TEST METHODS FOR SHORT-RANGE LETHALITY EVALUATION OF FULL-SCALE HYPERSONIC KINETIC-ENERGY MISSILES

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ABSTRACT

Lethality evaluation tests of anti-armor missile systems require flight-test of tactical missiles against threat targets under highly controlled impact conditions. Variables such as terminal dive angle, impact velocity, missile orientation at impact, hit-point on the target, and shot-line through the target all must be carefully controlled and documented to properly evaluate and analyze the damage caused and extrapolate this data to other impact conditions. Development missile systems have difficulty achieving control of the impact conditions at early stages in the program due to immature or nonexistent missile guidance technologies and hardware.

Lethality data is traditionally generated through a combination of subsystem testing and predictive analysis. This approach has proven acceptable for traditional anti-armor missile systems, but fails to capture the damage mechanisms or damage levels produced by hypervelocity kinetic energy missiles. The high velocity requirements of kinetic-energy missiles prevent the use of test facilities and test methods traditionally utilized in the development of anti-armor missiles and analytical tools do not fully capture target damage effects, therefore combining subsystem test data with predictive analyses is not an option.

Kinetic energy missiles require significant range to achieve full velocity where efficient penetration is achieved. However, these missiles will be tactically utilized in engagements at much shorter ranges. The missile will be accelerating at impact in these short-range scenarios, therefore the rocket motor is thrusting and contains unburned propellant, the quantity decreasing as engagement range increases. This ever-changing missile configuration adds to the difficulty in conducting short-range impact tests since each engagement range requires a different missile configuration to properly represent tactical conditions. This paper will present and discuss two methods of conducting impact tests and generating lethality data for development of kinetic energy missile systems for a variety of missile mass properties, targets, and impact velocities.

The first method to be discussed utilizes a high-speed sled track. This method employs large rocket motors to accelerate a multi-stage sled-train to the desired velocity. The missile simulant is separated from the sled-track and flies a short distance to the target while the other sled hardware is diverted below the target to prevent additional target damage. This method requires conducting flyout tests to determine the flight dynamics of each different velocity or missile configuration. This method has been proven to yield hit-point accuracies tighter than has been demonstrated with tactical guided missiles and can be tailored to accommodate large or small missiles.

The second method to be discussed involves utilizing high-tension ropes to guide the missile to the desired hit-point. This method has recently been developed at Redstone Arsenal, AL and provides a cost-effective alternative that can be adapted to a wide variety of engagement ranges and impact angles with minimal hardware alteration. This method employs multiple high-strength high-tension ropes stretched between a tower at the launch point and the target. The missile simulant "rides" the ropes, propelled by a rocket motor, to impact at the desired hit-point on the target. Velocity and unburned propellant at impact are controlled by flight distance. The ropes are terminated either on the surface of the target (armor targets) or extend through the face of the target (wall targets) to control both the hit-point and impact orientation with respect to the target. The trajectory is tightly controlled by the tension in the ropes, which also allows for more accurate in-flight data collection. The missile size that can be tested with this method is currently limited to smaller (less than 100 pounds at launch) systems, but future development may address this scenario if need justifies.

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1. INTRODUCTION

The advent of the Army's vision for a lightweight, rapidly deployable Objective Force has elevated the importance of parameters such as size and weight of weapon systems supporting this future force. Over the past two decades, the U.S. Army Research, Development, and Engineering Command (RDECOM), Aviation and Missile Research, Development, and Engineering Center (AMRDEC) at Redstone Arsenal, AL has been developing advanced kinetic-energy missile concepts and supporting technologies to defeat current and future armored threats as well as other high-value targets. The objective of these efforts has been to demonstrate advances in close-combat hypervelocity missile technology over current and near-term line-of-sight weapons systems with specific interest in miniaturization of components and a reduction in overall missile system size and weight without sacrificing lethality. This requirement also applies to targets engaged in short-range urban scenarios as well as targets engaged in long-range open battlefield scenarios.

Developing this new generation of kinetic energy missiles requires extensive impact lethality testing to evaluate the effectiveness of various concepts. Analytical methods currently do not capture the target damage mechanisms of high-energy impacts, implying that system design trades and accurate damage predictions can only be made based on empirical data. This data is required early in the design process, before the physical layout of the missile is firmly established and open to optimization. This paper outlines two different test methods that have been developed to accurately document the lethal capabilities of a full-scale hypervelocity kinetic-energy missile prior to conducting guided flight tests and highlights advantages, disadvantages, and limitations of each.

2. BACKGROUND

Traditional kinetic-energy penetrators are utilized in armor-piercing fin-stabilized discarding-sabot (APFSDS) tank-fired ammunition. These projectiles are developed and tested in their operational environment – fired from a large-caliber cannon. Kinetic-energy missiles present a challenge to the developer in that the lethal mechanism cannot be tested in its operational environment early in the program. This presents significant challenges to the developer because the penetrator must be designed to survive the extreme (40,000+ g's) cannon-launch environment and must be evaluated as a bare rod, but function tactically in a missile airframe. Experience has proven the lethal mechanism integration into the missile airframe to be a very critical factor in penetration performance.

Bare rod kinetic-energy penetrators deliver 10 megajoules (Mj) or less impact energy to the target and interact with the target plates undisturbed by other components. Long-rod penetrators housed inside a missile airframe deliver up to 40 Mj impact energy to the target, but the penetration process can be disturbed by ancillary missile components such as guidance components and mounting hardware. Long-rod penetrators for missile applications must be designed and integrated into the airframe from an overall system approach, and this integration must be evaluated early in the design process to insure system layout is correct before its too late to incorporate changes. Conducting sub-scale cannon-launched tests of missile simulants is difficult and not realistic because the simulants have to be designed to survive the high-g launch environment and no longer represent the internal missile component configuration. To accurately replicate the impact/penetration event and assess the damage to a target, full-scale tests must be conducted against full-scale targets. Early in the missile development process, missile guidance is not capable of producing high hit-point accuracy, so true flight-tests are not an option. The guidance must come from an outside source. The propulsion can be provided wither by the tactical motor or from an outside source. The major requirement on the missile or missile simulant is that the airframe and all internal components be accurately represented (material, size, weight, location, mounting scheme, etc…) to insure their interactions during the impact event are properly evaluated.

Currently, two methods of conducting these tests are available – sled and rope testing. The sled-test method utilizes external propulsion sources to accelerate the missile simulant to the proper velocity, releases the missile simulant to free fly a short distance to the target, and diverts the propulsion units away from the target. The rope-guided method utilizes near-tactical propulsion to accelerate the missile simulant down high-tension ropes to impact. Both methods provide the required hit-point accuracy and impact attitude (pitch and yaw) control.

2.1. High-Speed Sled Tests

The sled-test method has been in use for many years at many locations. This method has applications that range from very low-speed subsonic to hypervelocities in excess of Mach 8. Test objectives vary from conducting acceleration tests, high-speed captive tests, and impact tests. The missile impact tests can be conducted in two different manners: 1) The entire sled-train impacts the target, which is commonly used in shaped-charge warhead missile applications where the sled mass represents the actual missile mass. 2) The missile is separated from the sled-train and only the missile impacts the target. This method is used in high-speed, supersonic applications where the sled mass required to achieve the impact velocities exceeds the tactical missile mass.

The High-Speed Test-Track facility located at Holloman Air Force Base (HAFB), NM has conducted several test programs in support of AMRDEC hypervelocity missile development. This facility consists of a 50,787 ft (15, 480 m) long straight track consisting of two parallel, 57 lb/ft (85 Kg/m), crane rails with a 7 ft (213.4 cm) gauge. Additionally, there is a third parallel rail with a 2.2 ft (66.8 cm) gauge in the last 1,877 ft (6,157 m) of the facility. All rails are continuously welded and prestressed to remain under tension at temperatures below 125° F (52° Celsius). The final 195 feet or track is a decreasing radius downward spiral used to divert the motors and other non-missile hardware on a lower trajectory after leaving the end of the rail. This prevents unwanted sled hardware from impacting the targets.

A kinetic-energy missile impact test program conducted at HAFB in 2004 in support of AMRDEC was specifically designed to evaluate the damage effects of a 6 ft long, 6.5 in diameter, 100 lb launch mass KE missile impacting targets at very short ranges. In a tactical situation, the rocket motor contains approximately 50 percent of the original propellant and the missile has not accelerated to a velocity sufficient to produce hydrodynamic penetration. This scenario produced a unique set of challenges for test method development. The missile simulant was designed to closely replicate the tactical airframe, but required machine work on the final assembly before mounting to the sled. This machining process could not be performed on a missile with a loaded motor, so an alternate approach was developed. The motor needed to be half full at impact, but releasing a thrusting missile from the sled would decrease the hit-point accuracy of the test method. These are a few of the challenges faced in developing this specific test method.

The missile simulant was designed to replicate a tactical configuration with respect to components locations, materials, mass, and mounting stiffness. The propellant was loaded into a sealed canister and shipped separately for safety reasons. The canister was installed into the missile after all machine and prep work was performed on the sled, again for safety reasons. A flare was used on the simulant to replace the fins on the tactical missile. This was done to prevent any trajectory errors resulting from fin misalignments and to increase the static margin.

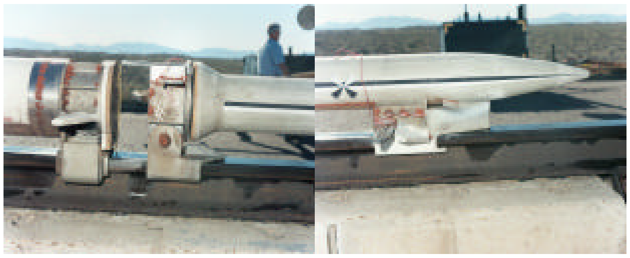

Figure 1. Aft mounting (left) and forward slipper (right)

The missile simulant is mounted to the sled track through a forward slipper and an aft pusher-plate/hinged slipper assembly as shown in Figure 1. The missile is connected to each slipper with explosive bolts, two vertical in the front and one horizontal in the rear. These bolts are fired by trackside screenboxes as the sled train enters the pulldown section of rail. In high-speed tests, aerodynamic lift causes the initial missile separation. Conplete separation is achieved by the missile continuing on a straight, horizontal flight path while the slippers travel down the pulldown.

The propulsion used to accelerate this sled train consisted of two MLRS motors, knows as Pupfish motors by the Air Force. The first stage was ignited by a static firing line and the second stage was ignited through trackside screenboxes. Figure 2 depicts the sled train prior to launch.

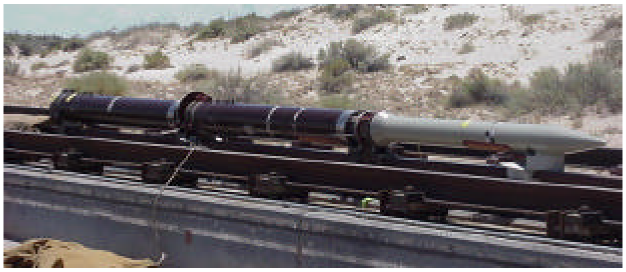

Figure 2. Low-Velocity sled train

The first low-velocity impact test was conducted in April 2004. The missile was released at the entrance to the pulldown and pretest analysis predicted the missile would cleanly separate from the slippers. After release, the missile quickly pitched upward and never fully recovered. This same test had been conducted at velocities in the Mach 5-6 region with complete success.

A comprehensive analysis was begun to calculate the aerodynamic forces and vibrational dynamics of the release and flyout events. In supersonic flight of missiles, a strong bow shock is produced off the tip of the missile. As velocities increase, the angle between the missile body and the shock wave decreases. This effort revealed that shock waves were reflecting off the forward slipper and interacting with the missile ahead of the center of gravity, which pushed the nose of the missile upward. This had not been a problem in the high-speed tests due to the much higher lift force separating the missile quickly and the more swept-back angle of the shock waves. Since the lift forces are reduced at lower velocities, the missile and slipper separation is a slower process. The increased shock angle also causes more shock impingement on the slipper, increasing the magnitude of the reflected shock. This gives the reflected shock more time to push on the nose. The missile was aerodynamically stable, but the flight time was not sufficient to correct the large pitch angle.

The second test incorporated changes to alleviate the problems in Test 1. The release point was moved 160 feet into the pulldown to take advantage of the downward orientation of the velocity vector at release. Analysis had shown that the vertical component of the velocity vector would counteract the forces from the reflected shock, producing an acceptable flight profile. This solution reduced the maximum pitch angle by nearly 20 percent, but did not provide an acceptable solution.

Figure 3. Shockwaves 5 ft after release

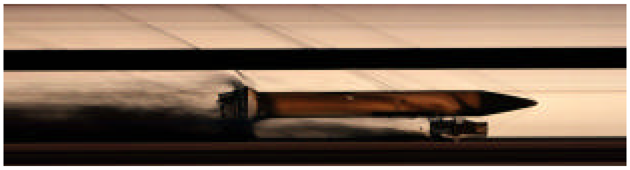

Figure 4. Shockwaves 50 ft after release

Figure 5. Shockwaves 100 ft after release

Three Focus Schlieren cameras were added to the second test to document the shock-wave interactions during missile release. Figure 3 shows the shockwave configuration immediately after the explosive bolts were fired. Figure 4 shows the configuration after the missile has traveled 50 ft. The leading shockwave is impinging on the lower portion of the slipper, but not being reflected back on to the missile nose. Figure 5 shows the configuration after another 50 ft of travel. The leading shockwave is reflecting off the slipper as predicted, but the shockwaves from the slipper are also impacting the missile body. These shocks had not been a problem in the high-speed tests and had not been accounted for in the previous analysis. Following this discovery, a complete computational fluid dynamics (CFD) analysis and a dynamic analysis simulation were conducted to fully simulate the release event. The results of the previous tests were replicated in the analysis, and various solutions were explored. The outcome was that no means of reducing the effects of the shock off the slipper with the current missile design existed. The only solution, without redesigning the test hardware, was to release the missile in a helium atmosphere to prevent formation of a bow shock off the slipper. Helium was chosen due to the reduced density and resultant increased sound speed. The sled train would be traveling slightly below Mach 1 in helium.

The third test employed a helium bag beginning 160 ft before the pulldown and extended the entire 180 ft length of the pulldown. Figure 6 shows the “greenhouse” constructed over the pulldown to contain the helium atmosphere. The release point was moved back to the beginning of the pulldown to give the missile a horizontal velocity vector at release. Figures 7, 8, and 9 show the success of these modifications. The shockwaves were not present in the helium and the missile released and separated without excessive pitch. The missile exited the helium with less than 5^{o} pitch, which was damped out by free-stream aero stability to less than 1^{o} at target impact.

Figure 6. Helium bag over pulldown

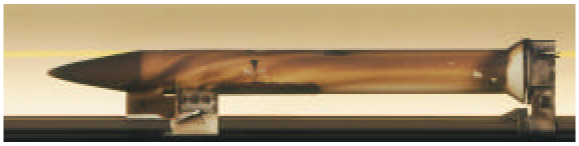

Figure 7. Missile in helium at release

Figure 8. Missile in helium 50 ft after release

Figure 9. Missile immediately after exiting helium

The benefits of sled testing include the capability to test a wide variety of missile configurations at velocities up to Mach 8 in free-stream air. The ability to tailor thrust by using various rocket motors and altering staging yields a limitless set of options. When the release scheme functions as planned, very precise hit-point accuracy can be achieved. The long acceleration profile produces a relatively benign launch environment, even when compared to flight-testing. The openness of the impact area easily accommodates constructing or placing almost any target of interest ranging from urban structures to combat vehicles.

The limitations of sled testing are very few, with cost being the primary factor. This test method, however, is relatively inexpensive in comparison to conducting guided missile flight tests. Other considerations of paramount importance include thermal effects, aerodynamics, sled vibration, and sled/target interaction. Because of the long acceleration profile, the soak time at velocity is high, yielding greater heat transferred to the missile skin and internal components. Thermal protective or ablative coatings must be applied for sled testing that are not required for flight. Sled vibration is something that must be considered because it contains vertical and horizontal (cross-track) components that are not present in missile flights. The magnitude of these forces is very well documented, but they still must be considered in when designing the missile. Sled hardware interacting with the target can be an issue, depending on the specifics of the test. Again, this is something that must be taken into consideration when developing the test layout.

2.2. Rocket-on-a-Rope

The Supersonic Rocket-on-a-Rope (SROAR) test method was developed as a low-cost and high-fidelity alternative to sled testing. This method utilizes high-tensioned ropes to deliver a payload directly to a desired target, at which point the ropes are terminated. The test missile flies on the ropes to a precise hit-point controlled by the location of the rope anchors. Trajectory, angle of attack, velocity, and impact obliquity can all be controlled by rope length, rope tension and target placement.

The basic concept of SROAR is not original in that several test facilities have used this technology for conducting controlled flights of several payloads. These facilities include Sandia National Laboratories dating back to the 1970's [3,4,6], White Sands Missile Range [7], and the Rocketball, Model-On-a-Wire (MOW) Facility [5] located at Redstone Arsenal, AL. All these facilities implement a single cable pulled to a desired tension and use rocket motors and/or gravity to accelerate the payload to velocity for data collection including target radar cross-section, sensor development, and aircraft target representation. All three facilities document peak velocities less than 300 m/s that are in the subsonic regime.

SROAR is the first method to use this technology to attempt velocities greater than Mach 1 or supersonic speeds. The basis of SROAR was a follow-on to Rocketball, a subsonic test facility at Redstone Arsenal used in radar and interceptor testing for active protective system development and evaluation. Due to such influence, original SROAR tests used a 7/32" diameter stainless steel strand as the guidance cable with a rated break strength of 6800 lbs and a linear density of 0.11 lb/ft. Early tests were performed to determine the ability to pull multiple cables to tension so that their shape closely matched one another along the length of the cable. The cable shape follows the well-known catenary equation developed by Galileo of the following form,

$$y = A\cosh\left(\frac{x+B}{A}\right) + K \tag{1}$$

$$A = \frac{T}{rg} \tag{2}$$

where y is the vertical displacement of the cable, x is the horizontal distance along the cable, A is the radius of curvature given by equation 2, T is the cable tension, r is the linear density per unit length, g is the acceleration due to gravity, and B and K are constants dependent on the endpoints of the cable. Electric winches and 0.1 percent accurate tension meters were purchased to closely match the tension in each line. Tests proved that the tensions could be maintained within a 10-20 lb window so that both cables mirrored one another down the entire length.

A major obstacle in reaching supersonic velocities along the cable was accelerating through a constant known as the cable wave speed or the wave propagation velocity defined as,

$$c \equiv \sqrt{\frac{T}{r}} \tag{3}$$

where T is the tension and r is the linear density per unit length. A 1976 paper by Rodeman, Longcope, and Shampine [6] describes a test conducted at the Sandia Facility in which a "sudden and dramatic failure occurred as the carriage was accelerated beyond the wave speed of the cable" at a velocity of 1.04*c*. Their analysis shows a singular cable response forms as a traveling mass is accelerated through the cable wave speed. At such time, two oppositely traveling jumps in displacement are formed and were validated in the test documentation through high-speed cameras. At a safe working tension of 4000 lbs on the 7/32" diameter steel strand to be used, the wave speed is 1082 ft/s—below Mach 1 and well below even the short-range engagement velocities of KE missile systems. In order to reach velocities in the Mach 1-3 velocity range on the steel cable, surpassing the cable wave speed would be unavoidable.

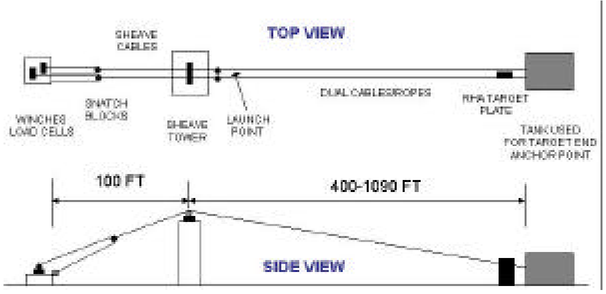

Figure 10. SROAR test setup

The first SROAR flight test was conducted in February 2003 at the Redstone Technical Test Center (RTTC) Test Area 1. The objective of the test was to guide a test article along a dual 7/32" diameter steel cable system and reach a peak velocity just above the cable wave speed. The 410 ft cables were pulled to 2250 lbs of tension resulting in a cable wave speed of c = 812 ft/s. The test article used a TOW Launch Motor for propulsion and had a launch mass of 11.8 lbs. The test setup is shown in Figure 10.

The test model flew down the entire length of the cables, reached a peak velocity 830 ft/s and impacted the steel target plate at 795 ft/s. Doppler radar data confirmed the test model just exceeded the cable wave speed, 1.02c, for a short duration.

Test 1 gave optimism that the cable wave speed could be surpassed without failure as documented in the Sandia test. Test 2 was conducted to sustain velocities well in excess of the wave speed and Mach 1 with a larger payload. The test article used a 2.75-inch rocket motor and had a launch mass of 21 lbs. The model is shown in Figure 11. The 600-ft dual cables were tensioned to approximately 3700 lbs resulting in a wave speed, c, of 1040 ft/s. The predicted velocity of the model at impact was 1895 ft/s, which would surpass the wave speed at a distance between 195 and 200 feet after launch. High-speed videos were positioned to cover the events of the model accelerating past c and Mach 1.

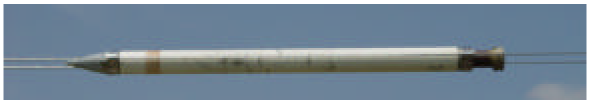

Figure 11. Test 2 model mounted on dual cables

Test 2 was conducted on 28 April 2003 at RTTC Test Area 1. The test model impacted the ground at approximately 400 ft downrange, broke apart and impacted the target location. From both high-speed video and post-test inspection of the cable, it was determined that both cables broke at the same time between 210 and 215 ft downrange of launch. The radar velocity at 210 ft was 1120 ft/s or 1.08c. High-speed video did not show any noticeable cable deformation at the time of failure.

Three tests were conducted in summer 2003 to develop a solution so that the steel cable would not fail when the wave speed was surpassed. Solutions included using a canted motor to counteract the transverse forces on the cable and changing the material in contact with the steel cable from hardened steel to a soft brass. All tests broke between 210 and 220 ft from launch at velocities ranging from 1.01c to 1.08c. The similar, if not exact results from all four tests pointed convincingly to the cable failure being solely due to the acceleration past the wave speed of the cable.

In order to reach supersonic velocities on the cable, the only viable option was to greatly increase the wave speed of the test cable. From equation 3, the only ways to accomplish this is to either substantially increase the tension of the cable, and/or substantially decrease the linear density. No steel cable on the market possesses a T / r ratio high enough to provide a wave speed in the desired Mach 2-3 velocity range.

A related disadvantage of the steel cable is the low radius of curvature, $T / r g$. The lower the radius of curvature, the greater the cable sag and larger the centripetal forces between the accelerating model and the cable. The sag in the cable prohibits the test model from flying a straight path to the target.

After researching alternative materials, the decision was made to purchase ¼-inch diameter Plasma 12-Strand rope made by Erin Rope Corp. with a rated break strength of 8000 lbs and a linear weight of only 0.016 lb/ft. The rope provided an increase of 1200 lbs in ultimate break strength and an 85 percent reduction in the linear density compared to that of the steel cable. At 5000 lbs of tension the wave speed of the 7/32" diameter steel cable is 1210 ft/s whereas the wave speed of the rope is 3170 ft/s (Mach 2.8). In addition, the radius of curvature increases from 45,450 ft to 312,500 ft for the steel cable and rope respectively.

One disadvantage of the rope compared to the steel cable is its resistance to wear and heat. Static tests were conducted to develop a heat shield for the rope directly behind the motor nozzle to prevent the motor plume from melting and/or eroding the rope. A two-part shield was developed that included a titanium tube and silicon-coated fiberglass sleeving that connected to the aft wire rider bracket and covered the rope throughout the flight.

After a heat shield was developed for the rope, the first true Rocket-on-a-Rope test was conducted in March 2003. Dual 400-ft long ¼-inch Plasma 12-strand ropes were tensioned to 3500 lbs resulting in a wave speed of 2650 ft/s. The test article used the 2.75-in rocket motor for propulsion and had a 22.5-lb launch mass with the addition of the heat shield. Figure 12 shows the test model just before launch mounted on the dual ropes.

Figure 12. Test model on dual-rope system

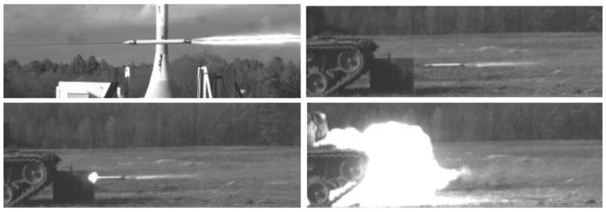

Figure 13. SROAR high-speed video still images

The test was conducted at RTTC Test Area 1 and was a success. The test article flew the entire length down the dual rope system without any rope failure. Radar data recorded a peak velocity of 1393 ft/s (Mach 1.23) just prior to impacting a steel target plate. Figure 13 shows four still images from the high-speed video coverage. The upper left image is shortly after motor ignition. The remaining three images are the test model just prior and after impact with the steel target plate at Mach 1.23.

Two tests followed the first successful SROAR test of reaching supersonic velocities. The tests again used the dual-rope system and the 2.75-in rocket motor for propulsion. The rope length was increased so that the burn time of the motor would be increased for reaching higher velocities.

The tests were conducted on 13 July 2004 at RTTC Test Area 1 and were both successes. The first test flew 610 feet and reached a peak velocity at impact of 1896 ft/s (Mach 1.68). The second test flew a length of 950 feet and reached a peak velocity at impact of 2313 ft/s (Mach 2.05). These tests further proved the SROAR test method by surpassing Mach 2.

As of September 2004, equipment has been purchased to build a facility for conducting future SROAR tests. The tests conducted to date have been 20-25 lb launch mass missiles. Future tests are planned to both increase the mass and velocity of the test missile to collect lethality data of a 100-lb KE missile at velocities in the Mach 1.5-Mach 3.0 regime. In addition, the SROAR test method is being used for future lethality tests of other non-KE missile systems.

The benefits of SROAR are wide-ranging and include precise target hit point accuracy, controllable angle-of-attack, accurate velocity profile, and a high-fidelity test missile due to minimal additional flight hardware for rope attachment. In addition, the rocket motor used for propulsion can be the tactical configuration as opposed to utilizing additional motors as in sled testing. Sled testing requires these additional motors to compensate for the heavy slipper attachment hardware to the rail whereas the rope attachment hardware can be less than five percent of the total launch mass. Additional benefits include a drastic reduction in cost compared to other test methods and a test facility that can be moved to different ranges with relative ease.

The limitations of SROAR are not yet fully understood or tested due to the relative newness of the method. The wave speed proved to be a limiting velocity in the case of using steel cables. If the wave speed is a limiting velocity with the rope as well, the maximum test velocity will be in the 3200-3600 ft/s (Mach 2.8-3.2) velocity range depending on a maximum safe working tension in the 5000-6000 lb range for the ¼-in diameter Plasma rope. Additional capabilities exist with respect to test item weight and velocity by utilizing different rope diameters, an area currently being investigated. Although it is yet to be determined, SROAR will most likely not be able to test at velocities in the Mach 4-8 range that the high-speed sled tracks have demonstrated. However, even with an upper bound on velocity, SROAR can be a low-cost alternative to testing KE missile systems at short-range engagement scenarios in the Mach 1-3 range.

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CONCLUSION

Impact testing will continue to be a vital part of kinetic energy missile development programs, both as a means of analytical verification and proof-of-concept. The test methods presented above offer two viable options for conducting highly controlled impact testing against a variety of targets. Both methods have strengths and weaknesses, and provide a complementary set of options for achieving the desired data set.