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Effect of Launch Tube Curvature on Ballistic Accuracy

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ABSTRACT

It is possible for two different launch platforms to produce centre of (shot) impacts (COIs), that differ in magnitude by several times the ammunition dispersion. It is difficult to discern what fraction of this variation is due to the launch tube alone, since changing tubes alters both the mounting conditions and the occasion. A means has been devised to 'change tubes' without altering the mount or the occasion, by merely changing the shape of a given tube within the same mount. This is accomplished by localised control of a gun barrel's axial thermal expansion, implemented through a series of temperature-controlled heating pads adhered to the outer barrel wall. Using this technique, it was found that a simple, yet very common, bow-shaped curvature to the right verses left, for example, produced a significant shift in COI. Furthermore, it was found that holding the barrel shape constant dramatically reduced the standard deviation (dispersion) of shot impacts about COI.

1. INTRODUCTION

The difference between the gravity-, wind-, and drag-corrected aim point and where a projectile actually hits the target is referred to as projectile jump. Projectile jump varies from round to round, but, in general, roughly two-thirds of the rounds will hit the target within one standard deviation (defined as the ammunition dispersion) of the centre of (shot) impact (COI) for a given lot of ammunition. However, for tank guns, COI can vary from barrel to barrel, mount to mount, and occasion to occasion by as much as five times the ammunition dispersion.

It is difficult to discern what fraction of this large error source is due to barrel differences alone, since changing tubes alters both the mounting conditions and the occasion. Some indication of barrel dependence was given in the 'rotated tube' test of Haug, *et al*[1]. They rotated a (pre-production) 120 mm M-256 barrel (Sl. No. 84) through 90° increments and recorded COI for 10-round groups at each orientation (Fig. 1).

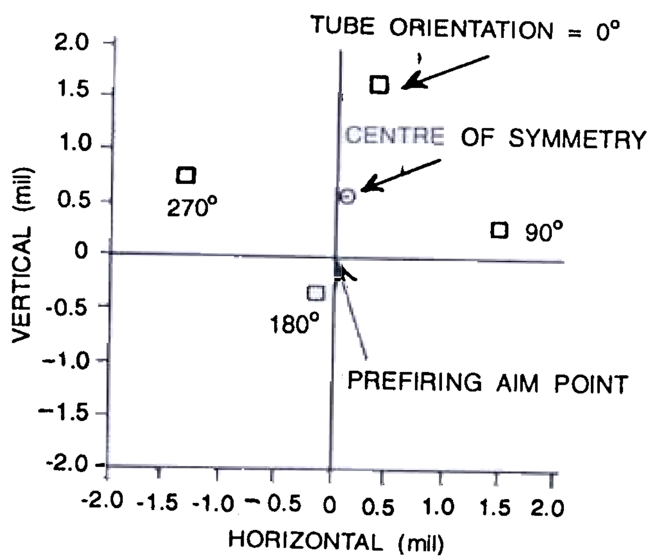

Figure 1. Centres of impact for 10-round groups fired through M-256 (Sl. No. 84) in rotated tube test.

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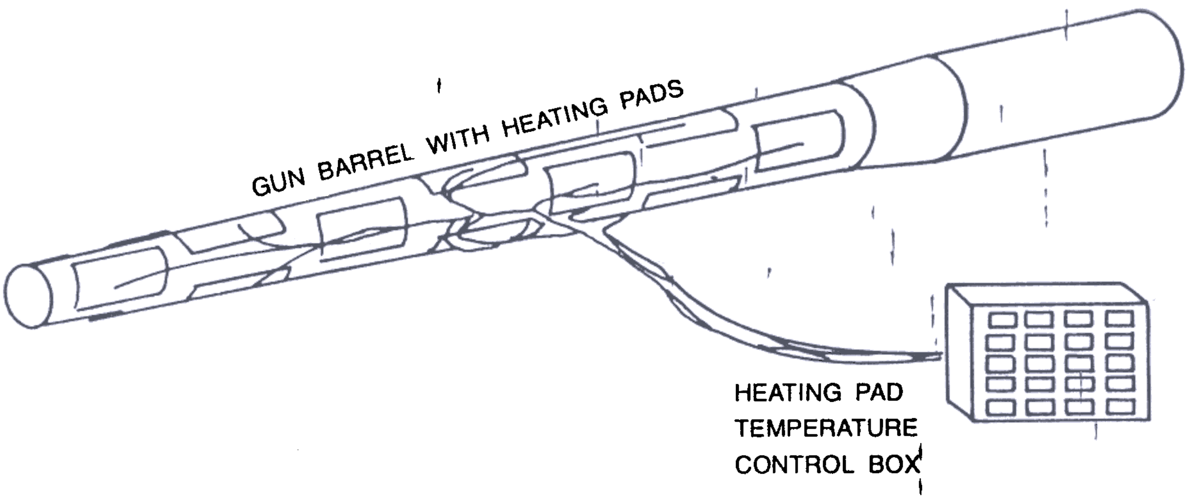

Figure 2. Illustration of temperature-controlled M-256 gun barrel

Each COI in Fig. 1 is spaced about 90° apart on a radius near 1.2 ± 0.3 mil from the centre of symmetry (Even though the prefiring aim point was at the horizontal and vertical origin for each orientation in Fig. 1, the centre of COI symmetry appears to be shifted about 0.5 mil vertically. This shift in the centre of symmetry above the prefiring aim point might be caused by a positive shift in muzzle pointing angle at the time of shot exit. Such a change in muzzle angle during in-bore travel could result from the upward barrel rotation caused by the torquing action of the centre of gravity (CG) offset in the recoiling breech assembly). We might speculate that rotating the centreline accounts for the average radial displacement (1.2 mil), while the mount and occasion change that accompanies each rotation could account for the fluctuation (± 0.3 mil) in COIs about the average. However, there is no way of knowing for certain if this is the correct partitioning of effects, since the three contributing factors (centreline, mount and occasion) are inseparable in such a test.

The significance of COI-centreline test described here is that the centreline can be changed without remounting the barrel. Thus, there is no doubt that the centreline is the sole contributor to COI change. Furthermore, because the centreline can be controlled, a high degree of launch-condition repeatability can be maintained. This helps to minimise the contribution that shot-to-shot variation in gun dynamics makes to ammunition dispersion.

2. CONTROLLING CENTRELINE

A series of heating pads was adhered to the outer wall of an M-256 120 mm tank gun barrel (Sl. No. 2971), as illustrated in Fig. 2. A small hole in the centre of each pad accommodated the placement of a thermocouple used to measure the barrel temperature. The temperature of the barrel under each pad could be stabilised by automatic or manual control of the heating pad's on-off switch. It was thus possible to control cross-barrel temperature differences (CBTDs), and hence control differential thermal expansion across the tube. This allowed the barrel centreline to be changed as desired. A detailed description [2] of the experimental set up and validation of the thermal bend control can be found.

For simplicity, the analysis was limited to the horizontal plane, where fewer factors influence gun dynamics. In the vertical plane, the unidirectional effects of gravity on the barrel and projectile add complexity to the analysis of gun dynamics. Furthermore, it is known[3] that the effects of the breech CG offset will over-shadow the effects of centreline curvature on vertical plane gun dynamics. To further simplify the experiment, only a simple bow shape, or half-sine wave curvature, to

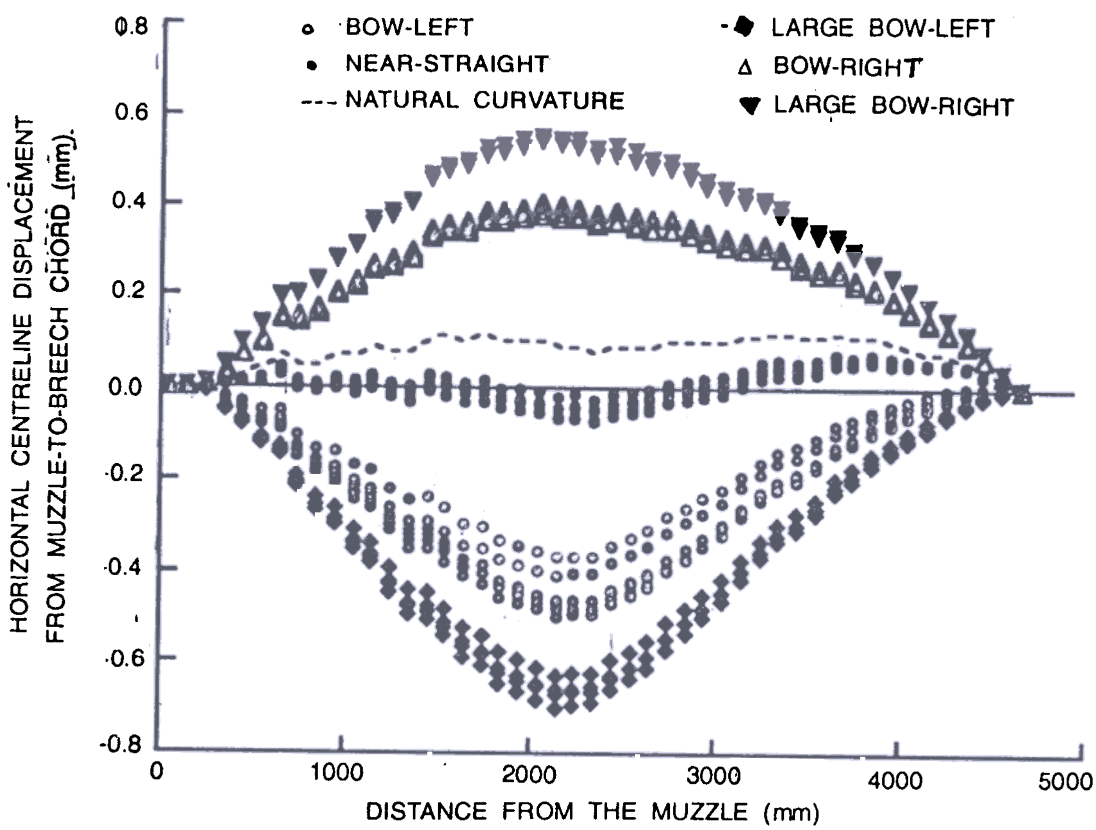

Figure 3. Manufactured and heating-pad-induced horizontal centreline curvatures prior to firing M-256 (Sl. No. 2971)

the left and right, as well as a near-straight centreline were chosen for analysis. The magnitude of the bow shape was varied twice in each direction to give a total of five trial cases, which were distinguished as bow-left, bow-right, large bow-left, large bow-right, and near-straight in the horizontal centreline plots of Fig. 3.

How do these five trial cases relate to the natural curvatures found in the general population of tube centrelines? In the dispersion study[4], 20 M-256 tubes were examined. Of these 20, 15 had a simple bow shape in either the horizontal or vertical plane, much like '2971'. Five of the 20 had bows that were as large as the bow-left/right curvatures of Fig. 3. A simple bow shape is the first natural mode of vibration for a barrel; hence, such a shape may dominate the centreline curvature in barrels firing on the move over 'bumpy' terrain.

The centreline plots of Fig. 3 (with the exception of the natural centreline for '2971') are not based on actual measurements, since the standard, optically-based, measuring instrument will not function properly in an above-ambient temperature bore, like that created when applying the heating pads. Rather, they are based on theoretical predictions using 'the thermal bend model[5]. Past testing has, however, shown that there is a good agreement between the thermal bend model and the obtainable experimental measurements.

There are several centreline plots drawn in Fig. 3 for each of the five general curvature cases. For example, there are five distinctly different plots for the bow-left case. Each plot represented the centreline profile when a round was fired. The small variation in plots for the same case attests to the fact that it was not possible to maintain exact control over the CBTDs, which affect thermal bend. In actuality, six rounds were fired for the bow-left case, with two plots overlaying each other.

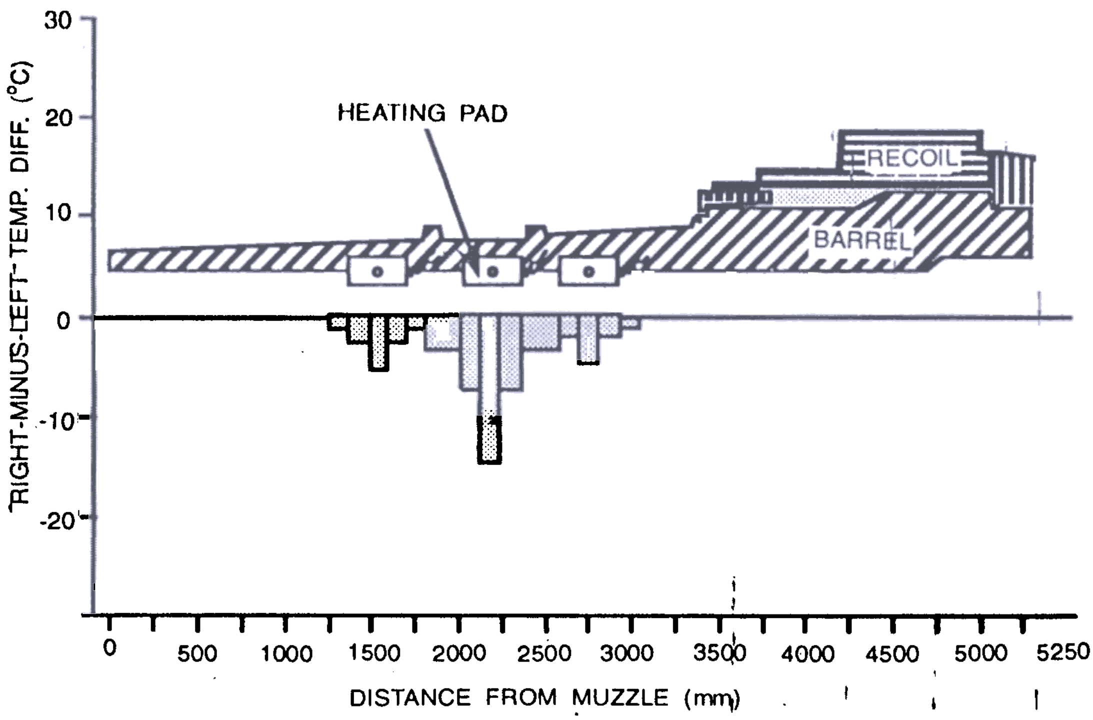

Figure 4. CBTD profile needed to induce the average bow-left configuration

Regardless of the number of plots that can be distinguished, there were at least four rounds fired for each general curvature case. Figure 4 shows the average CBTD profile for the bow-left plots of Fig. 3.

3. MEASURING CENTRE OF IMPACT

In total, 29 rounds of the same lot M-865 target practice, cone-stabilised, discarding sabot, training (TPCSDS-T) ammunition were used in this test. To reduce the dependence of occasion-to-occasion differences on the results, the firings were so sequenced that a round was fired with the centreline bowed to the left; then a near-straight centreline was fired; and then a round was fired with the centreline bowed to the right. This left-straight-right pattern was repeated, with (on an average) a round being fired every 30-60 min. Six test rounds were fired per day.

The pointing angle of the muzzle end of the gun could be changed by altering the breech angle, or, it could be changed by thermal distortion of the barrel between the breech and the muzzle. To gauge the motion of the breech angle, a 20 power telescope (Wye scope) was placed in a special cradle that was rigidly attached to the outside wall of the recoil cylinder, which holds the breech end of the barrel. The Wye scope was used to read a grid board located at 103 m downrange. The accuracy of this reading was considered to be 0.01 mil. The muzzle angle was measured using Aberdeen Proving Ground muzzle scope. The reading accuracy of this 8 power muzzle scope is considered to be 0.05-0.10 mil.

After the CBTD pattern needed to create a specific curvature (one of the five general shapes shown in Fig. 3) was established, a check of the breech and muzzle pointing angle was made. This check ensured that the proper curvature was indeed present prior to firing a round. For example, Fig. 5 shows a typical day's record (day 3) of the muzzle-minus-breech pointing angles prior to firing (zero represents the unheated barrel). It can be seen that the measurements were close to those expected from thermal bend modelling for each of the three configurations. The end-to-end thermal

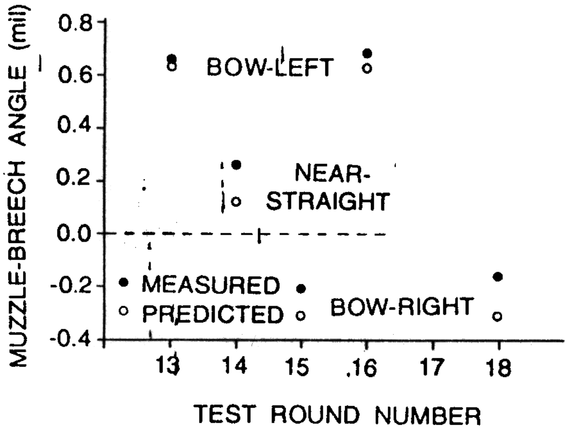

Figure 5. CBTD-induced change in the end-to-end thermal bend of the barrel, as measured by the muzzle-minus-breech pointing angle.

bends for the bow-left and bow-right cases were symmetric about the near-straight case, as expected. However, the near-straight case required a small thermal bend to the gunner's left in order to compensate for '2971's' small natural bend to the gunner's right (Fig. 3) resulting in the small positive offset seen in Fig. 5.

After firing each round, the target impact location was marked, and later measured relative to the initial (first round) aim point. The horizontal distance from the initial aim point, divided by the distance to the target (953 m), was used to convert the shot impact location into an angular deviation (in mil). The prefiring muzzle pointing angle (also measured relative to the original 'line-of-fire') was subtracted from the shot impact angle, and this difference was defined as the horizontal jump angle for each round. Finally, the mean horizontal jump angle was computed and defined as COI for the group of rounds associated with each specific barrel curvature.

4. COMPARISON OF COIs WITH CENTRELINE CURVATURES

The first comparison is between COIs and centreline curvatures of the bow-left, bow-right, and near-straight configurations. An illustration of the results is displayed in Fig. 6. For the bow-left case, the horizontal COI falls 0.30 mil to the left of the muzzle pointing angle, whereas, for the bow-right case, the horizontal COI falls only 0.02 mil to the left of the aim point. For the near-straight barrel, COI lies in the middle of the bow-left and bow-right result, viz, 0.14 mil to the left of the aim point. It can be seen from the schematic of Fig. 6 that relative to the near-straight case, inducing a bow-left will move the muzzle to the right and the shot impacts to the left. Conversely, forming a bow-right will move the muzzle to the left and the shot impacts to the right of the near-straight case.

When the barrel is distorted into the large bow-left configuration, COI lies, surprisingly, at virtually the same location as the smaller bow-left firing—in this case, 0.29 mil to the left of the aim point (Fig. 7). Similarly, COI for the large bow-right firing lies at the same location as the smaller bow-right firing, viz., 0.02 mil to the left of the aim point.

The results for all five firing configurations are summarised in Table 1. It should be noted that on day 1, only four of six test rounds were considered 'good' data rounds, with no entries (Table 1) for the bow-right configuration. The exclusion of the bow-right trials was based on the fact that the CBTD patterns for these two rounds were not deemed sufficiently close to the bow-right

Table 1. Horizontal jump values for five-barrel curvatures

	M-865 impact angle minus muzzle angle (mil)				
	Large bow-left	Bow-left	Near-straight	Bow-right	Large bow-right
Day 1		−0.29	−0.31		
		−0.35	−0.20		
Day 2		−0.16	−0.30	−0.05	
		−0.53	−0.067	−0.37	
Day 3		−0.18	−0.12	+0.18	
		−0.27	+0.13	+0.16	
Day 4	−0.35				+0.26
	−0.26				−0.14
	−0.37				+0.18
Day 5	−0.09				−0.14
	−0.26				−0.24
	−0.42				
Avg. jump	−0.29	−0.30	−0.14	−0.02	−0.02
Std. Dev.	0.12	0.14	0.17	0.25	0.22

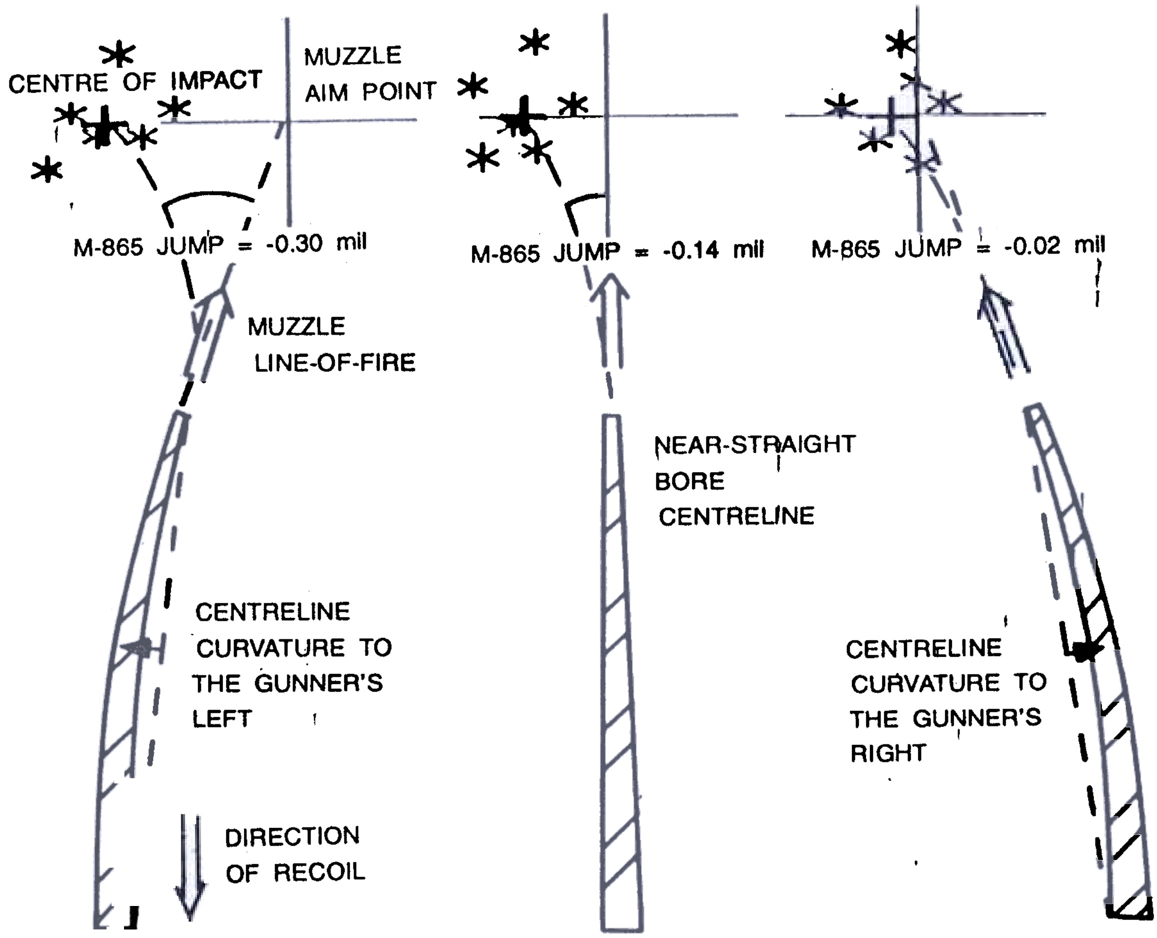

Figure 6. Illustration of M-865 COI verses centreline curvature (in the horizontal plane) for three of five bent barrel cases

configuration. Such a problem did not occur again during the course of firing, because control of the CBTDs was changed from automatic to manual after the day 1. This provided better control over the repeatability of centreline curvatures for all configurations.

It is worth noting that the 0.18 mil pooled standard deviation across the five groups of Table 1 is significantly lower ($P < 0.005$) than the 0.29 mil horizontal dispersion obtained from the lot acceptance test (LAT) for this particular lot of M-865. However, this is expected, since in this test, unlike the LAT, the centreline curvature, and hence gun dynamics, is virtually the same for every round fired in each group. For this reason, the pooled standard deviation from this test is probably better representative of the 'true' horizontal dispersion than that obtained from the LAT. Moreover, it can be inferred from such a substantial decrease in dispersion that if barrel curvature was unwavering from round to round, it could notably improve hit probabilities at longer ranges.

5. CONCLUSIONS

Controlled changes of the bore centreline with heating pads provide a means to isolate the effects of tube-to-tube variation on the fall of shot without entailing a mount or an occasion change. Five simple centreline profiles were examined. The shape changes were all made in the horizontal plane to avoid the complexities introduced by gravity and the large vertical CG offset of the breech.

It was found that same lot M-865 rounds fired through a nearly straight tube were grouped about

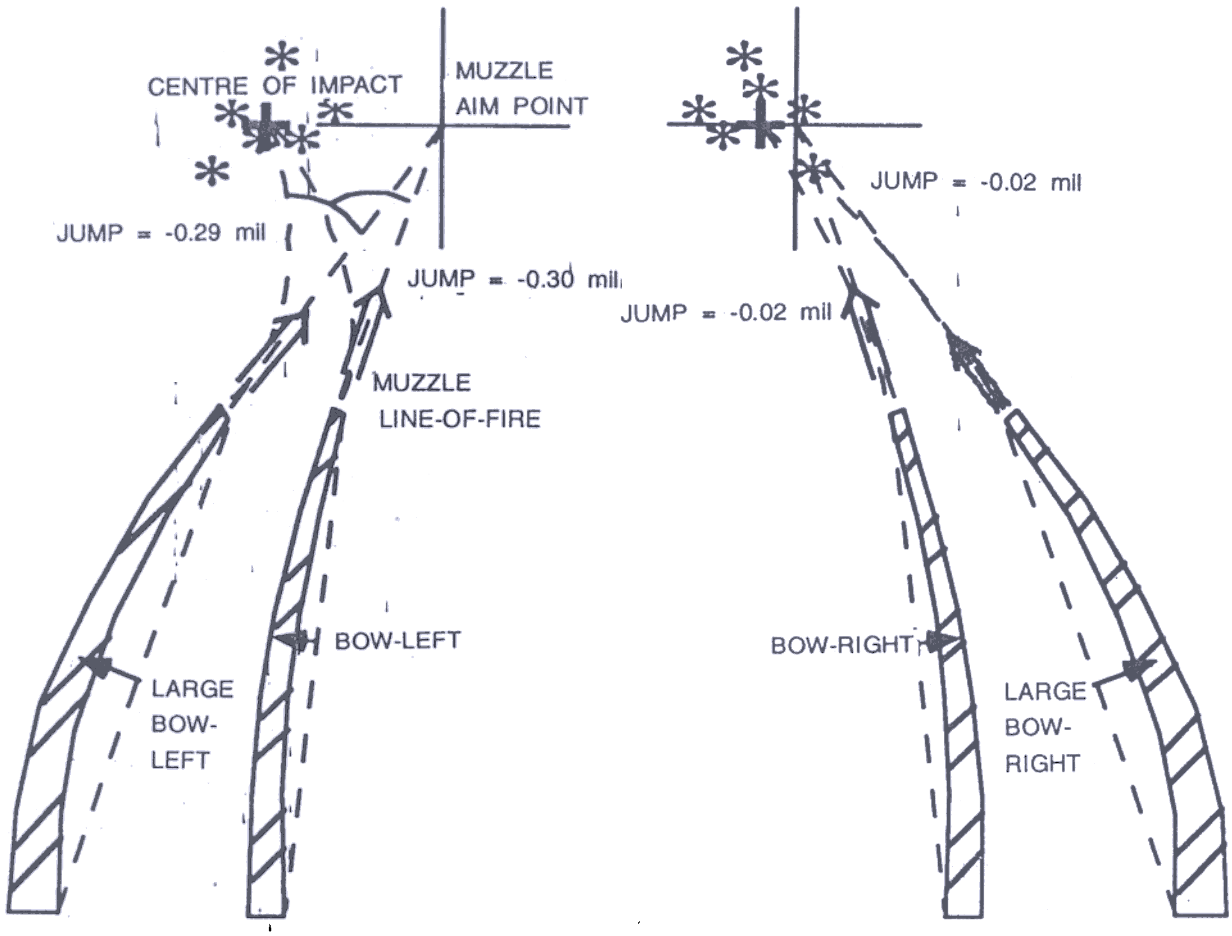

Figure 7. M-865 COI verses centreline for larger verses smaller barrel bends

COI (mean jump angle) that was on the gunner's left of the prefiring muzzle aim point (– 0.14 mil). When the bore centreline had a bow to the left, the mean jump angle was more negative than the near-straight case (– 0.30 mil from the aim point), but when the centreline was bowed to the right, the mean jump angle was more positive than the near straight case (– 0.02 mil from the aim point). Surprisingly, a change in magnitude of the left- and right-bows did not change the mean jump angles. Overall, the average COI for all five cases was about – 0.15 mil.

Assuming that the M1A1 fleet has roughly the same number of right-bowed barrels as left-bowed barrels, we might expect the fleet COI for M-865s, which is + 0.15 mil, to be close to our 'five-barrel' average, – 0.15 mil. The difference raises the question of whether the mount used in our test biased COIs to the left-bowed barrels. In the test of Walbert & Petty[6] it was found that COIs for the same tube mounted in different tanks varied by as much as 0.8 mil. Since the difference between our same-mount, five-tube COI and the fleet COI is only 0.3 mil, it seems plausible that the bias to the left could be mount-related.

Regardless of what bias the mount may impart, the changes in COIs between the bow-left and bow-right centrelines were of the same order of magnitude as the LAT-based ammunition dispersion. This demonstrates that tube-to-tube variability, even for simple shapes, can be a significant contributor to tank-to-tank variation in shot impacts. The results also led to the inference that holding a tube shape relatively constant dramatically reduces impact dispersion, which would greatly increase hit probabilities at longer ranges.

As a final note, thermal distortion of the barrel due to uneven firing heat input, vertically stratified cooling (e.g., thermal droop), or unidirectional solar heating, can cause a bow-like-change in the bore centreline. If a muzzle reference system is used to correct for this type of distortion, it could degrade accuracy more than when no corrections at all were made, since the change in jump was found here to be opposite in direction to the change in muzzle angle.

REFERENCES

1. Haug, B.T.; Petty D.W. & Walbert, J.N. Dynamics of a rotated 120 mm gun tube. Proceedings of the DEA-G-1060. Meeting on Launch Dynamics, Meppen, Germany, 1988.
2. Bundy, M.L. Temperature-controlled bending of a gun tube. US Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, USA, 1996. BRL-MR-315.
3. Erline, T.F. & Kregel, M.D. Modelling gun dynamics with dominant loads. US Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, USA, 1988. BRL-MR-3683.
4. Wilkerson, S. Possible effects of gun tube straightness on dispersion. US Army Research Laboratory, Aberdeen Proving Ground, MD, USA, 1995. ARL-TR-767.
5. Bundy, M.L. Gun barrel cooling and thermal droop modelling. US Army Research Laboratory, Aberdeen Proving Ground, MD, USA, 1993. ARL-TR-189.
6. Walbert, J.N. & Petty, D.W. Assessment of firing of the M1E1 with an indexed gun tube. US Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, USA, 1985. BRL-MR-3458.