EXPERIMENTAL RESULTS FROM SOLID ARMATURE TESTS AT THE CENTER FOR ELECTROMECHANICS AT THE UNIVERSITY OF TEXAS AT AUSTIN

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***Abstract* - The Center for Electromechanics at the University of Texas at Austin has conducted a number of solid armature tests in the 90 mm gun facility over the past two years. Several different base push and mid-body drive armatures and projectile packages have been tested in the 50 m deep vertical test range. Results from some of those tests, including in-flight photographs and x-rays, will be presented. The C-shaped armature's evolution from a base push monolithic aluminum slug to a mid-body drive, two piece, armature/sabot will be discussed. Issues involved with both base push and two part armature/sabots and ways to deal with those issues will be addressed.**

C-shaped Monolithic Armature

The C-shaped armature design presently tested at CEM-UT is based on armature work done in a 14 mm square bore gun and a 45 mm round bore, half-scale version of the 90-mm gun presently used at CEM-UT. Results from those early tests are presented in [1]. As noted in [1], CEM-UT chose to pursue a solid armature instead of a plasma armature in the beginning of the 90 mm, single-shot gun (SSG) program for a number of reasons. Two of those reasons are reduced bore wear and higher efficiency associated with a true solid armature [2]. While the present C-shaped armature does transition to a "short arc" plasma/solid armature at ~1,000 m/s it still maintains a lower voltage than a pure plasma armature.

The first monolithic C-shaped armature with an integral payload, shown in Fig. 1, was tested on shot #12 in the 45 mm, half-scale gun. This design evolved from the "fishbone" armatures tested in the square bore gun and the cylindrical fishbone designs tested earlier in the 45-mm gun. This early design eventually evolved to the 90-mm version shown in Fig. 2 which was tested at 8.1 MJ (2.440 kg at 2.577 km/s) of muzzle energy on shot #20 of the 90-mm gun.

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Fig. 1. First C-shaped armature tested in 45-mm gun on shot #12

The most obvious difference between the two designs is the addition of the rear borerider. The front borerider was added to the 45 mm cylindrical fishbone armature after shot #7 of the 45-mm gun to prevent arcing to the front portion of the package. The rear borerider was added after shot #9 in the 90-mm gun to help seal the plasma generated by the transitioning armature and stabilize the package.

The early C-shaped armature with an integral payload provided a safe, robust package with a mass approximating the mass of future packages that would carry a tactical payload. The 7075 aluminum package also served as a test of the material the sabot designers would ultimately use. This package allowed CEM-UT to test the railguns, switching, power supply and diagnostics associated with the 9-MJ gun system. The design also had the potential to be developed as a base-push armature for packages provided by projectile contractors and as an integrated armature/sabot which could be used to carry test projectiles. While the 8.1-MJ test proved the ability of the system to launch

Fig. 2. Armature with integral payload launched on shot #20 at 8.1 MJ

packages near the peak design level, it may also have revealed a flaw in the details of the C-shaped armature design. Flash x-rays taken at the muzzle show that one of the contacts on the package failed. Whether this was a result of a mechanical failure resulting from the bore condition or whether it indicates a design flaw is not certain. Conservative calculations [3] of the action seen by the armature show that the contact reaches 89% of its melting temperature during a 6-MJ launch. If this does in fact occur, it may weaken the contact material even in the short time period of the launch. The contact profile design may also have been a factor. Because these contacts were machined on a taper to assure interference between the contacts and the rail surfaces, the measured diameter of the profile at the rear of the contact was slightly larger than the actual rail diameter. When the contact is pressed into the gun bore, this results in a slight gap (~0.0025 mm or 0.010 in.) between the center of the armature contact and the center of the rail. The size of the gap depends on the bore diameter and contact taper. This is probably remedied early in the launch as the outer contact edges are worn and softened, but may cause additional heating. The contacts in this design are also very stiff and may have had problems continuing to contact the rails as the contact surface was ablated.

The monolithic armature with an integral payload served as the workhorse of the facility for the first year and a half of testing in the 90-mm gun, providing a test package for 14 of the first 21 shots. During that time, the packages, which ranged in mass from 2 to 2.5 kg, were accelerated at up to 104 kgees and to a velocity of 2,577 m/s. The armature, which was designed for a peak gun current of 3.2 MA saw an actual peak current of 3.4 MA on shot #11. While the monolithic armature and integral payload was designed as a test package, it was primarily of interest as an armature. It would require additional modifications to make it useful as a vehicle for launching sabots and/or penetrators.

Base Push Armature

The first use of the C-shaped design to launch a flight configured projectile was in support of the DARPA/DOE/Kaman Sciences Corporation (KSC) Unguided Hypervelocity Projectile Program (UHVP). Background information and early test results from that program are available [4]. CEM-UT provided the base-push armatures to test Kaman's UHVP packages in both the 45- and 90-mm guns at CEM-UT. The C-shaped armature design was also used to test base-push packages provided by Ford Aerospace as part of their D1 program.

One of the goals of the UHVP program was to launch tactically configured projectiles from EM guns. Armature development, however, was not considered to be within the program scope. Therefore, Kaman Sciences and CEM-UT jointly began considering ways to integrate the CEM-UT Task B armature with Kaman Sciences' projectiles. One of the KSC projectile designs was a base-pushed, light antiarmor/air-defense projectile (LAAP). It consisted of a tungsten forward penetrator with a Vascomax aft skirt. Because of this projectile's high acceleration capacity and history of successful launches from powder guns, it was considered an ideal candidate for testing from EM guns.

Because of the lack of experience with launching tactically configured projectiles from railguns, a conservative approach was taken to prevent damage to the gun bore. Potential failure mechanisms were identified as:

- Arcing to the projectile
- Structural failure due to axial acceleration
- Structural failure due to balloting loads
- Tumbling of the armature during launch

In order to address structural concerns, it was decided that all projectiles must be launched from powder guns before launch from the CEM-UT railgun could be attempted. CEM-UT had demonstrated high-energy launches with a base-pushing armature and an integral dummy mass which provided package stability. The challenge in launching LAAPs from EM guns was progressing from single component, monolithic-launch packages to much more complex packages with discarding sabots.

Ultimately, aluminum sabots were to be used for launching LAAPs from EM guns; however, these sabots had not yet been tested from powder guns. The first projectile packages consisted of a LAAP with a solid plastic sabot; similar configurations had been successfully tested in 90 mm powder guns at accelerations of over 90,000 gees. Plastic sabots were selected for two major reasons: they are superior insulators and in the event of structural failure, the material would be confined and would keep the projectile centered in the bore.

Two shots were made with multipiece payloads in the 45-mm gun. The first attempt was shot #4, in which the launch package consisted of a full-scale LAAP with a separating G-10 sabot driven by a cylindrical fishbone armature. Postshot examination of the gun revealed bore damage indicative of armature failure, which was probably a result of excessive package mass. The total package mass was 1,445 kg, of which 331 g was armature. This is equivalent to a mass of 11.6 kg being shot from the 90-mm gun, which far exceeds the design parameters. The additional mass adversely affects armature stresses and temperature. The package was totally redesigned and on shot #15, a 413-g package consisting of a half-scale LAAP and a nonseparating glass-filled polycarbonate sabot driven by a C-shaped armature. This shot was successful and the design served as a baseline for testing in the full-scale 90-mm gun.

Once the 90-mm gun was proofed out with monolithic packages, a test was conducted with a Vascomax slug designed to represent the LAAP in base configuration and mass. A Vascomax pusher plate was imbedded in the front face of the armature to accommodate the bearing loads generated during launch. The truncated C-shaped armature was coupled to the nonseparating polypropylene sabot with a tapered pilot stub machined into the nose of the armature. A matching counterbore was cut into the rear of the sabot. The slug was launched on shot #5 and the 2,476 g package survived launch as expected. The next shot consisted of a similar slug with a separating sabot. Again, the projectile package survived launch and although the plastic sabot was broken at muzzle exit, the dummy projectile travelling at 1,724 m/s penetrated the 127 mm thick steel target.

Once the initial slug tests were finished, three attempts were made to launch the actual LAAP with a similar polypropylene sabot. In the first test, shot #8, a power supply problem resulted in very low muzzle velocity and little useful data. For the next two tests, shots 15 and 17, a better grade of polypropylene (Polypropylux 944) was selected for the separating sabot. The sabot failed on shot #15 and was accelerated ahead of the package on shot #17, probably because of improved plasma sealing. The tungsten nosetip broke at the joint between it and the Vascomax aft skirt on both tests.

Because the goal of the program was to ultimately use aluminum sabots and the plastic was failing structurally, it was decided to forego additional tests with plastic sabots and begin testing aluminum saboted packages. CEM-UT had demonstrated the ability of aluminum to withstand the short rise times experienced in the railgun. Therefore, no fundamental structural problems were anticipated (or experienced) with the use of aluminum as a sabot material. The first launch package design incorporated an interlock to prevent separation of the armature and sabot. Five shots were made with this projectile/sabot/armature interface design.

For the first test, shot #22, a composite overwrap was used to prevent sabot deployment. Muzzle x-rays did not capture the front portion of the package and the high speed movie film could not confirm that the nosetip was intact. In each of the next four UHVP tests, shots 23, 24, 25, and 26, nosetip failure was experienced. A representative x-ray of the projectile package at muzzle exit showing the nosetip failure on shot #25 is shown in Fig. 3.

The projectile had survived launch accelerations of greater than 90 kgees from powder guns, yet the highest acceleration experienced in this series of shots was calculated as less than 70 kgees. Possible failure mechanisms were identified as; excessive jerk, balloting, kick at muzzle exit, launch package eccentricity, stress concentration in the tungsten joint, and loose projectile/pusher plate interface. Later in the program a shock wave propagating up, and being amplified by, the conical Vascomax skirt was also suggested as a possible cause of the tip failures.

Because jerk was initially identified as the most likely failure mechanism, the acceleration profile was modified to reduce jerk. Using thermal opening switches the jerk was lowered from 500 to between 200 and 300 Mgees/s and on shot 26 jerk was calculated at 73 Mgees/s. This order of magnitude reduction in jerk did not eliminate the tip breakage. Projectile modifications were also made to mitigate the effect of jerk on the projectile nosetip and reduce any additional stress on the nosetip joint. Photographic data indicated the same type of failure in the joint between the tungsten tip and the Vascomax skirt on each shot. Balloting was considered a less likely mechanism, because the nosetip was only slightly displaced at muzzle exit; balloting severe enough to result in nosetip failure should cause noticeable lateral deflection as well. CEM-UT and Combat Systems Test Activity (CSTA) both measured bore straightness and it was within acceptable limits. The gun bore insulators were also patched before several tests to assure the smoothest bore possible. Launch package eccentricity and the projectile/pusher plate interface were controlled by maintaining tight machining tolerances and designing a positive contact between the pusher plate and projectile.

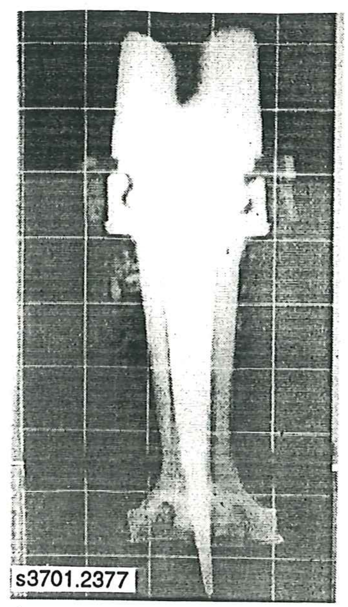

Fig. 3. Muzzle x-ray taken on shot #25 illustrating tip breakage

Through a joint effort by CEM-UT and KSC, a new projectile/sabot/armature interface design was developed to incorporate a polypropylene strain buffer between the pusher plate and armature. This strain buffer was also designed to function as an obturator in case plasma blow-by was experienced. The design greatly simplified launch package fabrication and reduced the sensitivity to machining and assembly tolerances. One shot was attempted with the LAAP with tungsten penetrator. Although the sabot and strain buffer survived launch, the nosetip failed again.

The UHVP Program allowed for one final shot from the CEM-UT Task-B gun. In order to increase the chance that the projectile would survive launch, the tungsten nosetip was replaced with a Vascomax nosetip designed to approximate the mass and static margin of the LAAP. Because Vascomax has a much higher yield strength than X21C tungsten (272 ksi vs. 162 ksi) and is less brittle, this experiment would help bound the problem from a materials standpoint. The assembled 3,148 g launch package used on shot #34 is shown in Fig. 4. In this test, all launch package components survived launch and a muzzle velocity of 1.6 km/s was achieved. An x-ray of the package immediately after muzzle exit is shown in Fig. 5.

Nosetip failures experienced in the LAAP shots from the CEM-UT railgun remain somewhat of a mystery. Any of the aforementioned mechanisms could cause the failures observed, but existing data are insufficient to definitively determine the cause. Actual projectile acceleration data would help solve this mystery. Acceleration and jerk profiles used for analysis are based upon the gun current waveform. While the integration of these acceleration profiles accurately match resultant muzzle velocity, it is not known how well these computed values match the actual acceleration and jerk experienced by the projectile.

Two Piece Armature/Sabot

As the UHVP testing neared its end, the development of the C-shaped armature continued. With the system proven at full energy, the requirements on the armature were modified. The mass of the armature needed to be reduced and the armature would eventually be required to carry penetrators with a high L/D ratio. In addition to this, it still had to provide a stable design that allowed testing of the 9-MJ system to continue when the supply of contractor supplied packages lapsed. Besides eliminating the need for the cumbersome base push joint designs the integrated armature/sabot design offered other advantages from the projectile designers point of view. The integrated approach facilitates mid-body drive of the projectile which makes launching longer projectile designs feasible. At this point in the program however, no two-piece armature had ever been tested in CEM-UT's 90-mm SSG. Modifying the C-shaped armature design which had a large data base seemed to be a safe evolutionary step rather than a revolutionary change.

Over a series of several shots, the mass of the armature portion of the package was reduced from 1,200 to 900 g. The stiffness of the armature contacts was also decreased substantially during this period. This is evident in the reduced loading force required for the lower mass armatures (10,000 lb. vs. 30,000 lb.). While the increase in armature compliance is felt to be advantageous in the later stages of the launch, when the contacts have been ablated, it may actually be detrimental in the early stages. A high interference pressure between the contacts and the rails

Fig. 4. UHVP launch package with strain buffer tested on shot 34

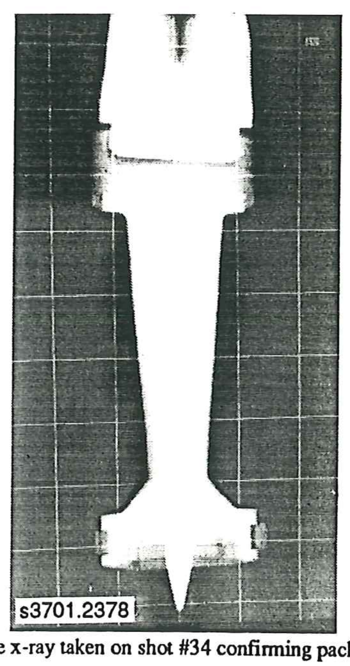

Fig. 5. Muzzle x-ray taken on shot #34 confirming package integrity

assures that the constriction forces created by the current turning from the rails into the armature contacts do not force the contacts off the rails. One parameter commonly used to assure an adequate contact pressure is a minimum contact force of 2.2 lb.f/kA of gun current. The maximum contact pressure, however, should be held to less than the 10,000 psi yield strength of the copper rail material.

Another difference between the early design and the reduced mass armature is the process by which the contacts are machined. As noted previously, the original C-shaped contacts were machined on a taper which resulted in a small gap between the rails and the center of the contacts. In the reduced mass design, the contacts are deflected prior to machining. Cutting the outer diameter (OD) of the contacts to the gun bore dimension while in the deflected position results in a better fit to the bore and more uniform pressure across the contact.

With these modifications incorporated, the first reduced mass armature was tested on shot #27 at 1,552 m/s. The design was eventually tested to 2,033 m/s on shot #31. These early tests of the package proved encouraging. While the armature did transition at near the same velocity as the original C-shaped design, at approximately 800 m/s vs. 1,000 m/s, the muzzle volts at exit are lower for the more compliant design. The lower overall muzzle voltages equate to lower losses which increases the overall efficiency of the package and reduces rail erosion.

On shot #31, a 19 mm diameter hole 75 mm deep was machined into the rear of the armature. Addition of that hole served as the starting point for the modifications that would be required for the armature to carry a penetrator. With shot #31 proving that a penetration between the two contacts did not adversely affect armature performance, a steel rod was threaded through the package for the next reduced mass test, shot #39.

On shot #39, the armature served primarily as a load for a low energy test of the power supply but it also proved that the steel rod protruding from the front and rear of the armature package did not reduce armature performance. The biggest step in the armature development program came on shot #40 when the C-shaped armature was fired as a two piece design carrying a mid-body driven threaded rod. While the package was not allowed to separate due to the thick boreriders, it was the first test of the two piece C-shaped armature and also the first time the "integral payload", used for the entire 9 MJ SSG test program, was configured as a separating sabot.

The most recent test of the reduced mass C-shaped armature was on shot #45 when the two piece armature/sabot shown in Fig. 6 was fired at 1,320 m/s. For this shot the forward portion of what had once been considered a "dummy payload" was configured as a sabot scoop. With a package velocity of 1,300 m/s, a static pressure of 2.80 MPa on the scoop was calculated using formulas presented in [5,6] for packages accelerated in light gas guns and railguns. V-grooves were cut into both the front and rear bore riders to assure that they would fail on the sabot split lines at the calculated separation force. A 19 mm diameter, threaded steel rod was fitted with an aluminum stabilizing skirt to provide a stable mid-body driven payload. The threaded rod also prevented axial shifting between the two armature/sabot halves. The inside portion of the contacts were also machined differently than earlier reduced mass armatures to allow for the addition of an aft penetrator support cone to the armature in the future.

During shot #45, the integrated armature/sabot performed well in bore and exited the muzzle intact as shown by the muzzle x-ray in Fig. 7. Symmetrical tears, 180° apart, in the polyethylene sabot stripper hanging 15.5 m from the muzzle confirmed that the sabot had separated cleanly prior to reaching the stripper. High speed film, shown in Fig. 8, taken just above the sabot stripper and x-rays taken 0.05 m above the target show the projectile intact and flying straight prior to target impact. The steel projectile penetrated 83 mm deep into the 127 mm thick 4130 steel target at a location 133 mm off centerline. This test allowed CEM-UT to confirm the proper operation of all the systems necessary for documenting a projectile package launch.

While the launch of the mid-body driven projectile with a C-shaped armature on shot #45 was the most recent step in the evolution of the design it was certainly not the last.

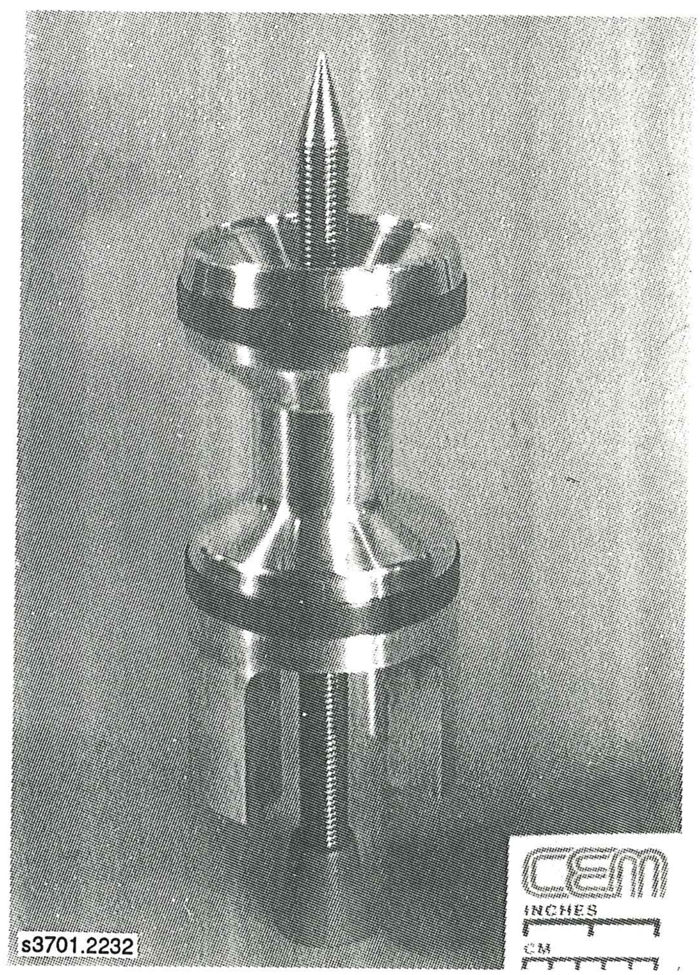

Fig. 6. CEM-UT two piece armature/sabot and projectile

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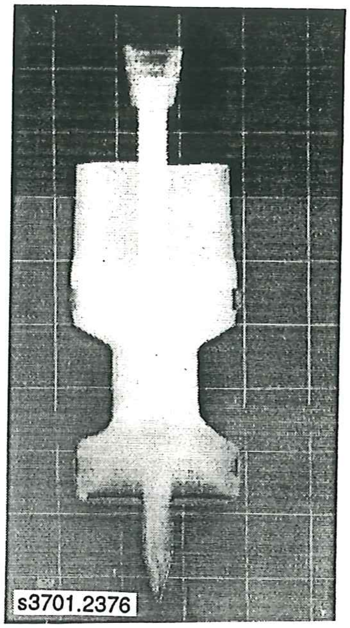

Fig. 7. X-ray taken half a meter from the muzzle on shot #45

Future tests may concentrate on increasing package energy, reducing package mass or testing a particular feature brought into question by contractor testing in the 90 mm SSG. There are also several questions still to be answered about the package design. These include the maximum projectile length and mass the package can carry and the peak action the armature can withstand. Working to answer those questions helps CEM-UT understand some of the issues that package designers have to face. The design process has also helped establish a set of safe base criteria and a package evolution that other package designs can follow in the future. Finally, it gives CEM-UT a package that a projectile designer can use to test a projectile in an EM gun without having to go through a complete armature and sabot development program.

Conclusion

The armature development program at CEM-UT has been very successful overall. In the past three years many firsts have been achieved in the 90-mm SSG. Packages designed under four different contracts and by four different design groups have been tested. Several tactical rounds have been fired and aluminum sabots were successfully launched for the first time. The C-shaped armature design has now evolved to the point that the armature and sabot can be integrated. Both the integrated armature/sabot design and the base push designs exist and are available to launch a variety of packages without further armature development.

Acknowledgments

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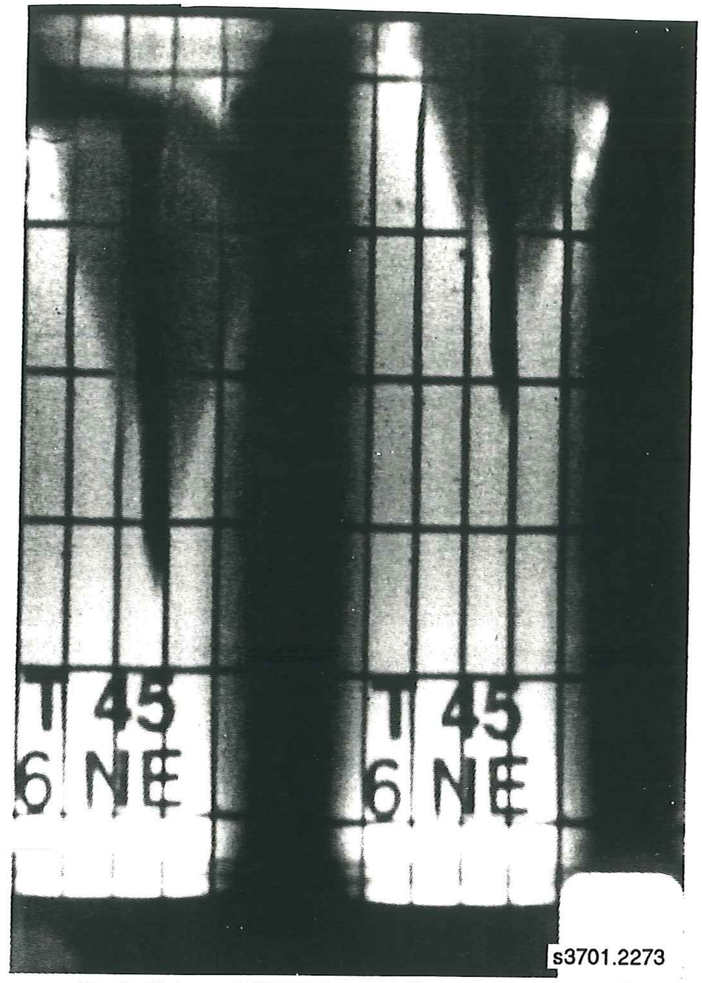

Fig. 8. High speed (20,000 frames/s) film taken on shot #45

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