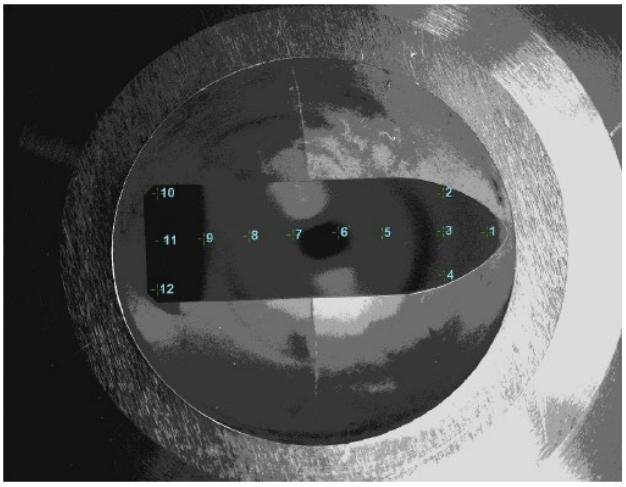
isopropanol bath, while NLO-2002 was measured in an ethanol bath. The use of different alcohol baths is not material related. Insufficient isopropanol remained for measurements on NLO-2002, so ethanol was used instead. The density data are summarized in the Table 4.

**Table 4 Density of BS41 cores**

| Lot | Measured density (g/cc) | Theoretical density (g/cc) | Relative density (%) |
|---|---|---|---|
| BELL-1985 | 14.86 | 14.95 | 99.4 |
| NLO-2002 | 14.66 | 14.71 | 99.7 |

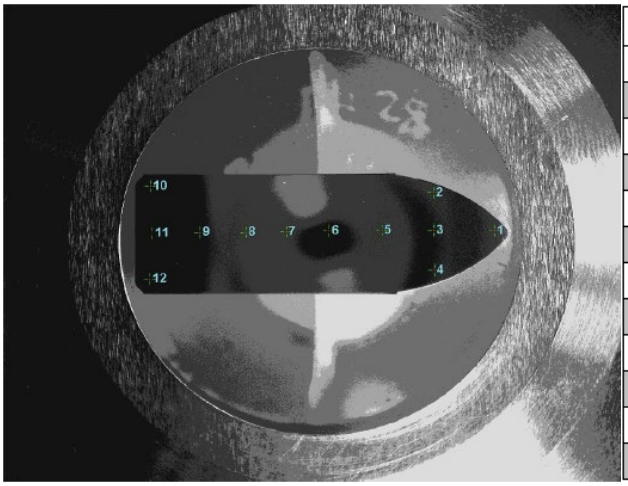
## 3.4 Microhardness

Microhardness was measured using Vickers indentation on a Struers Duramin-A300. The average Vickers Hardness Number (VHN) for BELL-1985 was 1476 with a standard deviation of 41; NLO-2002 was 1544 with a standard deviation of 24. However, when converting to the Rockwell A hardness (HRA) scale, both lots are approximately 90 HRA. The data are summarized in Figs. 7 and 8.




| Pointnr. | Hardness |
|---|---|
| 1 | 1565 |
| 2 | 1475 |
| 3 | 1463 |
| 4 | 1397 |
| 5 | 1528 |
| 6 | 1452 |
| 7 | 1492 |
| 8 | 1463 |
| 9 | 1469 |
| 10 | 1475 |
| 11 | 1481 |
| 12 | 1452 |

**Fig. 7 BELL-1985 microhardness overview**




| Pointnr. | Hardness |
|---|---|
| 1 | 1522 |
| 2 | 1553 |
| 3 | 1591 |
| 4 | 1540 |
| 5 | 1578 |
| 6 | 1534 |
| 7 | 1559 |
| 8 | 1534 |
| 9 | 1528 |
| 10 | 1522 |
| 11 | 1559 |
| 12 | 1510 |

**Fig. 8 NLO-2002 microhardness overview**

## 3.5 Microstructural Analysis

The as-received cores were sectioned, mounted in epoxy, and ground/polished using standard metallographic techniques. The cross sections were then examined using optical (Nikon Eclipse MA200) and electron (Zeiss Supra40-VP) microscopy. The microstructures are presented in Figs. 9–11.

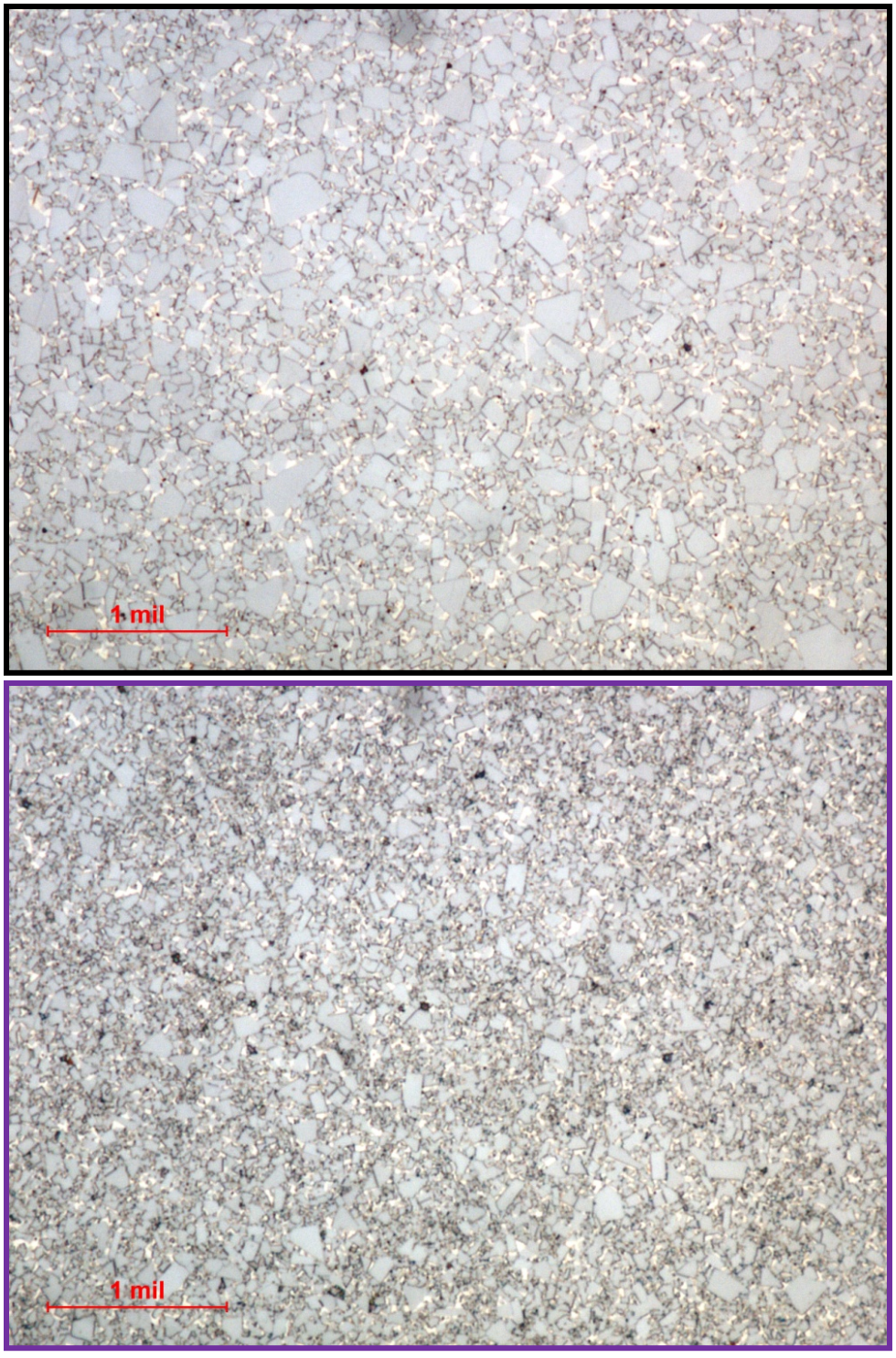



**Fig. 9 Microstructure of BS41-1985 (Top) and BS41-2002 (Bottom) taken at 100×**

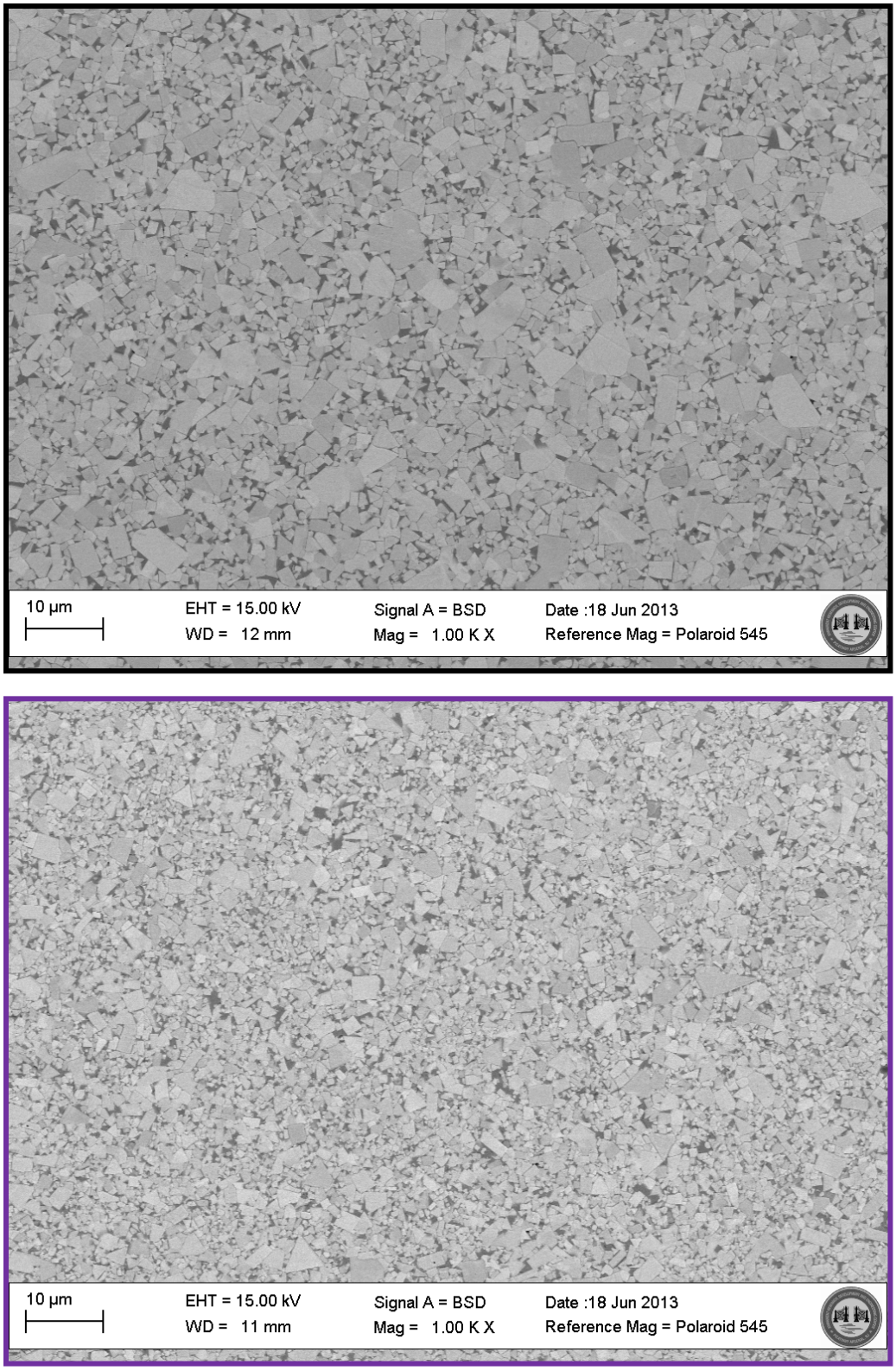



**Fig. 10 Microstructure of BELL-1985 (top) and NLO-2002 (bottom) taken at 1000×**

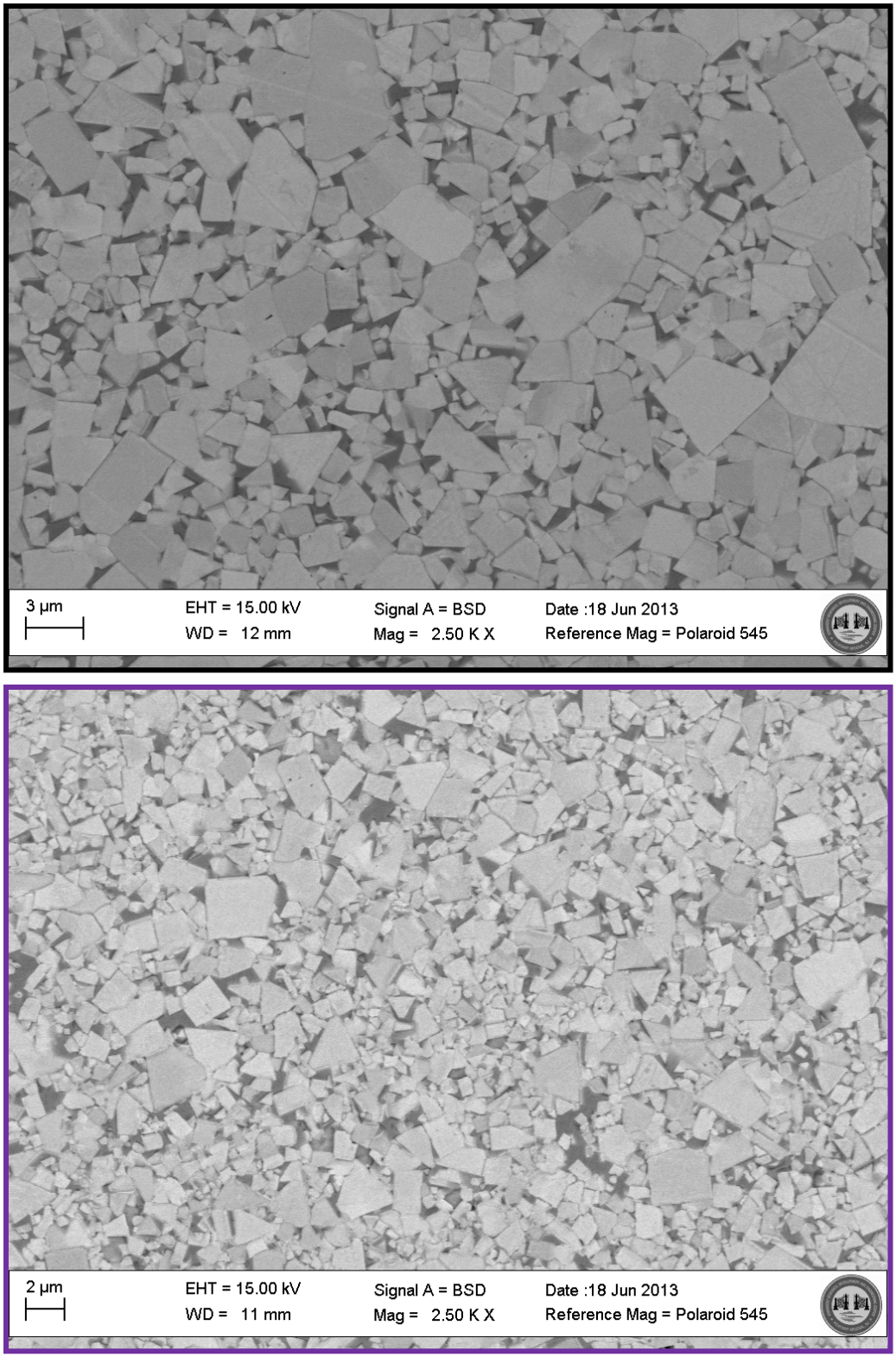



**Fig. 11 Microstructure of BELL-1985 (top) and NLO-2002 (bottom) taken at 2500×**

It can be seen that NLO-2002 has a much finer grain size than BELL-1985. Given the chemical composition of NLO-2002, it is believed that TiC and TaC were used as grain growth inhibitors. This would provide more microstructural control over the processing parameters. In the bulk, the fine microstructure results in Hall–Petch strengthening as evidenced by the slightly higher microhardness. By extension, it is anticipated that NLO-2002 will have a higher strength as compared to BELL-1985.

A thorough grain size analysis was not performed on the cores due to the lack of measurement software and the time involved using manual measurements. However, a rough approximation of grain size can be attained from the micrographs. BELL-1985 has a bimodal distribution with the smaller mode being approximately 1 μm and the larger mode being approximately 5–10 μm. NLO-2002 also has a bimodal distribution where the smaller mode is approximately 0.2–0.5 μm and the larger mode is approximately 2–3 μm.

## 4. Ballistic Comparison

The primary concern with the new contract was whether the ballistic performance of the NLO-2002 bullets was equal to the performance of the historical BELL-1985 bullets. Initial semi-infinite penetration experiments were conducted into rolled homogeneous armor (RHA) steel, Class 1 MIL-DTL-12560H,[6] prior to the $V_{50}$ testing on HHA that was called out in the contract requirements. Additional concerns about the NLO-2002 WC cores being tougher than the BELL-1985 cores, especially in light of the increased Co content in the NLO-2002 WC cores, led to the development of an asymmetrical loading experiment to assess the brittleness of both cores.

### 4.1 Semi-Infinite Penetration

Semi-infinite experiments involve shooting a penetrator into a target with sufficient thickness such that the rear surface of the target plate is not deformed. For these experiments, both lots of bullets were fired into nominal 76.2-mm-thick RHA plates at 0° obliquity. The semi-infinite experiments yielded useful ballistic data while working out the propellant-velocity loading curves and assessing the flight characteristics of the bullets. If the different WC core lots penetrate as rigid bodies and are of the same shape and mass, the expectation would be that the semi-infinite results would be similar.

The bullets were fired into the RHA blocks at multiple velocities and then sectioned after the experiments so that penetration depth could be measured from the original surface of the steel block. In cases where the impact crater was free of penetrator

material, the hole depth was measured directly without sectioning the blocks. The thickness and hardness of the RHA target plates were measured for reference. Projectile velocity and total yaw were measured using an orthogonal flash radiograph system as described by Grabarek and Herr.[7] The results are provided in Table 5 showing the projectile lot, the thickness and hardness of the RHA target plate, the bullet velocity and total yaw at impact, and the measured depth of penetration into the RHA.

**Table 5 BS41 semi-infinite penetration into RHA at 0° obliquity**

| Projectile lot | RHA thickness (mm) | RHA hardness (HBW) | Striking velocity (m/s) | Total yaw (°) | Depth of penetration (mm) | Shot no. (LAT) |
|---|---|---|---|---|---|---|
| BELL-1985 | 75.9 | 302 | 609 | 0.25 | 21 | 8541 |
| BELL-1985 | 75.9 | 302 | 658 | 1.03 | 23 | 8542 |
| BELL-1985 | 75.9 | 302 | 677 | 0.56 | 25 | 8540 |
| BELL-1985 | 75.9 | 302 | 792 | 0.25 | 31 | 8543 |
| BELL-1985 | 75.9 | 302 | 908 | 0.90 | 37 | 8544 |
| BELL-1985 | 75.9 | 302 | 1008 | 1.25 | 43 | 8545 |
| NLO-2002 | 76.6 | 302 | 603 | 1.77 | 21 | 9799 |
| NLO-2002 | 76.6 | 302 | 609 | 0.75 | 21 | 9798 |
| NLO-2002 | 76.6 | 302 | 664 | 1.25 | 24 | 9800 |
| NLO-2002 | 76.6 | 302 | 736 | 1.25 | 27 | 9808 |
| NLO-2002 | 76.6 | 302 | 772 | 0 | 29 | 9801 |
| NLO-2002 | 76.6 | 302 | 828 | 1.50 | 33 | 9806 |
| NLO-2002 | 76.6 | 302 | 903 | 1.25 | 36 | 9802 |
| NLO-2002 | 76.6 | 302 | 1005 | 1.50 | 43 | 9803 |

The contract for the NLO-2002 bullets also required that the total yaw of the bullet would be less than 2° for at least seven out of eight shots. As a rule of thumb, high yaws at impact can reduce the penetration depth for bullets. This 2° total yaw limit was chosen because RHA penetration should be unaffected by total yaws below 2°. As can be observed from the table, all bullets from both lots flew with less than 2° total yaw. The NLO-2002 bullets were successfully fired eight times with acceptable yaws, thereby satisfying the yaw requirement of the contract. Since no shots had to be disregarded due to high yaw, the RHA semi-infinite penetration for both bullet lots is shown graphically in Fig. 12. As expected, the semi-infinite penetration for both bullet lots was very similar.

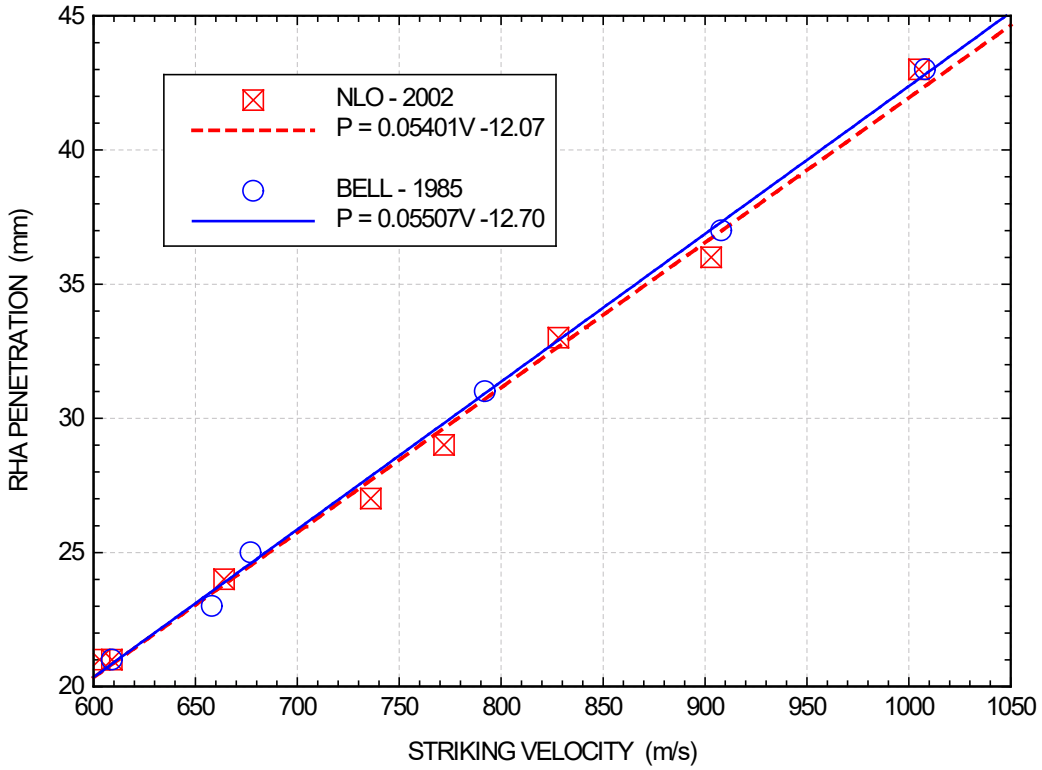



**Fig. 12 BS41 semi-infinite penetration into RHA at 0° obliquity**

## 4.2 Contract Required $V_{50}$ Experiments

$V_{50}$ experiments per MIL-STD-662F[8] were a requirement for the NLO contract in 2002. The $V_{50}$, the velocity at which 50% of the impacts will perforate the target, is obtained by firing an equal number of partial penetrations (PPs; projectile stopped by target) and complete penetrations (CPs; projectile perforates target) within a specified velocity spread, in this case, two PPs and two CPs within 18.3 m/s (60 ft/s). The bullet striking velocity (Vs), vertical pitch, and horizontal yaw were obtained using an orthogonal flash radiograph system described by Grabarek and Herr.[7] Total yaw is obtained through the vector sum of pitch and yaw.

MIL-DTL-662F[8] was modified by replacing the 0.5-mm aluminum alloy (AA) 2024-T3 witness plate with a paper break screen placed on the back surface of the target plate. When a piece of projectile or target tears this screen, the circuit is broken, and timers are engaged, which energize flash radiographs. The size, shape, and velocity of the material exiting the target are recorded for these CPs. If the X-rays did not initiate, the shot was a PP. The use of flash radiographs allows the assessment of the exiting bullet core to determine if the core has fractured. If the core broke into more than two pieces, this would indicate that it is too brittle.

The BELL-1985 bullets were fired into a 300-mm × 450-mm × 25.37-mm-thick HHA plate (MIL-DTL-46100E) measuring 477 HBW and mounted at 0° obliquity. The data are provided in Table 6. Three BELL-1985 shots had total yaws above 2°. The PP with high yaw was disregarded from the analysis because the higher yaw would bias the shot toward being a PP. The two CPs were not disregarded since, even if the higher yaw biased the shot toward being a PP, the actual result was a CP. The core residual velocity ($V_R$) and residual length ($L_R$) after exiting the target are also recorded in the table. The four-shot $V_{50}$ obtained was 738 m/s with a standard deviation of 4 m/s. Taking this $V_{50}$ and adding three standard deviations yielded the 750-m/s maximum $V_{50}$ that was established as the 2002 contract requirement. The BELL-1985 cores did not break into more than two pieces during impacts.

**Table 6 $V_{50}$ results for the BELL-1985 bullet vs. 25.37-mm HHA at 0° obliquity**

| $V_S$ (m/s) | Pitch (°) | Yaw (°) | Result (CP/PP) | $V_R$ (m/s) | $L_R$ (mm) | Comments |
|---|---|---|---|---|---|---|
| 721 | –0.25 | 0.50 | PP | NA | NA | … |
| *732* | *–2.25* | *0.75* | *PP* | *NA* | *NA* | *Disregard* |
| 734 | –1.25 | 0.25 | *PP* | NA | NA | … |
| 735 | 0.75 | –1.00 | *CP* | 153 | 31 | Intact penetrator |
| 736 | 0.75 | 0.25 | *PP* | NA | NA | … |
| 745 | –1.25 | 1.00 | *CP* | 34 | 6 | Plug; intact penetrator in plate |
| 759 | 0.25 | 1.25 | CP | 160<br>66 | 20<br>10 | Nose<br>Tail |
| 762 | 1.25 | 2.00 | CP | 190 | 31 | Intact penetrator |
| 770 | 1.00 | 3.00 | CP | 146 | 20.8 | Nose;<br>Tail in plate |
| 770 | –0.25 | 0.50 | CP | 164<br>103 | 18.9<br>13.9 | Nose<br>Tail |
| 787 | 0.25 | 1.75 | CP | 277<br>235 | 22<br>14 | Nose<br>Tail |
| 805 | 0.25 | 0.50 | CP | 244 | 31 | Intact penetrator |

**$V_{50}$ = 738 m/s**

**Standard deviation = 4 m/s**

**Velocity spread = 11 m/s**

**Zone of mixed results = 1 m/s**

**Maximum required $V_{50}$ for new contract = 750 m/s (738 + 3 × 4 m/s)**

Note: *PP* and *CP* indicate the shots used to calculate the $V_{50}$ limit velocity.

The NLO-2002 bullets were fired into the same 25.37-mm-thick HHA plate at 0° obliquity to establish a $V_{50}$. Table 7 provides the firing data for the NLO-2002 bullets. The $V_{50}$ for the NLO-2002 bullets was 746 m/s, which is below the 750-m/s maximum set by the contract. All NLO-2002 shots had a total yaw below 2° and all of the WC cores were intact after impact. The more detailed $V_{50}$ ballistic data are provided in Appendix C.

**Table 7 $V_{50}$ results for the NLO-2002 bullet vs. 25.37-mm HHA at 0° obliquity**

| $V_S$ (m/s) | Pitch (°) | Yaw (°) | Result (CP/PP) | $V_R$ (m/s) | $L_R$ (mm) | Comments |
|---|---|---|---|---|---|---|
| 738 | 0.25 | 0.25 | *PP* | NA | NA | … |
| 744 | 0 | 1.75 | *PP* | NA | NA | … |
| 748 | –0.25 | 0.50 | *CP* | 115 | 7 | Spall; intact penetrator in plate |
| 753 | 0 | 0.75 | *CP* | 104 | 33 | Intact penetrator |
| 754 | 0 | 0 | CP | 13 | 3.8 | Spall; intact penetrator in plate |
| **$V_{50}$ = 746 m/s**<br>**Standard deviation = 6 m/s**<br>**Velocity spread = 15 m/s**<br>**Zone of mixed results = None** | | | | | | |

Note: *PP* and *CP* indicate the shots used to calculate the $V_{50}$ limit velocity.

## 4.3 Asymmetric Loading Experiments

As noted earlier, the concern that the NLO-2002 WC cores were substantially tougher than the BELL-1985 cores, especially in light of the increased Co content in the NLO-2002 WC cores, led to the development of an asymmetrical loading experiment to assess the brittleness of both cores. Both projectiles were to be fired at the same velocity into a thin plate of HHA placed at 45° obliquity. The HHA plate at high obliquity would subject both WC cores to an asymmetric load that would tend to shatter the cores. A large difference in brittleness in the cores was expected to show up as a drastic change in the character of the core debris upon exiting the HHA plate.

A 6.83-mm-thick plate of HHA (MIL-DTL-46100E) with a hardness of 512 HBW was set at 45° obliquity for these experiments. The nominal impact velocity for both bullets was selected to be 1000 m/s, the muzzle velocity of the round. The bullet striking velocity ($V_S$), vertical pitch, and horizontal yaw were measured using

an orthogonal flash radiograph system as described by Grabarek and Herr.[7] A break screen was placed on the back of the HHA plate to activate another set of flash radiographs behind the HHA plate at nominally 201 and 402 µs, respectively. These radiographs would allow the identification and measurement of size and velocity for WC debris exiting the back of the HHA target plate.

Figure 13 shows the results of the BELL-1985 bullet at 998 m/s and the NLO-2002 bullet at 994 m/s after impacting the same 6.83-mm-thick HHA plate at 45° obliquity. The bullet (not shown) is traveling from the right, passes through the inclined plate, and two images of the shattered WC core are seen on the left. For the BELL-1985 core, the WC is heavily fractured with the largest piece traveling 917 m/s toward the left. For the NLO-2002 core, the WC core is also heavily fractured and the largest piece traveling to the left at 927 m/s. Based on the limited data provided here, no substantial difference in the fracture behavior of the WC cores was noted. The impact process was stochastic, so these experiments were not a hard requirement of the contract but a more subjective gathering of information. More detailed data for these experiments are provided in Appendix C.

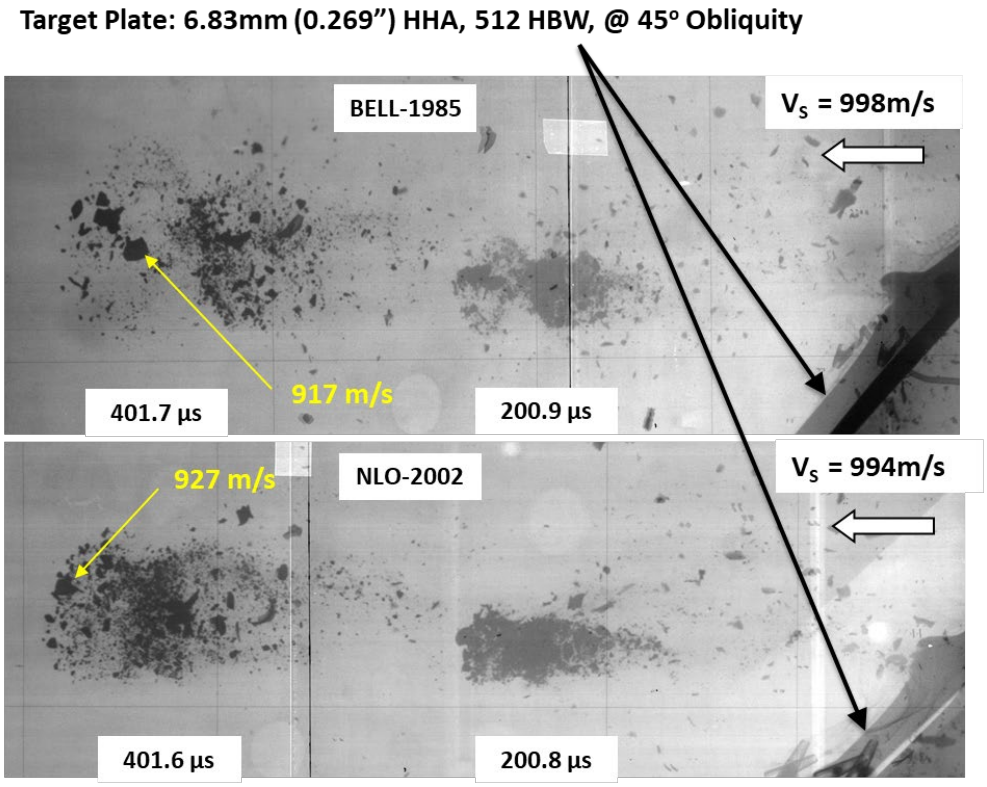



**Fig. 13 Results of asymmetric loading experiments: BELL-1985 (top) and NLO-2002 (bottom)**

## 5. Summary and Conclusions

A qualified surrogate for WC-cored, 14.5-mm API BS41 projectiles was needed for laboratory experiments and armor plate military specification acceptance testing. ARL performed an analysis on the existing (BELL-1985) and new (NLO-2002) domestic surrogate 14.5-mm API BS41 projectiles to establish new projectile performance compared to the existing domestically produced surrogate. The NLO-2002 bullets were subject to the contract requirements listed in Appendix B. There was no attempt to compare either surrogate to the actual Soviet WWII BS41 projectile.

The overall bullet and core dimensions and masses were assessed with reference to the projectile drawings in Appendix A. The NLO-2002 bullets met the drawing requirements and appeared very similar to the BELL-1985 bullets. One major difference between the NLO-2002 and BELL-1985 bullets was that the BELL-1985 bullets had an incendiary fill while the NLO-2002 bullets used an inert fill. The inert fill for the NLO-2002 bullets made them easier to ship and store without adversely affecting projectile penetration. The BELL-1985 bullets are identified by a gray-painted tip, while the NLO-2002 bullets have no paint on the bullet tip.

An assessment of the WC core materials for both lots was also performed. The BELL-1985 core composition was WC with 6% Co binder. The NLO-2002 core composition was WC with 7.5% Co, 0.25% TiC, and 0.25% TaC. Thus, the measured density of the BELL-1985 WC cores was 14.86 g/cm$^3$ while the NLO-2002 cores were 14.66 g/cm$^3$. The microstructure of the cores is a bimodal distribution for both lots. For the BELL-1985, the average size for the small mode was 1 and 5–10 μm for the large mode. For the NLO-2002, the average size for the small mode was 0.2–0.5 μm and for the large mode 2–3 μm. The use of TiC and TaC sintering aids in NLO-2002 allowed for a finer microstructure as compared to BELL-1985. As a result, the measured microhardness is slightly higher in NLO-2002 (1544 HVN) compared to BELL-1985 (1476 HVN). While the mechanical properties of NLO-2002 were slightly superior, it must be noted that it had a higher Co content and a lower theoretical density.

The primary concern with the new contract was whether the ballistic performance of the NLO-2002 bullets was equal to the performance of the historical BELL-1985 bullets. Initial semi-infinite penetration experiments were conducted into RHA steel, Class 1 MIL-DTL-12560K, at 0° obliquity. Not surprisingly, no real differences were observed in the penetration of both lots into RHA.

Baseline $V_{50}$ limit velocity experiments were conducted with the BELL-2002 lot fired into a 25.37-mm-thick HHA plate at 0° obliquity and a $V_{50}$ of 738 m/s was

obtained with a standard deviation of 4 m/s. The contract requirement for the NLO-2002 bullets was then set at a maximum $V_{50}$ of 750 m/s (738 + 3x4 m/s). When the NLO-2002 bullets were fired into the same 25.37-mm-thick HHA, the $V_{50}$ obtained was 746 m/s, which met the contract requirement. The NLO-2002 bullets had to demonstrate total yaws below 2° for 7 out of 8 shots and the actual performance was below 2° in 14 out 14 shots.

An additional concern that the NLO-2002 WC cores were tougher than the BELL-1985 cores, especially in light of the increased Co content in the NLO-2002 WC cores, led to the development of an asymmetrical loading experiment to assess the brittleness of both cores. Each bullet was fired at the same nominal velocity into a 6.83-mm-thick HHA plate at 45° obliquity with the goal of observing the condition of the WC core exiting the plate. In both cases, the cores were heavily fractured upon exit, thus indicating that concerns about increased toughness of the NLO-2002 lot were unfounded.

Based on physical measurements, flight yaw, and ballistic performance, the NLO-2002 surrogate BS41 bullets appeared to equal or exceed the performance of the legacy surrogate BELL-1985 BS41 bullets; therefore, the NLO-2002 bullets were accepted as qualified replacements under the terms of the contract.

## 6. References


1. MIL-A-46100C. Armor plate, steel, wrought, high-hardness. Army Materials and Mechanics Research Center; 1983 June.
2. MIL-A-46063E. Armor plate, aluminum alloy, 7039. Army Materials and Mechanics Research Center; 1977 Mar.
3. Bell JJ Jr. Brass Extrusion Laboratories, Ltd. Letter to R Van Caneghem, US Army Combat Systems Test Activity. Personal communication, 1984 Dec 18.
4. MIL-DTL-46100E. Amendment 4. armor plate, steel, wrought, high-hardness. DEVCOM Army Research Laboratory; 2019 July.
5. MIL-DTL-46063H. Amendment 2. armor plate, aluminum alloy, 7039. Army Research Laboratory (US); 2000 June.
6. MIL-DTL-12560H. Armor plate, steel, wrought, homogeneous (for use in combat vehicles and for ammunition testing). Army Research Laboratory; 1990 Nov.
7. Grabarek C, Herr L. X-ray multi-flash system for measurement of projectile performance at the target. Ballistic Research Laboratory (US); 1966. Report No.: BRL-TN-1634.
8. MIL-STD-662F. $V_{50}$ ballistic test for armor. Army Research Laboratory (US); 1997 Dec.

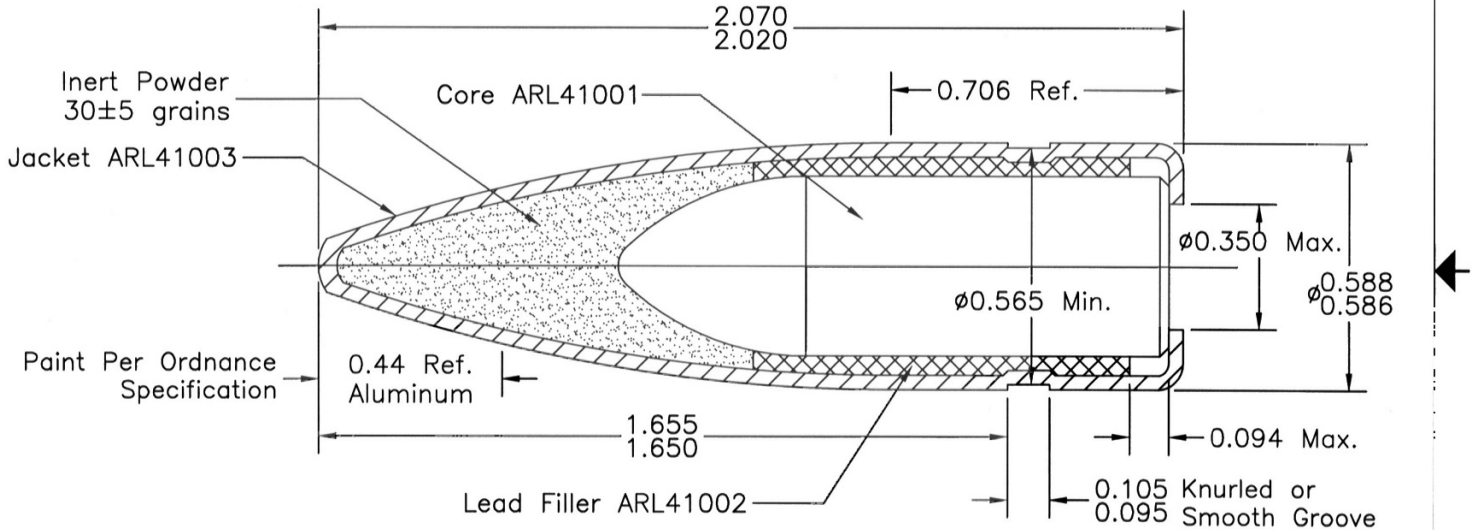
# Appendix A. 14.5-mm BS41 Drawings

NOTES:

1. Final weight of part shall be 975±15 grains (63.2±1.0 grams).

2. Based upon US Army Print No. FC–6087.

| REVISIONS | | | | |
|---|---|---|---|---|
| ZONE | REV | DESCRIPTION | Date | APPROVED |




**FOR INFORMATION PURPOSES ONLY.**
**NOT FOR PRODUCTION USE.**
**DRAWINGS ARE NOT UP TO DATE.**

| | |
|---|---|
| UNLESS OTHERWISE SPECIFIED:<br>Dimensions in inches<br>Linear dim's ±0.010"<br>Angular dim's ±0.5°<br>Finish is 125 microinches | U.S. Army Research Laboratory<br>Aberdeen Proving Ground, MD 21005–5066<br>14.5mm AP BS41<br>Projectile Assembly |
| DESIGNED M. Burkins<br>DRAWN M. Burkins | SIZE A \| FSCM NO. BURKINS \| DWG NO. ARL41000 \| REV<br>Scale 3:1 \| Date 4 Feb 2002 \| Sheet 1 of 1 |

NOTES:

1. Material shall be sintered tungsten carbide of the following nominal composition:

   Cobalt: 6%
   WC: Remainder

2. Transverse rupture strength shall be 50,000 psi minimum.

3. Density shall be 14.5–15.2 g/cc.

4. Rockwell hardness on O.D. shall be 86 to 92 A–Scale.

5. Final weight of part shall be 585±6 grains (37.9±0.4 grams). Length to vary to meet the weight.

6. Based upon US Army Print No. FB41212.

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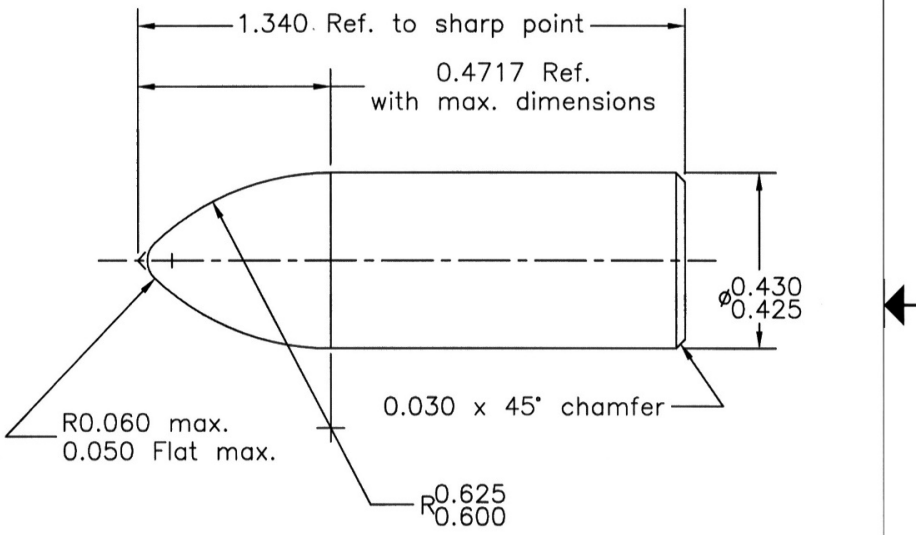


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|---|---|
| UNLESS OTHERWISE SPECIFIED:<br>Dimensions in inches<br>Linear dim's ±0.010"<br>Angular dim's ±0.5°<br>Finish is 125 microinches | U.S. Army Research Laboratory<br>Aberdeen Proving Ground, MD 21005–5066<br>14.5mm Tungsten Carbide Penetrator Core |
| DESIGNED M. Burkins<br>DRAWN M. Burkins | SIZE A \| FSCM NO. BURKINS \| DWG NO. ARL41001 \| REV<br>Scale 3:1 \| Date 24 Jan 2002 \| Sheet 1 of 1 |

NOTES:

1. Material shall be 98% Lead, 2% Antimony.

2. All dimensions are approximate.

3. Final weight of part shall be 175±2 grains (11.3±0.1 grams). Length to vary to meet the weight.

4. Based upon US Army Print No. FB41214.

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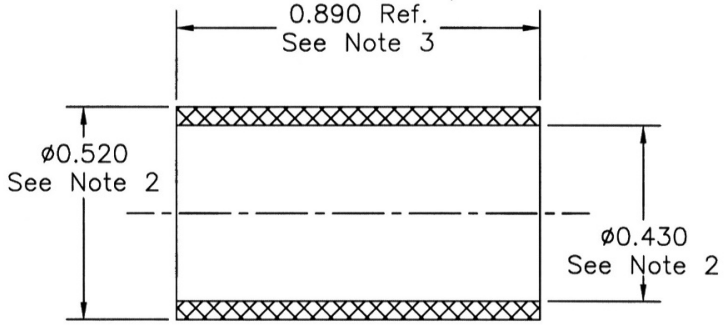


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| | |
|---|---|
| UNLESS OTHERWISE SPECIFIED:<br>Dimensions in inches<br>Linear dim's ±0.010"<br>Angular dim's ±0.5°<br>Finish is 125 microinches | U.S. Army Research Laboratory<br>Aberdeen Proving Ground, MD 21005–5066<br>14.5mm Lead Filler |
| DESIGNED M. Burkins<br>DRAWN M. Burkins | SIZE A \| FSCM NO. BURKINS \| DWG NO. ARL41002 \| REV<br>Scale 3:1 \| Date 31 Jan 2002 \| Sheet 1 of 1 |

NOTES:

1. Material shall be strip stock, 1008 CR Annealed, commercial quality.

2. Copper plate O.D. from 0.0001 to 0.0005" thick. Plating on I.D. optional.

3. Final weight of part shall be 185±2 grains (12.0±0.1 grams). Length to vary to meet the weight.

4. Based upon US Army Print No. FB41213.

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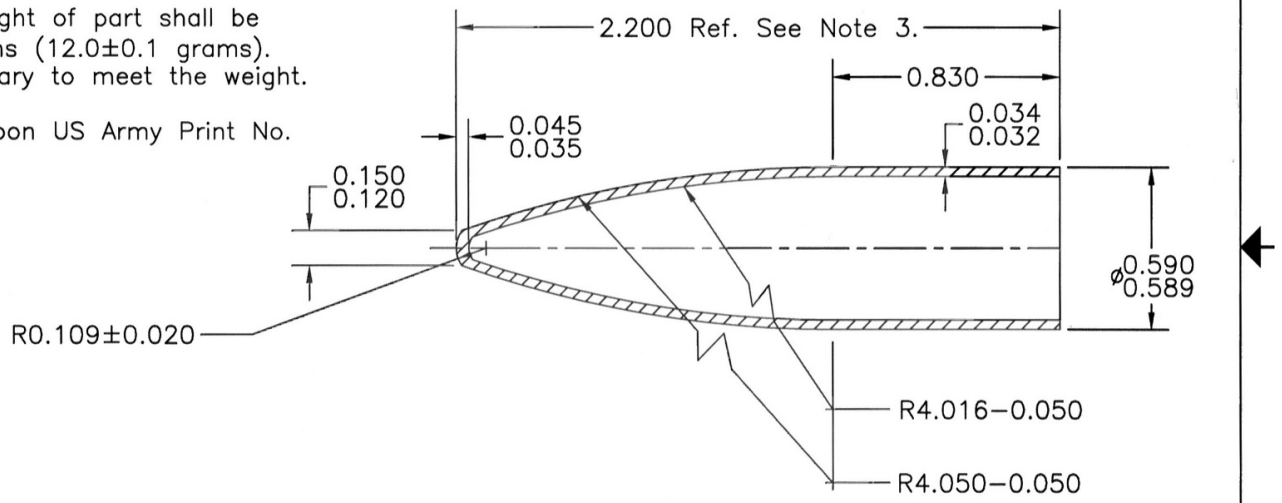



**FOR INFORMATION PURPOSES ONLY.**
**NOT FOR PRODUCTION USE.**
**DRAWINGS ARE NOT UP TO DATE.**

| UNLESS OTHERWISE SPECIFIED: | U.S. Army Research Laboratory | | | |
|---|---|---|---|---|
| Dimensions in inches<br>Linear dim's ±0.010"<br>Angular dim's ±0.5°<br>Finish is 125 microinches | Aberdeen Proving Ground, MD 21005–5066 | | | |
| | 14.5mm Jacket | | | |
| DESIGNED M. Burkins | SIZE A | FSCM NO. BURKINS | DWG NO. ARL41003 | REV |
| DRAWN M. Burkins | Scale 2:1 | Date 10 Apr 2002 | Sheet 1 of 1 | |

## Appendix B. Contract #DAAD17-02-C-0105 Specifications

The appendix appears as it was submitted, without editorial change.

Specifications for 14.5mm AP BS41 Inert Projectiles

30 January 2002

1. The tungsten carbide cores shall be produced per drawing #ARL41001 from a single lot of material and the same process.
2. The 14.5mm projectile assembly shall conform to drawing #ARL41000.
3. The 14.5mm projectiles shall undergo the following quality assurance testing prior to acceptance:
    a. The length, diameter, and mass of the delivered projectiles will be sampled to determine conformance to drawing #ARL41000.
    b. The projectiles will be fired at a 0.999" thick steel plate, 477 BHN hardness, conforming to MIL-A-46100, placed at 0 degrees obliquity. A Soviet 14.5mm KPV machine gun, identification # 543, modified for a 20mm screw-on breech, will be placed 76" from the target plate. The projectiles will be loaded into Soviet cartridge cases with 37mm M2 propellant and M36A1E1 percussion primers. An orthogonal flash radiographic system will used to determine the velocity, vertical pitch, and horizontal yaw of the projectile just prior to striking the plate. The bullets will be fired at the target plate to determine a V50 Ballistic Limit per MIL-STD-662F. The projectiles shall demonstrate the following:
        1) The V50 Ballistic Limit shall be 750 m/s or less.
        2) The combined vector sum of pitch and yaw, as measured 64" from the muzzle of the weapon, shall not be greater than 2 degrees for more than 1 shot out of every 8 shots.
        3) The tungsten carbide core shall not deform or break into more than 2 pieces during the penetration process, as determined by flash x-rays (in the case of perforating cores) or by examining the core in the plate (in the case of non-perforating cores).

## Appendix C. Ballistic Data

The appendix appears as it was submitted, without editorial change.

Material: HHA (MIL-A-46100)

Obliquity: 0°

Thickness: 25.37 mm (0.999 in)

Hardness: 477 HBW

Penetrator: 14.5 mm BS41, Contract #DAAD05-85-C-4197, Gray tip

4 Shot V50 Limit Velocity: 738 m/s Std Dev: 4 m/s

| $V_S$ (m/s) | Pitch (°) | Yaw (°) | Result (CP/PP) | $V_R$ (m/s) | $L_R$ (mm) | $M_R$ (g) | $P_R$ (mm) | Comments | LAT no. |
|---|---|---|---|---|---|---|---|---|---|
| 721 | –0.25 | 0.50 | PP | NA | NA | NA | PIP | … | 8232 |
| *732* | *–2.25* | *0.75* | *PP* | *NA* | *NA* | *NA* | *PIP* | *Disregard* | *8234* |
| 734 | –1.25 | 0.25 | *PP* | NA | NA | NA | PIP | … | 8237 |
| 735 | 0.75 | –1.00 | *CP* | 153 | 31 | Intact | NA | Penetrator | 8236 |
| 736 | 0.75 | 0.25 | *PP* | NA | NA | NA | PIP | | 8235 |
| 745 | –1.25 | 1.00 | *CP* | 34 | 6 | NM | PIP | Plug; intact penetrator in plate | 8233 |
| 759 | 0.25 | 1.25 | CP | 160<br>66 | 20<br>10 | NM<br>NM | NA | Nose<br>Tail | 9720 |
| 762 | 1.25 | 2.00 | CP | 190 | 31 | Intact | NA | Penetrator | 9721 |
| 770 | 1.00 | 3.00 | CP | 146 | 20.8 | 22.0 | NA | Nose; tail in plate | 9719 |
| 770 | –0.25 | 0.50 | CP | 164<br>103 | 18.9<br>13.9 | 18.2<br>16.7 | NA | Nose<br>Tail | 9718 |
| 787 | 0.25 | 1.75 | CP | 277<br>235 | 22<br>14 | NM<br>NM | NA | Nose<br>Tail | 8231 |
| 805 | 0.25 | 0.50 | CP | 244 | 31 | Intact | NA | Penetrator | 8230 |

NA = Not Applicable; NM = Not Measured
Values in the VR, LR, and MR columns are for the penetrator unless otherwise specified in the Comments column.
PP = Partial Penetration; CP = Complete Penetration. CPs occur when a paper break screen on the rear of the target initiates a flash radiographic system.
*PP* and *CP* indicate the shots used to calculate the V50 limit velocity.
PIP = Penetrator in Plate; penetration cavity blocked.

Material: HHA (MIL-A-46100)

Obliquity: 0°

Thickness: 25.37 mm (0.999 in)

Hardness: 477 HBW

Penetrator: 14.5 mm BS41, Lot #ARL-02-C-0105

4 Shot V50 Limit Velocity: 746 m/s Std Dev: 6 m/s

| $V_S$ (m/s) | Pitch (°) | Yaw (°) | Result (CP/PP) | $V_R$ (m/s) | $L_R$ (mm) | $M_R$ (g) | $P_R$ (mm) | Comments | LAT no. |
|---|---|---|---|---|---|---|---|---|---|
| 738 | 0.25 | 0.25 | *PP* | NA | NA | NA | PIP | … | 9813 |
| 744 | 0 | 1.75 | *PP* | NA | NA | NA | PIP | … | 9809 |
| 748 | -0.25 | 0.50 | *CP* | 115 | 7 | NM | PIP | Spall; intact penetrator in plate | 9812 |
| 753 | 0 | 0.75 | *CP* | 104 | 33 | 38 | NA | Intact Penetrator | 9810 |
| 754 | 0 | 0 | CP | 13 | 3.8 | 4.2 | PIP | Spall; Intact Penetrator in plate | 9811 |

NA = Not Applicable; NM = Not Measured
Values in the VR, LR, and MR columns are for the penetrator unless otherwise specified in the Comments column.
PP = Partial Penetration; CP = Complete Penetration. CPs occur when a paper break screen on the rear of the target initiates a flash radiographic system.
*PP* and *CP* indicate the shots used to calculate the V50 limit velocity.
PIP = Penetrator in Plate; penetration cavity blocked.

US Army Research Laboratory
8 November 2002

Material: HHA (MIL-A-46100) Obliquity: 45°

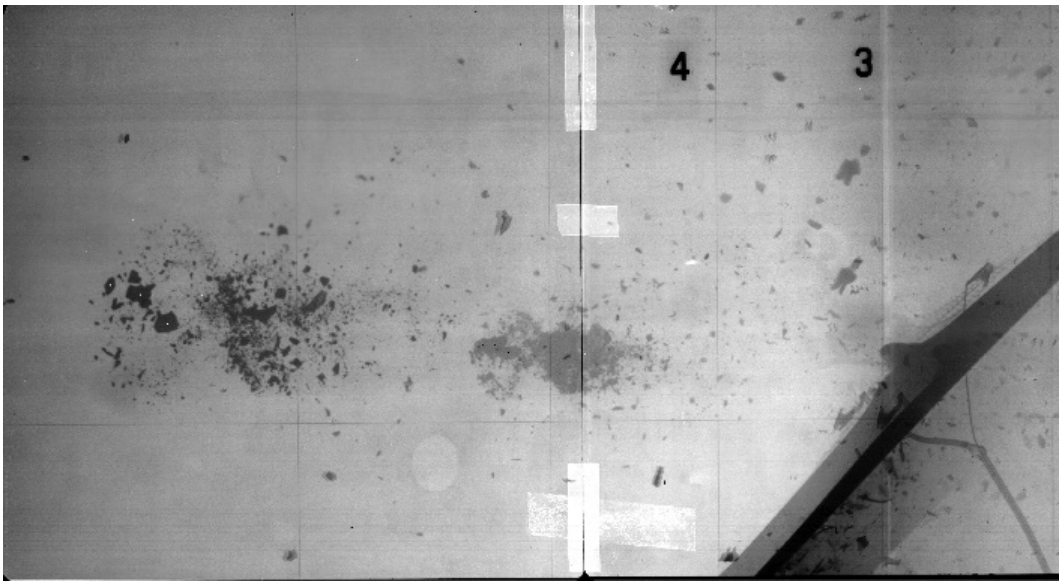
Thickness: 6.83 mm (0.269 in)

Hardness: 512 HBW

Penetrator: 14.5 mm BS41, Contract #DAAD05-85-C-4197, Gray tip

| $V_S$ (m/s) | Pitch (°) | Yaw (°) | Result (CP/PP) | $V_R$ (m/s) | $L_R$ (mm) | $M_R$ (g) | Comments | LAT no. |
|---|---|---|---|---|---|---|---|---|
| | | | | 996 | 6 | NM | | |
| 998 | 0.50 | 0 | CP | 958 | 12 | NM | … | 9700 |
| | | | | 917 | 12 | NM | | |

NA = Not Applicable; NM = Not Measured
Values in the VR, LR, and MR columns are for the penetrator unless otherwise specified in the Comments column.
PP = Partial Penetration; CP = Complete Penetration. CPs occur when a paper break screen on the rear of the target initiates a flash radiographic system.



US Army Research Laboratory
17 January 2003

Material: HHA (MIL-A-46100) Obliquity: 45°

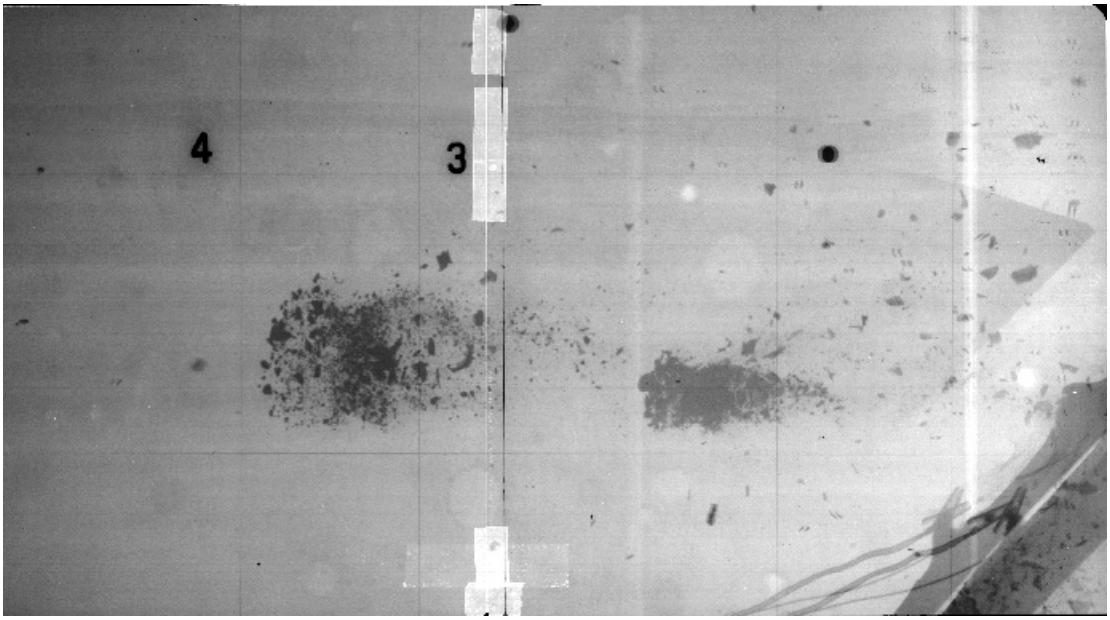
Thickness: 6.83 mm (0.269 in)

Hardness: 512 HBW

Penetrator: 14.5 mm BS41, Lot #ARL-02-C-0105

| $V_S$ (m/s) | Pitch (°) | Yaw (°) | Result (CP/PP) | $V_R$ (m/s) | $L_R$ (mm) | $M_R$ (g) | Comments | LAT no. |
|---|---|---|---|---|---|---|---|---|
| 994 | 1.25 | –1.00 | CP | 927 | 8 | NM | Largest piece | 9814 |

NA = Not Applicable; NM = Not Measured
Values in the VR, LR, and MR columns are for the penetrator unless otherwise specified in the Comments column.
PP = Partial Penetration; CP = Complete Penetration. CPs occur when a paper break screen on the rear of the target initiates a flash radiographic system.



## List of Symbols, Abbreviations, and Acronyms

| | |
|---|---|
| AA | aluminum alloy |
| Al | aluminum |
| API | armor-piercing incendiary |
| ARL | Army Research Laboratory |
| ATC | US Army Aberdeen Test Center |
| BELL | Brass Extrusion Laboratories, Ltd |
| Ca | calcium |
| Co | cobalt |
| CP | complete penetration |
| CSTA | US Army Combat Systems Test Activity |
| DEVCOM | US Army Combat Capabilities Development Command |
| Fe | iron |
| HBW | Brinell Harness using a WC indenter |
| HHA | high-hardness armor |
| HRA | hardness on the Rockwell A scale |
| K | potassium |
| $L_R$ | residual length |
| Mg | magnesium |
| $M_R$ | residual mass |
| NA | not applicable |
| Na | sodium |
| Nb | niobium |
| Ni | nickel |
| NLO | New Lenox Ordnance |
| NM | not measured |

| | |
|---|---|
| PIP | penetrator in plate |
| PP | partial penetration |
| RHA | rolled homogeneous armor |
| S | sulfur |
| Ta | tantalum |
| TaC | tantalum carbide |
| Ti | titanium |
| TiC | titanium carbide |
| $V_{50}$ | velocity at which the target is expected to be perforated by the penetrator 50% of the time |
| VHN | Vickers Hardness Number |
| $V_R$ | residual velocity of core |
| $V_S$ | striking velocity of projectile |
| W | tungsten |
| WC | tungsten carbide |
| XRF | X-ray fluorescence |

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19 (PDF) DEVCOM ARL FCDD RLW MC B PLACZANKIS FCDD RLW ME J LASALVIA P PATEL S SILTON J SWAB FCDD RLW MF K DOHERTY E HORWATH K LIMMER FCDD RLW LH L MAGNESS FCDD RLW PD M KEELE FCDD RLW PE M BURKINS D GALLARDY J HOGAN E KLIER M KLUSEWITZ D LITTLE M LOVE P SWOBODA FCDD RLW PG N GNIAZDOWSKI