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Plastic Guidance Fins for Long Rod Projectiles

Mark L. Bundy
US Army Research Laboratory, MD-21005-5066, USA

ABSTRACT

Projectile tail fins on long rod kinetic energy (KE) penetrators serve the same purpose as fletchings (feathers) on an arrow, namely, they help align the projectile axis with its velocity vector. This reduces the projectile's yaw and hence reduces its aerodynamic drag. In addition, a low yaw angle at target impact helps to maximise the projectile's target penetration. It is typical for projectiles to exit the gun muzzle and enter free flight at some non-zero yaw angle. Aerodynamic forces acting on yawed tail fins create a stabilising torque about the projectile's centre of gravity (CG). This torque can be increased by making the fin material lighter. Most conventional long rod penetrators fired from high performance guns have tail fins made from aluminium. However, aluminium can undergo catastrophic oxidation (rapid burning) in-bore. Coating aluminium with Al_2O_3 (hardcoat) prevents ignition of the substrate, provided solid propellant grain impacts do not chip the brittle hardcoat off the surface. Plastic is lighter than aluminium and less exothermic when oxidized. Therefore, other factors aside, it is conceivable that plastic fins could increase projectile stability while incurring less thermal erosion than aluminium. However, thermal loads are not the only concern when considering plastic as an alternative tail fin material. The mechanical strength of plastic is also a critical factor. This paper discusses some of the successes and failures of plastic fins, at least relatively thin-fins, for use as KE stabilisers.

1. INTRODUCTION

Sub-calibre long rod projectiles utilise kinetic energy (KE) to impart damage to the target. The more aligned the rod axis is to its velocity vector (i.e. the smaller the yaw angle), the less KE is lost to aerodynamic drag. In addition, the lower the yaw angle at target impact, the more armour it will penetrate. Hence, stabilising the penetrator to favour a minimum yaw angle is an important factor in damaging the target.

Most KE penetrators maintain flight stability by using near-full-calibre tail fins that extend from the base end of the projectile. It is typical for projectiles to exit the gun muzzle and enter free flight at some non-zero yaw angle. In free flight, aerodynamic forces on yawed tail fins create a stabilising torque about the projectile's centre of gravity (CG). The torque can be increased by making the fin assembly as light as possible, since this moves the CG further forward on the rod. The most common KE fin material is aluminium, coated with an aluminium oxide surface layer (hardcoat) (steel tail fins have been used sucessfully, but are not favoured because of their weight). The hardcoat provides considerable, but not complete, protection from thermal erosion.

Prior to launch, KE tail fins are buried within the propellant bed of the ammunition cartridge case. After propellant ignition[1], but before muzzle exit, the fins are exposed to high propellant gas

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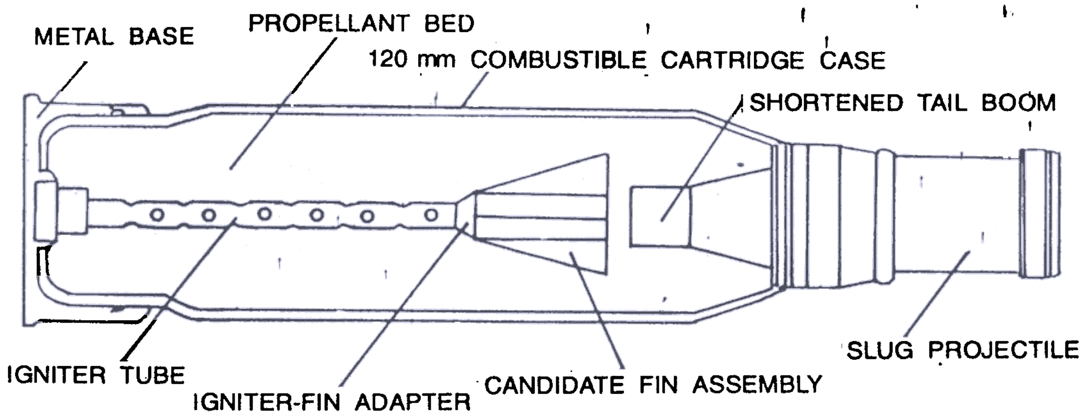


Figure Experimental setup for testing candidate fin assemblies

temperature (e.g. ~ 3400 °K) and pressure (e.g. ~ 500 MPa) as well as propellant grain impacts (~ 100 m/s). The relative motion between the propellant grains and the fin creates a thermally abrasive in-bore environment that can remove pieces of the aluminium hardcoat. Once the hardcoat has been removed, a series of in-bore events can produce rapid erosion of the exposed aluminium substrate. Furthermore, where in-bore fin erosion has taken place, that area is susceptible to additional out-of-bore erosion from aerodynamic heating as it travels downrange, particularly for high velocity, long time-of-flight rounds. Not only will the loss of fin surface area reduce stability, it will reduce accuracy because it does not occur symmetrically on each fin blade.

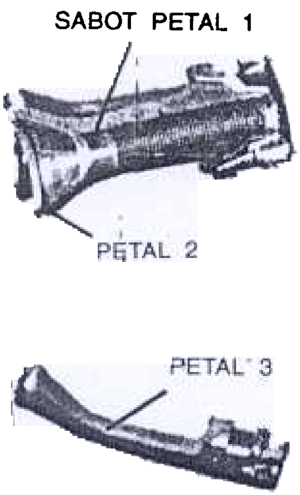
Plastic is lighter than aluminium and less exothermic when oxidized. Other factors aside, this would imply that plastic fins could increase projectile stability while undergoing less thermal erosion than aluminium. However, thermal loads are not the only concern when considering plastic as an alternative fin material. The mechanical strength of plastic is also a critical factor. For example, when the projectile exits the muzzle at a non-zero yaw angle, the reverse muzzle gas flow can potentially bend the fins beyond their yield point, leading to fin fracture, decreased rod stability, and consequently, loss of projectile accuracy.

The results presented here highlight some of the successes and failures, both thermally and mechanically, of plastic guidance fins, at least relatively thin plastic fins, on long rod penetrators.

2. TEST PROCEDURE

Tail fins on large calibre (bore diameter) KE penetrators are expected to function for at the most 3 s, or roughly 3-4 km downrange. Since target impact destroys the projectile, it is not possible to physically examine the fins after firing. Some information can be obtained from high-speed photographs of the projectile inflight. Additional information can be gained from yaw card imprints (the pattern left by the projectile after flying through a thin, cardboard-like material placed along the line-of-fire). However, photographs and yaw cards does not provide detailed information about the fin surface damage, especially that which occurs while the fin is in-bore.

To obtain detailed information about the effects of in-bore heating, alone, a special test fixture was designed. Rather than fly the fins downrange, the candidate tail fin assembly (hub and blades) is attached to the end of a (bayonet-type) igniter tube, which extends from the base of a standard 120 mm (calibre) combustible cartridge case, as shown in Fig. 1. In this configuration, the fin assembly remains in the gun chamber during and after the firing event, and is, therefore, available for post-firing inspection. Essentially, all of the propellant must pass through the static fin assembly. Hence, the fins are exposed to more of the abrasive action of the two-phase (propellant gas and solid grain) flow than they



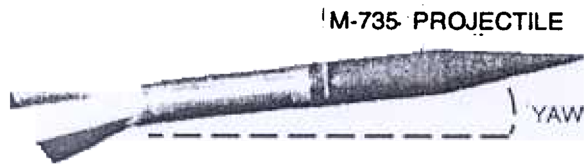


Figure 2. High speed photograph of M-735, just after sabot discard, ~ 9 m downrange from muzzle

would be if they were attached to the end of the projectile, moving down-bore along with the propellant. Nevertheless, subjecting the fins to thermal conditions that are more extreme than those incurred in a conventional launch provides a rigorous test for evaluating the in-bore success or failure of candidate fin materials.

The projectile fired in the static fin test configuration is a slug round with a portion of its stabilising tail boom removed to provide space for the test fin assembly to be attached to the end of the igniter tube. Standard 120 mm ammunition propellant was used to launch the modified slug at the same muzzle velocity as a typical 120 mm projectile. Inspection of the post-fired fin included assessment of the fin surface condition (e.g. breakage, warping, melting, etc) and a measurement of blade thickness, before versus after firing, to determine the extent of erosion.

Based on the static test results, several of the more 'successful' alternative fin designs were selected for dynamic (normal launch) testing. An M-735, 105 mm (calibre) KE projectile, shown entering free flight in Fig. 2, was chosen as the test-bed projectile for carrying the candidate fin assembly downrange*. The basis for choosing a 105 mm carrier projectile, as opposed to a 120 mm projectile, was economics: the M-735 being less expensive than a comparable 120 mm round. Even though 105 mm ammunition uses propellant with a slightly cooler flame temperature than 120 mm ammunition (e.g. ~3000 K versus ~3400 K), the launch acceleration, muzzle exit velocity, and exposure to uneven muzzle exit pressure is virtually the same in the two-gun calibres, which is the emphasis of the dynamic test phase.

Post-firing assessment of the candidate fin performance was based on high-speed free flight photographs (e.g. Fig. 2) and downrange yaw cards. In some cases(when the fins failed), it was possible to obtain microscopic (using a scanning electron microscope (SEM) inspection of post-launched fin pieces found on the ground near the muzzle.

3. PROTOTYPE FIN DESIGNS

Three types of high temperature plastics were examined for use as molded tail fins; they were: polyketones, polyimides and phenolics. Fins were made from these resins with and without fibre fillers. In general, there are advantages and disadvantages of fibre reinforcing of the fin. For example, a thin fin made from unfilled resin may be tough enough to absorb—without breaking—the short duration in-bore stresses created by propellant grain impacts, but it may flex beyond its elastic limit when subjected to the longer duration out-of-bore stresses created by uneven muzzle exit pressures. Adding chopped fibres to the injected

* The discarding, full-calibre sabot petals shown in Fig. 2 provide in bore support for the sub-calibre KE rod; sabot seperation from the rod after launch is due to differential aerodynamic drag.

resin to strengthen it against asymmetric muzzle, exhaust flow also increase its brittleness, in some cases, to the extent that in-bore propellant grain impacts may chip a thin, fibre-filled blade. Filling the resin with longer fibres (e.g. by hand laying a broad cloth into the mold prior to processing) may increase the strength of a thin blade to the point where it is no longer chips in-bore or breaks out of bore. But with this solution, the simple, inexpensive process of injection molding the fin is no longer possible.

Injection molded fins were made from either a polyimide, or, one of two polyketones. In particular, the materials selected for injection molding were: polyetherimide (PEI) from General Electric Co., polyetheretherketone (PEEK) from ICI, and polyaryletherketone (PAEK) from BASF Corp. In addition to fabricating unfilled fin assemblies from these three thermoplastic materials, some PEI and PEEK fins were 40 per cent filled with chopped carbon fibres to increase their strength, while some PAEK fins were 30 per cent filled with short strands of E-glass, for the same purpose.

Compression-molded fins were made from several broad cloth materials pre-impregnated with phenolic resin having one or more additives. In particular, the materials selected for the compression-molded fins were chosen from ICI's Fiberite line of ablative broad goods used in the aerospace industry. They were: MX-4600 (a polyamide modified phenolic resin with ~ 10 μm diameter E-glass fibre reinforcement), MX-2646 (a polyamide-modified phenolic resin with ~ 10 μm diameter silica fibre reinforcement), and MXBE-55 (an elastomeric-modified phenolic resin with hollow E-glass fibre reinforcement, ~10 μm diameter).

In addition to differences in composition, strength was also changed by varying the thickness of the fin blades. Two fin thicknesses were examined: 1.02 mm and 1.52 mm. For comparison, the aluminium fin on the M-735 KE projectile is 3.18 mm thick at the base of the fin, where it joins the hub, and 2.03 mm thick at the tip of the fin. The rationale for selecting plastic fin thicknesses that were less than the standard aluminium fin was to begin with the thinnest conceivable fin (saving the most weight and aerodynamic drag,) then, if necessary to increase fin strength, open up the mold (an irreversible step). However, due to unforeseen budget cutbacks to this project, the strategy of progressing from thin to thicker fins was never completed beyond the second mold iteration, 1.52 mm, which was still roughly one-half the typical aluminium fin thickness. The test matrix for materials and dimensions is summarised in Table 1.

Table 1. Test matrix for candidate fin assemblies

Injection molded		Compression molded
Unfilled resin	Short fibre-filled resin	Long fibre prepreg
PEI hub and blades (1.02 mm thick)	PEI, reinforced with 6.4 mm long carbon fibres in hub and blades (1.02 mm thick)	MX-4600 (polyamide-modified phenolic), reinforced with a glass fibre broadcloth in hub and blades (1.52 mm thick)
PAEK hub and blades (1.02 and 1.52 mm thick)	PEEK, reinforced with 6.4 mm long carbon fibres in hub and blades (1.02 mm thick)	MX-2646 (polyamide-modified phenolic), reinforced with a silica fibre broadcloth in hub and blades (1.52 mm thick)
	PAEK, reinforced with 6.4 mm long glass fibres in hub and blades (1.02 and 1.52 mm thick)	MXBE-55 (elastomeric-modified phenolic), reinforced with a glass fibre broadcloth in hub and blades (1.52 mm thick)

4 RESULTS

The outcome from the static fin test can be grouped as follows: The post-fired fins were either (i) significantly eroded; (ii) fractured (chipped); (iii) warped; or (iv) virtually undamaged, with the exception of a fairly uniform, but minor degree of ablation. Their results are summarised in Table 2 and the results for standard aluminium fin are also included for comparison.

Table 2. Assessment of static firing test results

Eroded		Wraped	No significant damage
M-735 aluminum fin (Fig. 3)	MXBE-55 (Fig. 4(b))	PEI, unfilled hub and blades, 1.02 mm thick (Fig. 6)	MX-4600 (Fig. 7)
MX-2646 (Fig. 4(a))	PEI, fibre-filled hub and blades, 1.02 mm thick (Fig. 5)	PAEK, fibre-filled hub and blades, 1.02 mm thick (like Fig. 6)	PAEK, both unfilled and fibre-filled hub and blades, 1.52 mm thick (Fig. 8)
	PEEK, fibre-filled hub and blades, 1.02 mm thick (like Fig. 5)		

As results in Table 2 reveal, two of the statically tested fins incurred erosion damage, one of them being the standard aluminium fin. As reported by Bundy[1], *et al*, and shown in Fig. 3, erosion of the aluminium fin is most severe at the leading edge, receding ~ 1.0 mm. A degree of nonuniformity can also be seen along the fin edge, varying from one blade to the next. The streak-like patterns extending downstream from the fin edge are deposits of Al_2O_3 resulting from the vapourisation and subsequent oxidation of the aluminium substrate at the leading edge.

Erosion of the compression-molded MX-2646 fin in Fig. 4(a), was far worse than shown in Fig. 3 for the aluminium fin*. Roughly 50 per cent of the fin height was eroded (erosion also occurred in the width of the fin, perpendicular to the plane of view). It appears (note micrograph inset) that relatively large pieces of the silica crossweave were

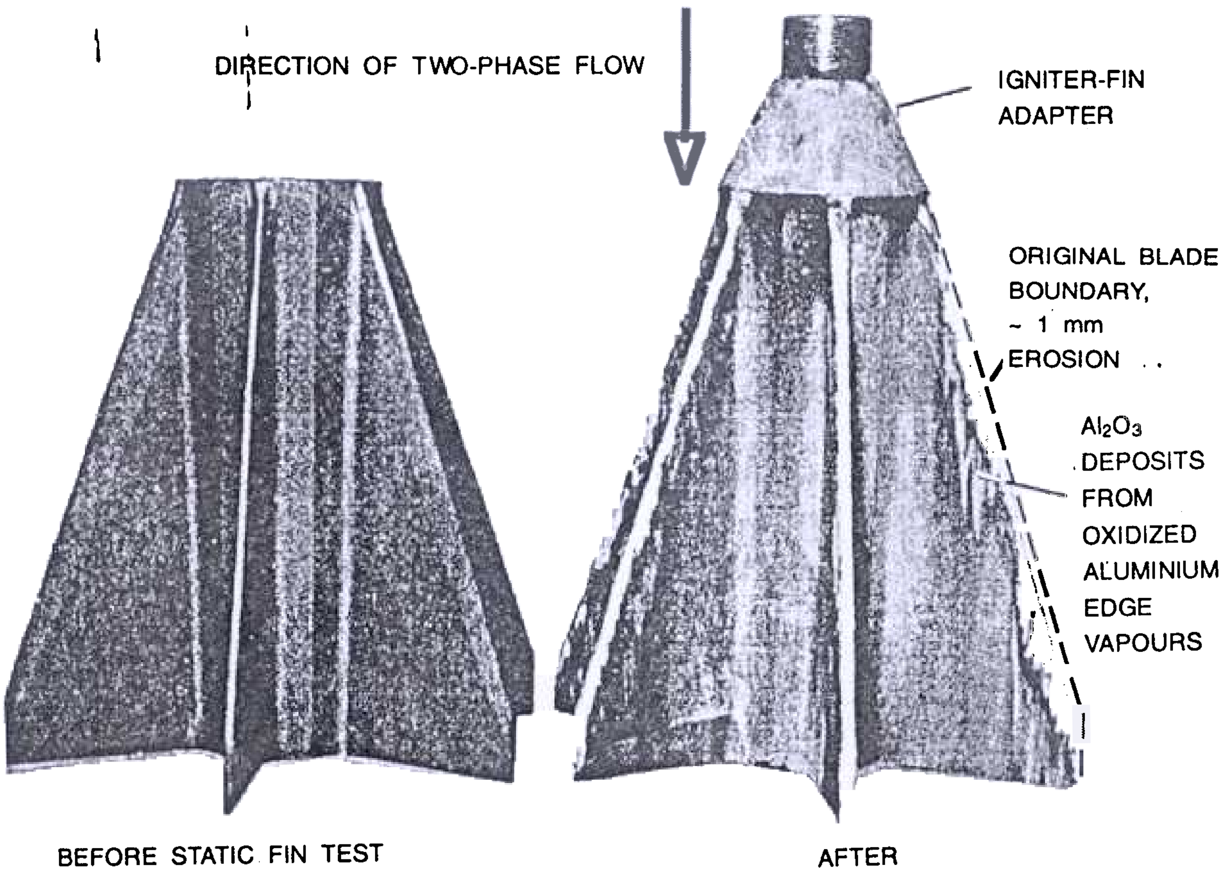


Figure 3. Static firing test result for the standard M-735 aluminum fin

* In the static fin test for compression-molded fins three different thermoset resins were tested simultaneously by pinching the root of each blade into a multijawed steel-collet, which was attached to the end of the igniter tube (Fig. 1).

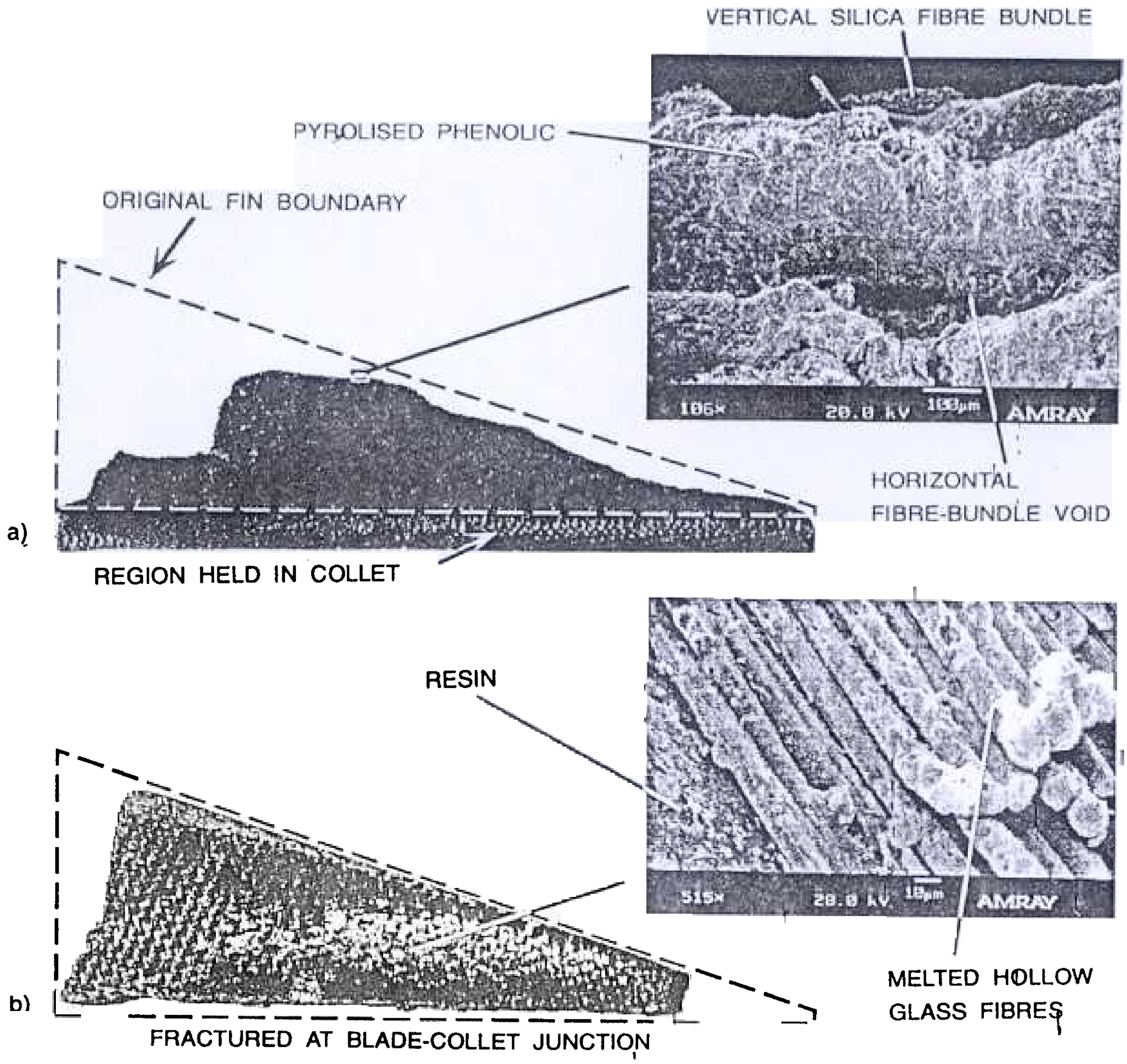


Figure 4. Static firing test results for (a) MX-2646 and (b) MXBE-55 compression-molded, fibre-filled, thermoset resins (1.52 mm blades).

extricated by the combustion event, leaving voids in the blade surface and increasing exposure of the unreinforced phenolic to the two-phase flow. It is likely that the exposed phenolic matrix was simply chipped away by propellant grain impacts.

The compression-molded MXBE-55 fin showed less erosion (Fig. 4(b)), than the MX-2646 fin (Fig. 4(a)), but is probably unacceptable as a fin material since it fractured at the blade-collet junction. It is speculated that the hollow glass fibres did not add sufficient strength, nor the elastomer sufficient toughness, to prevent large scale mechanical failure. Even though melted E-glass fibres were found on the blade surface, fibre bundles appeared to remain within the matrix, impeding erosion longer in this composite than in that of Fig. 4(a). The fin width diminished by ~0.05 mm on each side, the equivalent of perhaps four to five layers of 10 μm fibres.

Another fin material fractured in the static test was injection-molded PEI, with carbon fibre reinforcement in the hub and (1.02 mm thick)

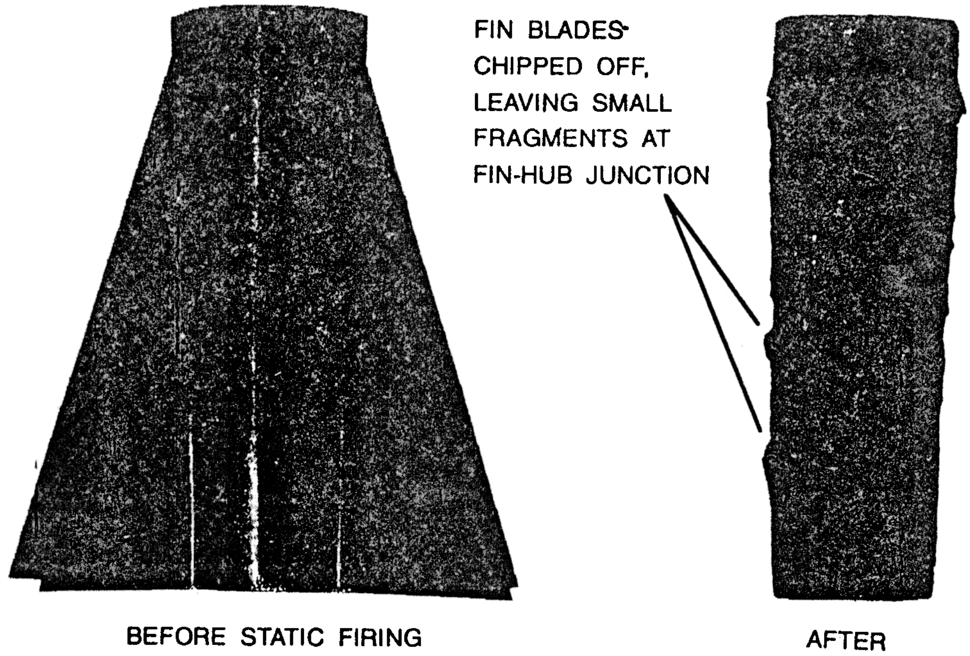


Figure 5. Static firing test result for PEI resin with 40 % carbon fibre filler (1.02 mm blades)

blades (Fig. 5). The appearance of rather sharp-edged fin fragments, where the root of the blade joins the hub, implies that the loss of fin blades is most likely due to chipping from propellant grain impacts. Finally, as recorded in Table 2, the 1.02 mm injection-molded PEEK fins, with carbon fibre filler also fractured in the static test. The fin loss was complete, much like that shown in Fig. 5.

Unlike the more brittle, fibre-filled PEI, unfilled PEI resin appears (Fig. 6) to be tough enough to resist fracture from propellant grain impacts. However, the fin blades were left warped by the static heating event. Apparently, the remaining blade material (eroded in thickness from 1.02 mm to ~ 0.7 mm) absorbed enough heat to be stressed beyond its elastic limit by thermal softening. Likewise, a similar level of heating and erosion left the injection-molded, fibre-filled, 1.02 mm PAEK fins warped, looking like those in Fig. 6.

There were three plastic fins that survived the static-heating test with virtually no damage. They were the MX-4600 compression-molded blade (1.52 mm thick) (Fig. 7) and the short fibre-filled and unfilled PAEK injection-molded fins (1.52 mm thick) as shown in Figs 8(a) & 8(b), respectively).

The SEM micrograph in Fig. 7 reveals melted and coalesced E-glass fibres separating from the underlying reinforcement. Thickness measurements indicate that ~ 0.07 mm of the glass and resin matrix was eroded from each side. Unlike the MXBE-55 fin, the 10 µm glass fibres in the MX-4600 blade were solid, this, in conjection with a difference in modifiers, increased the strength of the blade, preventing fin damage like that which occurred in Fig. 4(b). It is worth noting that the MX-2646 fin has the same resin and modifier as MX-4600—but different fibres (silica versus E-glass)—yet, the MX-2646 fin failed catastrophically ((Fig. 4(a) in comparison to Fig. 7)).

Increasing the blade thickness of the thermoplastic PAEK resin to 1.52 mm substantially improved the results (Figs 8(a) and 8(b)) (with and without fibre filler, respectively). As shown, there was virtually no damage to fin assembly after the

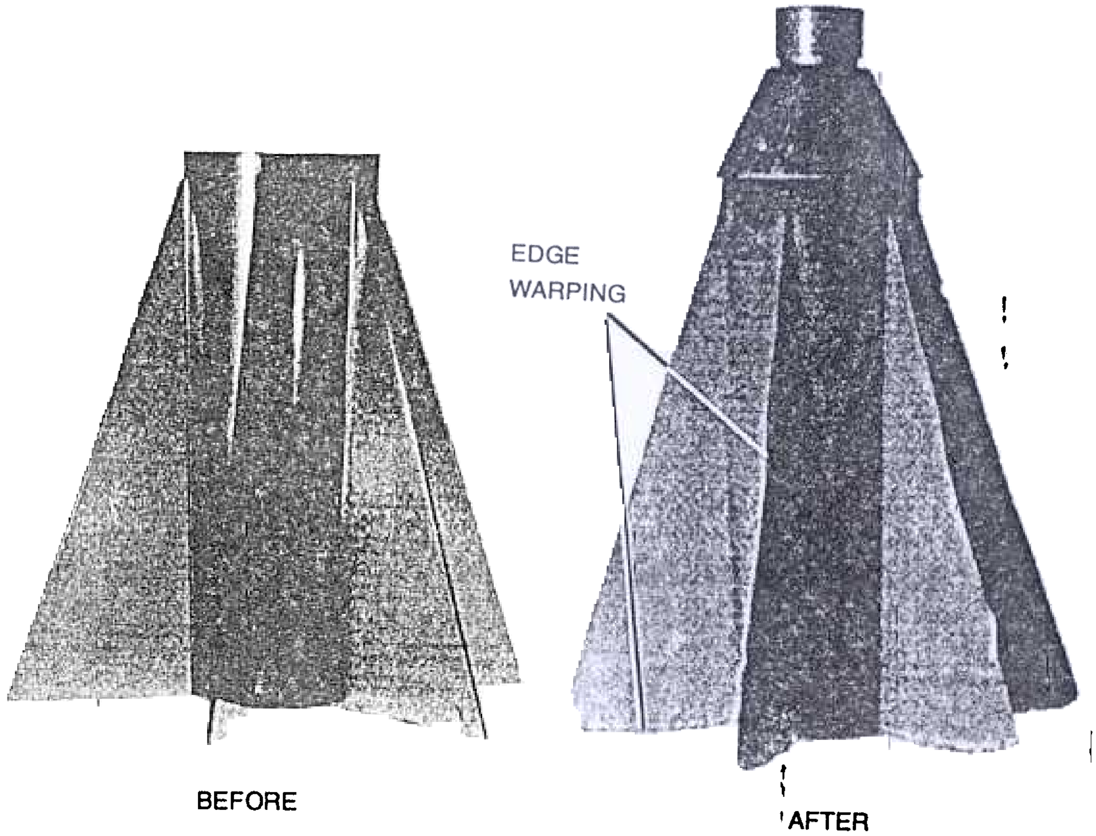


Figure 6. Static firing test result for unfilled PEI resin (1.02 mm blades)

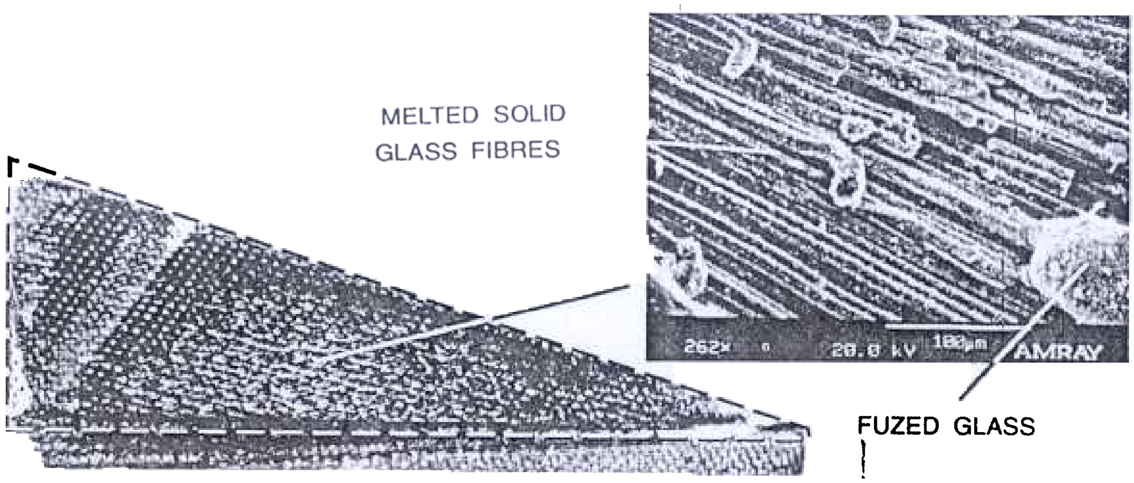
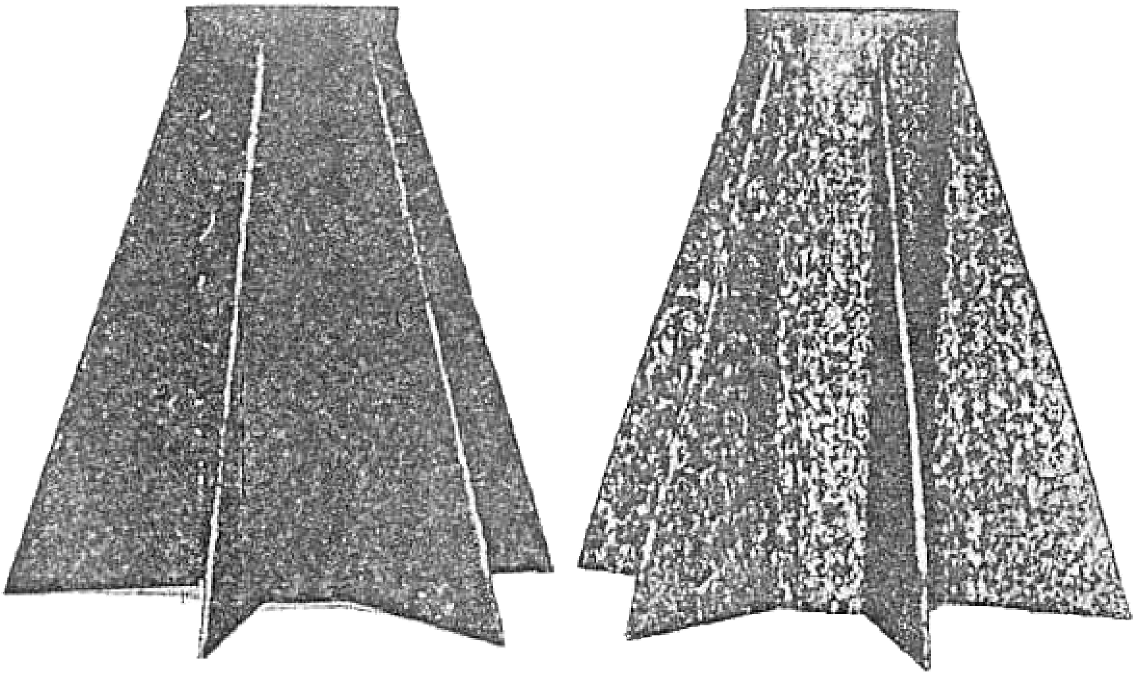


Figure 7. Static firing test result for MX-4600 compression-molded, fibre-filled, thermoset resin (1.52 mm blades)

static heating test. Overall, ~ 0.15 mm of composite material was thermally eroded from each side of the blades, leaving a fin thickness of ~ 1.2 mm. Apparently, adding 0.5 mm to the fin width prevented thermal softening from warping the blades as it had for the thinner (1.02 mm) PAEK fin assembly.

Out of the three fin materials that were virtually undamaged by the static firing test, the lightest was the unfilled PAEK fin assembly (hub



(a) (b)

Figure 8. Static firing test result for (a) PAEK resin reinforced with 30 % E-glass fibres and (b) unfilled PAEK resin (both had 1.52 mm thick blades).

and blades) at 70 g. the filled PAEK was slightly heavier (75 g) followed by the MX-4600 (110 g). All of them were considerably lighter than the 175 g standard M-735 aluminium fin.

5.

Table 3. Assessment of dynamic firing test results

Catastrophic failure	Borderline failure	Occasional success
Compression-molded MX-4600 hub and blades	Injection-molded, fibre filled PAEK hub and blades	Injection-molded, unfilled PAEK hub and blades

As indicated by the column headings in Table 3, there were no unequivocal successes among the fin designs tried. However, there were occasions when individual fin assemblies flew downrange with little or no apparent damage. Before discussing the occasional successes, the unsuccessful designs are discussed.

One of the most complete failures in the dynamic firing test was the compression-molded MX-4600 fin assembly (Fig. 9). In spite of the static firing success of ths polyamide-modified phenolic, with glass fibre broad cloth reinforcement, the broad cloth lay-up delaminated and was shred into hundred of tiny pieces after it left the muzzle. One explanation for the failure is that high pressure propellant gases entered into the

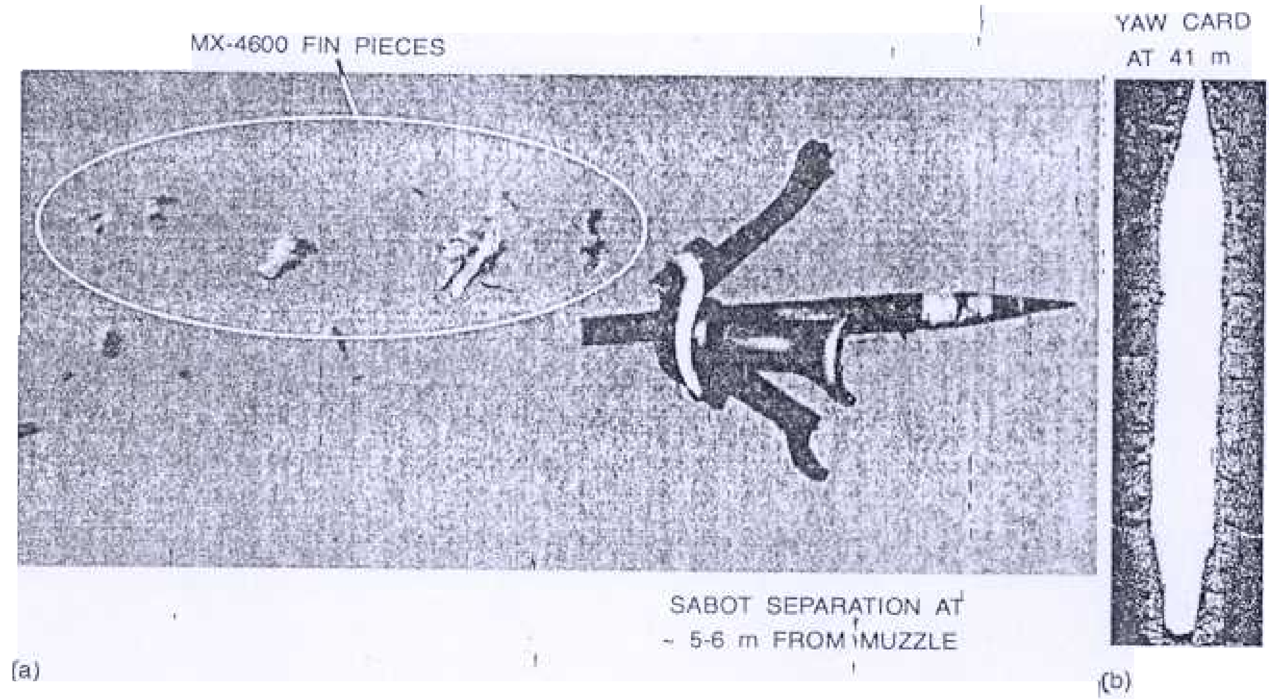


Figure 9(a). High speed downrange photograph, and (b) downrange yaw card imprint of M-735 rod launched with MX-4600 fins

interstitial cavities and voids between the fibres and resin while the assembly remained in-bore, but did not escape fast enough, once out-of-bore, to avoid exploding the part. Evidence that the failure occurred out-of-bore was based on the fact that only a small fraction of the fragments showed signs of in-bore exposure to high temperatures (i.e. melted or charred surface fibres).

Note that the rod in Fig. 9 is flying downrange with a yaw angle of ~ 5° at 5-6 m from the muzzle. Although this is not an unusually large yaw angle at this location (e.g. it is similar in size to that shown in Fig. 2 for the standard M-735), a fraction of a second later, at 41 m from the muzzle, the yaw card indicates that the angle has increased to at least 45°. This unacceptably high angle shows, by counter example, how important fins are to stabilising the rod and keeping the yaw angle small.

The fin assembly fabricated by injection molding PAEK, containing 30 per cent short glass fibres, was a borderline failure because in no cases did it enter free flight without some fin damage, like that shown in Fig. 10. It is speculated that if the KE rod has some non-zero angle of attack with respect to the reverse muzzle exhaust flow, which is almost certain to the case, then the dynamic pressure from this flow can bend the fin blades beyond their yield point. This would explain the large number of broken fin tips found on the ground downrange from the muzzle, one of which is shown in Fig 10. The SEM micrograph of the fin tip surface indicates that the blade surface is softened by the in-bore transient heating. It appears that when propellant grain fragments hit this soft layer, they leave crater-like imprints. Flat-bottomed craters imply that the plastic is not thermally softened, to the point of being inelastic, below a certain depth, in his case ~ 0.03 mm. Thickness measurement of the fin fragments revealed that ~ 0.05 mm of surface material was eroded from each side of the baldes; this is abut one-third the level of erosion that occurred in the static firing test.

Even though the loss of fin surface area was not complete in Fig. 10, it was significant to the extent that it would be unacceptable in terms of the effect it has on destabilising the round, which is borne out by the high yaw angle of ~ 15° near 30 m from the muzzle. The unfilled PAEK fins gave the

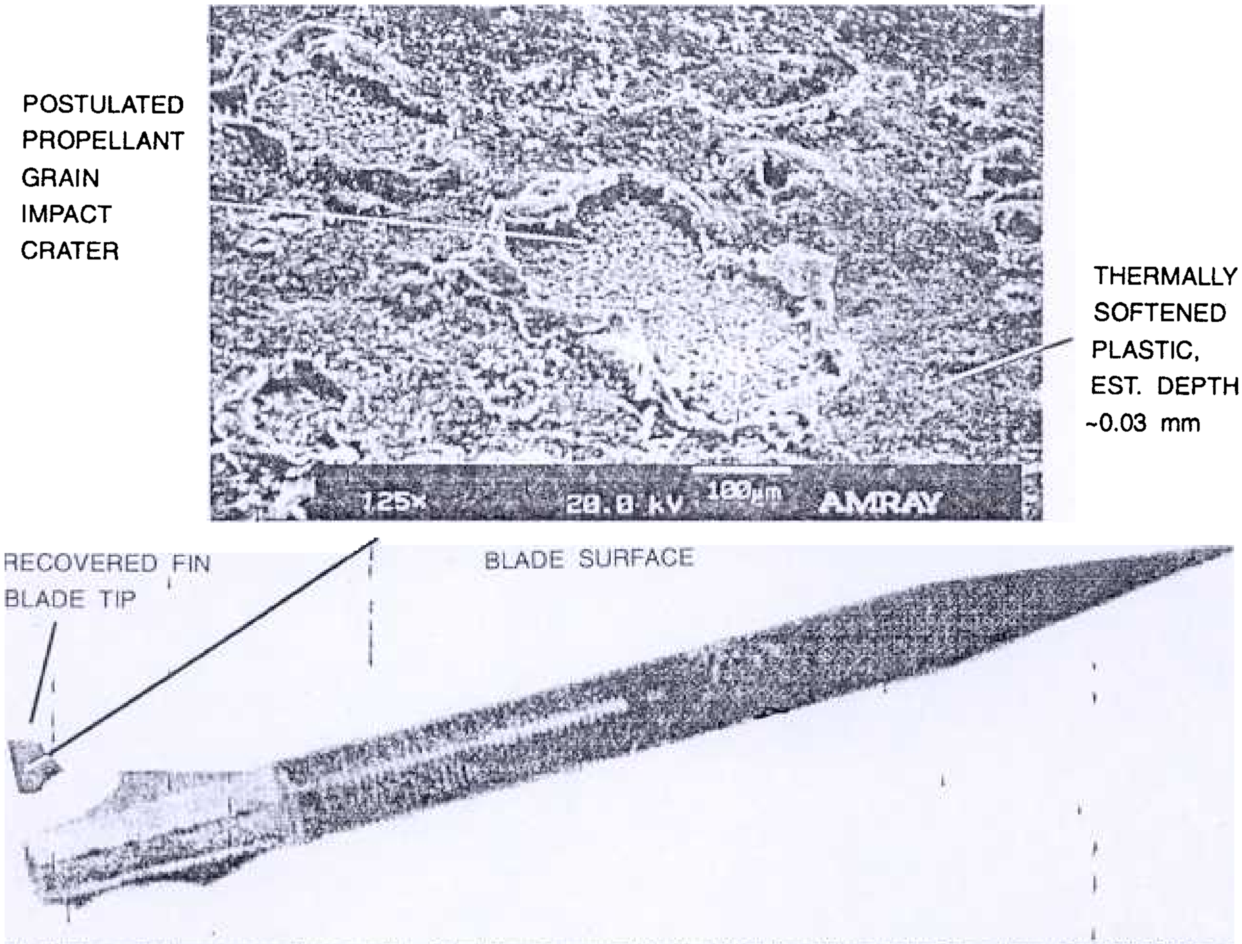


Figure 10. High speed downrange photograph (~30 m from the muzzle) of an M-735 rod launched with a fibre-filled PAEK fin assembly

most promising results. Out of two fin assemblies tested, high speed photographs and yaw card imprints showed that one assembly lost two of six fin tips due to fracture, with the remaining four tips exhibiting extreme flexure. However, the other PAEK fin assembly flew downrange essentially undamaged, as shown in Fig. 11. The yaw cards, at 41 m and 53 m from the muzzle, reveal that all fins are full span and none are chipped. There appears to be a slight flexing of some blades as indicated by the small curvature in the yaw card silhouette. (It is presumed that the blades are flexing because no permanent warping was observed in the more intense thermal environment of static firing).

It has been speculated that the initial yaw angle relative to the reverse muzzle exhaust flow contributes to the loss of fins, due to bending of the blades by asymmetric dynamic pressure loads. Unlike Figs 2 and 9, the yaw angle at ~ 7 m from the muzzle in Fig. 11 is small, < 1° and was probably small at muzzle exit. This would suggest that dynamic pressure loads were probably small at muzzle exit, which could help explain why there was not only no-fin-chipping, but very little fin-flexing. Furthermore, the continued low yaw angles at 41 m and 53 m from the muzzle (indicated by the near circular yaw card impacts) demonstrates that the fin is serving to maintain flight stability of the rod.

6. CONCLUSIONS & RECOMMENDATIONS

This report highlights the study of plastic fins for use on long rod KE penetrators. An M-735, a 105 mm round with a muzzle exit velocity of ~ 1600 m/s, was chosen as the carrier projectile for

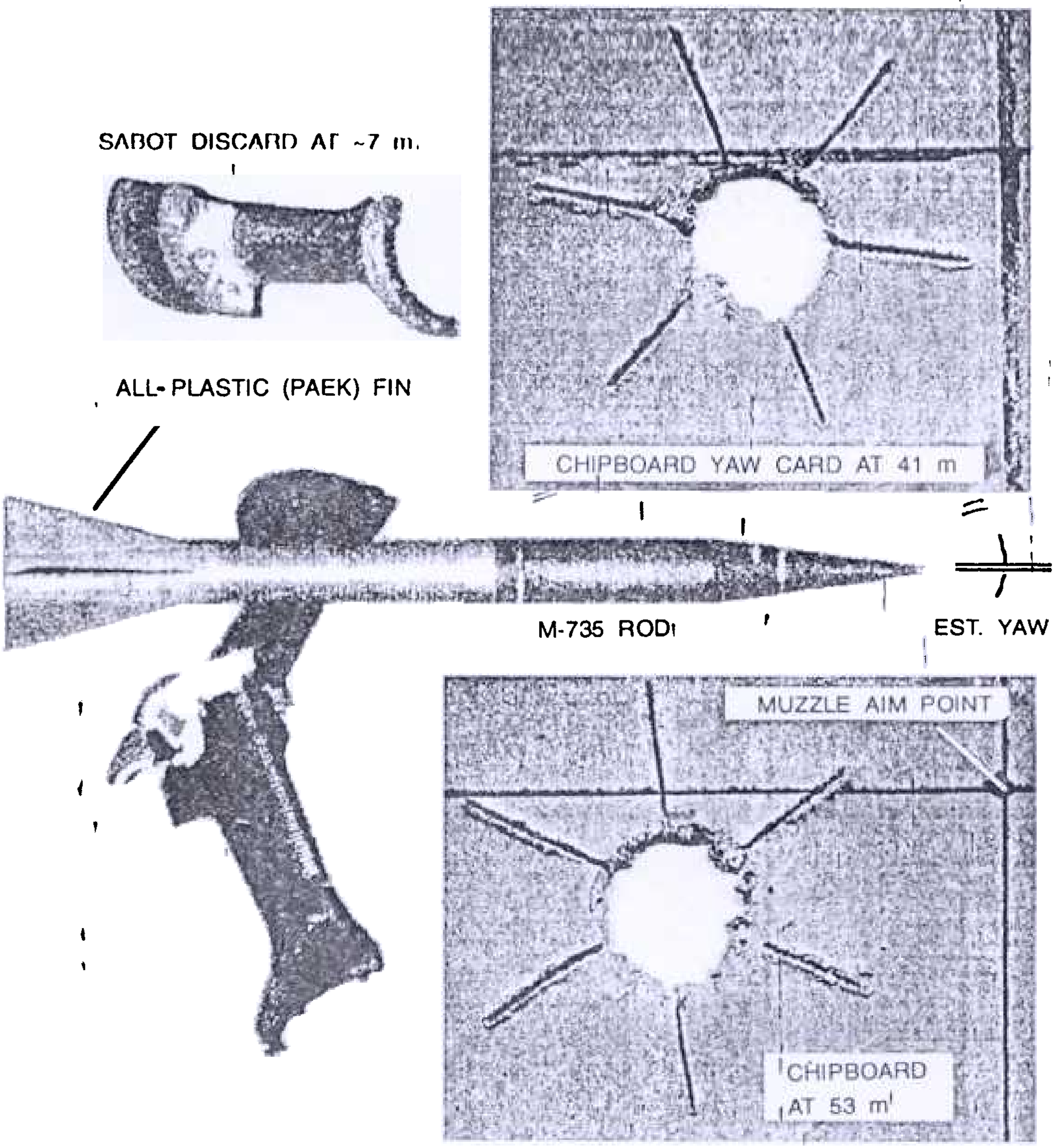


Figure 11. High speed photograph of an all-plastic (PAEK) fin assembly on a carrier M-735 long rod penetrator

test comparisons. Several types of plastics were evaluated, from specialised compression-molded broad clothes, pre-impregnated with thermoset resins (like those used in the acrospace industry), to more general purpose injection-molded engineering-type thermoplastics (such as PEEK).

The long range planning of the programme was to start with thin-molded fins, roughly one-third the blade thickness of the standard aluminium fin, then open up the mold (an irreversible step) as necessary, to increase the blade thickness (strength). However, lack of continuing funds halted the programme at the second fin thickness iteration, which was still only one-half the standard aluminium fin thickness. Nevertheless, a great deal was learned about the use of plastics for this application.

Eight-candidate fin materials were chosen for testing. Of these eight, only three performed better than aluminium in resisting in-bore damage from the two-phase propellant flow (as determined in static-fire testing.) These three then underwent further testing by launching them on a carrier M-735 rod. Of the three, only one was occasionally successful in stabilising the rod with no appreciable thermal erosion or mechanical damage (bent or chipped fins); it was made from an injection-molded, unfilled thermoplastic—PAEK from BASF Corp.

There is, however, considerable latitude for improvement of the 'occasionally successful design' without exceeding the drag and weight penalties of the standard aluminium fin. For example, it is believed that going from the current 1.52 mm, straight-cut PAEK fin to a 2-3 mm, tapered-cut (from tip to root) PAEK fin, would provide the necessary margin of safety to ensure a damage-free transition to free flight. Since such a shape is roughly the same as the baseline aluminium fin, there would not be any benefit from reduced drag, but the PAEK fin would offer a weight saving: weighing only 50-60 per cent as much as its aluminium counterpart. (Recall, a fin weight reduction improves flight stability because it moves the CG forward, which increases the stabilising moment). Most importantly, the test results showed that thermal erosion for such a plastic fin would be far less—and more uniform where it does occur—than for a comparable aluminium fin. For example, from the static firing test, it was shown that the PAEK fin had a fairly uniform erosion of ~ 0.15 mm, whereas, for the aluminium fin, the leading edge regression was 1 mm, and it varied from blade to blade. (Recall, non-uniform erosion creates non-uniform aerodynamic forces, which increases ammunition dispersion).

In general, this study proved that a thin (one-half as thick as the standard 2-3 mm aluminium fin), lightweight (40 per cent as heavy as the standard 175 g fin), all-plastic (PAEK) fin assembly can stabilise a large calibre (105 mm) long road (M-735) KE penetrator with virtually no in-bore thermal erosion (~ 0.05 mm surface regression). However, to prevent out-of-bore mechanical fin damage (bent or chipped blades), it appears that either the rod must exit the muzzle at small yaw angles, or the plastic fin blade must be made thicker. Hence, the critical factor in plastic fin design is not thermal erosion, as one might expect, but rather, it is the ability to flex without breaking in the reverse muzzle exhaust flow.

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