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Physics of Kinetic Energy Rod Warheads Against TBM Submunition Payloads

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PHYSICS OF KINETIC ENERGY ROD WARHEADS AGAINST TBM SUBMUNITION PAYLOADS

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ABSTRACT

New warhead technologies have been designed and developed to obtain high lethality against chemical and biological ballistic missile payloads. These new kinetic energy (KE) rod warheads slowly deploy high density metal penetrators in the target's direction. A high spray density cloud is generated which flood loads the payload inflicting catastrophic damage. These new warhead devices deploy 16 times more mass in the target direction compared to today's blast fragmentation concepts. The idea is to deploy a curtain of rods at low ejection velocities and let the missile and target closing velocities supply the kinetic energy.

Testing combined with analytical endgame analysis has shown that a dense spray pattern can obtain high lethality against thick walled submunitions. Parametric lethality trades show rods with small mass are a better choice compared to fewer larger projectiles. Given, a fixed warhead weight, it is better to have many small rods rather than a few large ones.

A new penetration code, which accounts for flood loading, is currently being developed to better model multiple rod impacts. Current endgame shotline codes raytrace each rod through the target, not distinguishing between the first, second or last impacts. A new model is developed which accounts for the first rod penetration compared to the last. This technique takes away target pieces along the penetrated shotline. These pieces are removed and if rods strike near the shotline, they penetrate with the benefit from the first rod.

KE-rod warheads are extremely lethal against TBM submunition payloads and are viable warhead candidates of future anti-ballistic missile systems.

1. INTRODUCTION TO ADVANCED WARHEAD CONCEPT

In today's theater missile defense environment there exists advanced Tactical Ballistic Missile (TBM) payloads that cannot be destroyed by advanced fragmentation warheads. Side spray, deformable or any other blast warhead only impacts one quarter of a target, while thick internal submunition components shield neighboring submunitions from fragment penetration.

There is a need for a new warhead mechanism that can achieve hard kills against cluster chemical targets but still maintain high lethality against cruise and aircraft threats. A hard kill is achieved when a submunition is perforated. However, a kill is also scored when its fuse is perforated or disabled. There is a strong desire to prevent any chemicals from reaching the ground given a TBM encounter. If live submunitions reach the ground then localized hot spots form with lethal doses of chemical. This is illustrated in Figure 1. Today's warheads must possess the ability to kill all submunitions reducing all lethal effects on the ground.

A KE-Rod warhead containing multiple bays of tungsten rods has been designed and analyzed as a candidate to achieve hard kills against cluster chemical threats. Raytheon has extensively studied and modeled these warheads since the early 1990s. It has been found through testing and analytical analysis that enhanced lethality is achieved with these warheads. Direct hit technology has also been studied in conjunction with KE-Rod warheads. Our findings show when a direct hit missile moves off the optimum aimpoint, there is a significant decrease in lethality.

This paper discusses and provides an overview of KE-Rod warhead technology. The lethality from this warhead is modeled with hydrocode and endgame simulations at a 3 ft miss. Obviously, penetration equations are an integral part of this analysis since lethality is solely based on rod penetration. A code named FATEPEN2R was developed by Applied

Research Associates (ARA) and inserted into RAYSCAN. RAYSCAN is a Raytheon version of a Navy endgame called SCAN originally developed at Pacific Missile Test Center (PMTC). A new rod penetration model call KARPPEN was developed and benchmarked to test data. These equations compute rod penetration with yaw and are based on Wollmann's equation at ISL in Germany. KARPPEN penetration equations are coded into RAYSCAN and compared to the FATEPEN2R model.

2. DIRECT HIT MODELING

Direct hit missiles are currently recognized as the only accepted way of killing all payload chemical submunitions. Many full, half and one-quarter scale tests have been performed demonstrating that the large kinetic energies imparted on these payload sweet spots do kill all submunitions. However, testing has shown that when a missile moves slightly off this sweet spot, lethality drops sharply. This is because the missile has a fixed diameter and is unable to generate enough radial energy to kill leeward side submunitions. Raytheon has extensively studied direct hit tests using SPHINX hydrocode and PEELS. Our verification studies clearly show that high lethality is achieved when hitting the sweet spot while low lethality occurs with nonoptimum hits. See Figure 2.

A direct hit missile only has centimeters of miss before lethality begins to decrease. The entire missile system must be considered where potential errors exist that may increase overall miss distance. One source of error is the radar system which can increase miss accuracy of the missile. There also exists errors from the interceptor missile where guidance, response time, divert capability and aimpoint determination are critical estimates that must be predicted accurately. Another major source of error that is undetectable is threat packaging uncertainties. This feature is of extreme importance because the payload internal characteristics drive miss distance and warhead design requirements. Each payload has its own unique payload location where maximum lethality is achieved. Direct hit lethality impact areas about these points are unique where slight misses generate reduced lethality. Our system does not possess knowledge of payload location, so a default distance is selected. This selected distance must contain an overlap area where direct hit lethality is high for all threats. This is illustrated in Figure 3.

3. KE-ROD DESCRIPTION

KE-Rod warheads are designed with 70-80 percent of the charge (C) plus mass (M) weight as metal penetrators. Blast fragmentation warheads, however, are typically designed with 50 percent explosive charge and 50 percent metal mass. Of the 50 percent metal mass only 10 to 15 percent is directed toward the target as illustrated in Figure 4. Current fragmenting warhead technology designs use a C/M ratio near 1.0 in order to achieve high launch velocity. These warheads only utilize a small percentage of the available metal in killing target payloads.

Since KE-Rod warheads are designed with small C/M ratios, they deploy all of their rods in the target direction. The idea is to launch a curtain of rods at low ejection velocities and let the missile and target closing velocities supply the total kinetic energy. This warhead concept design relaxes the fuzing accuracy requirements in computing the optimal burst point as compared to blast fragmentation warheads. A description of the KE-Rod warhead is illustrated in Figure 5.

Hydrocode studies in conjunction with testing has determined rod deployment velocity and ejection angles. These codes are a valuable tools in assessing rod warhead concepts and designs. When the aimed mode is fired, all the rods are directed towards the target. Typically, ejection angles vary between 25 and 75 deg. These deployment angles are achieved by selecting and detonating explosive packs which correspond to a desired ejection angle. If miss-distance is large, then a tight high density beam of rods could be deployed. However, if a small miss-distance is achieved, then a pattern of rods is deployed which spreads open quickly in order to cover the entire payload. The rod warhead design is parametrically analyzed showing rod core weight as a function of rod spacing and miss distance. This is shown in Figure 6. As a function of rod mass the spray density is plotted on the payload showing these warheads create many closely spaced shotlines. These tightly spaced shotlines create a flood loading phenomena which creates a large impulsive force on the entire target.

4. CURRENT TECHNOLOGY VERSUS KE-ROD WARHEADS

Today's missiles contain sophisticated guidance laws that enable them to guide and achieve direct hits.

This technology utilizes the entire missile mass with the relative velocity to kill all the TBM submunitions. The idea of developing a missile to achieve a direct hit is extremely lethal generating thousands of mega joules of energy. The KE-Rod warhead combined with a direct hit missile increases the volume of lethal material impacting the payload. This increased volume allows a missile to miss the sweet spot and still achieve high lethality. This is illustrated in Figure 7 where a missile impacted aft of the optimum aimpoint. The direct hit missile kills all the aft tier submunitions while the high density rods kill the first tiers. This combined weapon effect is highly lethal making it desirable to system engineers. This concept from an overall lethality perspective is illustrated in Figure 8. As the missile moves off the optimum aimpoint the fixed diameter missile radial energy is not enough to damage all the submunitions. There is a need for a conventional warhead mechanism that possesses the capability to kill a submunition payload. The KE-Rod warhead utilizes most of its total weight as metal penetrators where all rods are deployed in the target direction. The idea is to generate a missile encounter volume that is larger than the target which would allow for high lethality. A direct hit missile must impact near the payload center in order to kill the payload while a KE-Rod warhead possesses the ability to kill a payload given a miss off the target. Obviously, the miss is a direct function of the warhead weight. The larger the warhead weight the more rods deployed in the target direction. This high lethality is only achieved because all the warhead rods are deployed in the target's direction. Also, this warhead's small C/M ratio allows for more warhead weight to be designed as metal penetrators.

Current blast fragmentation or deformable warhead technology of today are not capable of perforating many of the chemical submunitions. These warheads utilize less than half the total warhead weight as fragments. Only 10 to 20 percent of the case weight is accelerated in the targets direction. This is illustrated in Figure 9 where the missile has missed the target by 3 ft. Today's warheads are designed with C/M ratios near 1.0 in order to obtain a high fragment velocity near the closing velocity. This ensures low obliquity angles for small high velocity fragments. The KE-Rod warhead has a small C/M with low deployment velocity. The idea is to create a high density cloud of rods and let the relative velocity create the kinetic energy. This concept allows a designer to use high density penetrators. These rods are designed with higher mass compared to standard blast warheads because they attack the TBM with strike angles ranging from 5 to 25 deg while blast fragmentation obliquities vary from 30 to 60 deg.

The main feature of the rod warhead is that it deploys 8 times more mass in the target direction compared to the deformable warhead. Also, This warhead deploys 31 times more mass in the target direction compared to the isotropic blast fragmentation and 16 times more mass than the velocity enhanced warhead.

5. ENDGAME SIMULATION OVERVIEW

Lethality predictions were performed with an 3-dimentional endgame simulation named RAYSCAN. This simulation is a Raytheon version of SCAN which was developed by the Navy at the Pacific Missile Test Center at Point Mugu, CA. RAYSCAN was modified to design and assess warheads against Ballistic Missiles. The code has been upgraded to address lethality of KE-Rod warheads. Below is a list of several major features of the simulation:

- Detailed warhead description (angle, velocity, projectile shape, number...)
- Penetration equations (FATEPEN2, TATE, KARPPEN)
- Detailed target model with 12 material selections
- Vulnerability Models
  - Total energy
  - Normal energy
  - Area removal
  - Explosive initialization (Jacobs-Rousland)
  - $P_K = C_1 + C_2M + C_3V$: C_1, C_2, C_3 = Constants
  - Table Lookup (Velocity / Mass / Obliquity)
  - COVART Data
- Parametric Trajectory or 6DOF Interface
- TDD or GIF Fuzing
- Blast Effects
- Graphical Display

A designer has the versatility to generate target models using actual component materials. These target materials are contained and predicted in the penetration equations. The FATEPEN2R penetration equations are incorporated in the endgame code where spheres, rods or parallelepipeds are potential projectile shapes. These equations compute tungsten fragment and rod penetration up to an L/D equaling 5.0. A new tungsten rod penetration model was developed by R. Karpp at Raytheon, which is based on yawed rod penetration equations by Wollmann (Germany) and Grabarek (U.S.A.). These residual mass and velocity equations are based solely on test data. A computer model was generated and inserted into RAYSCAN. These equations allow a designer to select different penetration equations as a function of application with L/Ds up to 35. A RAYSCAN target model of the generic TBM used for this paper is shown in Figure 10. Also, a yawed rod penetrator is shown defining all impact parameters.

6. LETHALITY MODELING METHODOLOGY

There is a need for a fast running simulation to model the effects of many rods impacting a target at one time. A rod flood loading damage model against submunition payloads is currently being developed. Currently, hydrocode technology gives the best insight to submunition damage when many rods impact a payload at the same time. The SPHINX hydrocode has been used to model these impact scenarios with good agreement to test data. SPHINX is a Smooth Particle Hydrocode (SPH) simulation developed at Los Alamos National Laboratory. Raytheon uses this simulation to analyze damage effects of many rods impacting target TBMs. However, there is significant difficulties in running such a large problem as with any hydrocode. It is difficult to generate the target and rods with enough particles or cell resolution to predict rod penetration accurately. We have had good success in running and matching test data using 350,000 particles. However, this resolution only resolves one particle across the submunition wall thickness with approximately 50 particles per rod. Also, it takes approximately 60 hours to run on a Dec 8400, 6 processor 300 MH computer. The hydrocode provides valuable insight on target damage with valuable visualization of submunition damage. It is extremely difficult to perform a warhead design trade study against any target because it requires hundreds or even thousands of SPH computer runs to optimize rod size, L/D, mass, material, velocity and spray density. A fast running engineering endgame simulation needs to be developed in order to model the damage effects seen using a hydrocode. A comparison between SPHINX and RAYSCAN warhead design simulation is shown in Figure 11.

Penetration Methodology

Yawed rod penetration equations and methodologies are critical in computing accurate lethality of rod warheads. Much work has been performed with normal impacts but yaw combined with high obliquity significantly complicates the calculation. Currently, Stephen Bless at the institute for Advanced Technology (IAT) and Jerry Yatteau at Applied Research Associates (ARA) are developing new yawed rod penetration methodologies. These studies combined with Wollmann and Grabarek were taken and generated into a new penetration yawed rod code named KARPPEN. The penetration formula from Wollmann is

$$\left(\frac{P}{L}\right)=\left(1.0-\frac{D}{L}\right)\mu\left(1.0-e^{-V/0.6}\right)^{8}+2.64\,\frac{D}{L}\left(\frac{V}{4}\right)^{2/3}$$

where $P_0 = L(P/L)$ and $P_1 = D(P/L)$. The total penetration is P while the rod length is L. The rod velocity is V while

$$\mu=\sqrt{\rho_P/\rho_T}$$

and the rod diameter is D. If D/L equals one then the left side of the equation equals zero. The penetration equation for a cube is now equal to right side of the equation. These equations are for tungsten projectiles penetrating steel plates only. The above equation is for normal impact while yaw impact methodologies are introduced by

$$P=\left(P_0-P_1\right)e^{-\alpha(\beta/\beta_{crit})^2}+P_1$$

where $\alpha = 0.2\ (L/D)^{-0.8}$. The critical yaw angle $\beta_{crit} = \sin^{-1}(H/D - 1.0/2\ (L/D))$ where β is the yaw angle of the rod at impact. The hole diameter H/D is

$$H/D=\left[Y_P/R_T+2\rho_p\left(V-U\right)^2/R_T\right]^{1/2}$$

where

$$U=\left[V-\mu\left(V^2+A\right)^{1/2}/\left(1-\mu^2\right)\right]$$

and

$$A=2\left(R_T-Y_P\right)\left(1-\mu^2\right)/\rho_T$$

The penetration rate is U while Y_P and R_T is the projectile and target strength.

The limit velocity of a yawed rod can be computed based on plate thickness. The plate thickness perforated with no yaw is $T_{po} = T_p/(P/P_0)$. T_p is the plate thickness perforated with yaw while P/P_0 has already been defined. The equation computing plate thickness with zero yaw can be modified to compute limit velocity for a yawed rod. Let,

$$T_{po} = T_p \left\{ \left(\left(P_0 - P_1\right) e^{-\alpha\left(\beta/\beta_{crit}\right)^2} + P_1 \right) P_0^{-1} \right\}^{-1}$$

where now

$$T_{po} = T_p \left\{ \left[\left(L\left(\frac{P}{L}\right) - D\left(\frac{P}{L}\right) \right) e^{-0.2(L/D)^{-0.8(\beta/\beta_{crit})^2}} + D\left(\frac{P}{L}\right) \right] \left(L\left(\frac{P}{L}\right) \right)^{-1} \right\}^{-1}$$

so now the limit velocity for a yawed rod is

$$V_L = \left[\frac{A(10.0\,D)^3 \left[\left\{ \left[L\left(\frac{P}{L}\right) - D\left(\frac{P}{L}\right) \right] e^{-0.2(L/D)^{-0.8(\beta/\beta_{crit})^2}} + D\left(\frac{P}{L}\right) \right\} \left(L\left(\frac{P}{L}\right) \right)^{-1} \right]^{-1} D^{-1}}{M_o} \right]^{1/2} (0.001)$$

where M_o is the initial rod mass and A is a constant.

New methodologies are being performed to investigate rod geometric integrity after plate perforation. These equations do not account for rod bending and fracture when yaw is introduced. Figure 12 is a test shot of a long L/D tungsten rod fired by Stephen Bless at IAT in Austin, TX. At obliquity with some yaw, there is significant bending and even fracturing of the rod. SPHINX hydrocode modeling demonstrated similar trends from actual test data. Short rods appear to be a much better choice against TMBs because they are significantly less sensitive to yaw.

The residual mass and velocity are based on the limit velocity in which is a function of the total penetration.

7. MULTIPLE IMPACT MODEL METHODOLOGY

Chemical submunitions are resistant to deep penetration from individual conventional blast fragmentation warhead fragments. One reason for this is due to the tight, dense packaging of these munitions. KE-Rod warheads offer missile designers a new warhead concept that can destroy many or all of the canisters. However, current endgame raytrace simulations predict lower overall performance when compared to lethality tests. Current endgame codes model rod penetration one rod at a time. This repetitious type of single impact analysis isolates each rod as an isolated event. If a rod warhead contained few rods, then this type of methodology would be correct. However, dense impact patterns containing hundreds of rods generate flood loading with momentum transfer effects that require additional modeling beyond the single rod impact raytrace model. This is illustrated with RAYSCAN in Figure 13. Three different flood loading damage enhancements could occur when many rods impact the payload from these kinetic energy rod warheads. These enhanced damage effects are modeled and are defined as follower rod model, momentum impact model and multiple impact model. Each model is specifically developed to account for extremely high density spray impacts by rod warheads.

Rod Follower Model

A penetration rod follower model was developed which requires modifying existing submunition geometry into thin shell elements. Consider a cloud of rods, the first penetrates a submunition along a shotline. This reduces target strength allowing a second rod to penetrate deeper into the target. Now, a second rod can take advantage of weakened submunitions along a given shotline.

A description of a single submunition from the RAYSCAN endgame code is shown in Figure 14. The steel shell is broken up into sixteen 45 deg arc shaped pieces. A thin parachute cap is located at the aft end while a fuse cap is inserted on the forward end. A solid liquid cylinder is inserted inside the submunition which represents chemical agent. A RAYSCAN picture is shown that illustrates the reduced submunition thickness along the shotline caused by a leading rod in the deployed cloud. Based on the rod warhead design and deployed cloud characteristics, the rods are separated into multiple waves. This penetration effect is compared to how a segmented rod penetrates versus a single continuous rod. These spaced rod impacts form a series of impacts which enhance overall penetration.

Momentum Impact Model

A momentum flood loading model is currently being developed in conjunction with the penetration degradation model. This model accounts for when the wave is highly dense and all the rods impact the payload at the same time. The RAYSCAN simulation computes the total number of rods that impact every submunition. Also, the penetration history of each rod is computed where the initial, final or residual kinetic energy is computed. From these calculations, the kinetic energy imparted in the submunition is the difference between the initial and final kinetic energy of the residual rod. So, the rod initial kinetic energy is

$$KE_o = \frac{1}{2} M_o V_o^2$$

where subscript "o" refers to initial. If the rod penetrates through the submunition then the residual energy is

$$KE_r = \frac{1}{2} M_r V_r^2$$

where subscript "r" refers to residual. The delta in kinetic energy between the initial and final is the amount of kinetic energy deposited into the submunition. The kinetic energy deposited into the submunition is computed as

$$KE_{sub} = \frac{1}{2}\left\{M_o V_o^2 - M_r V_r^2\right\} = \frac{1}{2} M_{sub} V_{sub}^2$$

This kinetic energy calibration is for complete perforation through the entire submunition. Many rods could impact and deflect or penetrate through and stop into the liquid. The kinetic energy of these rods combined with the kinetic energy of the perforated rods is

$$KE_T = \sum_{i=1}^{N} \frac{1}{2}\left(M_o V_o^2 - M_r V_r^2\right) + \sum_{i=1}^{N^*} \frac{1}{2} \overline{M}_o \overline{V}_o^2 = \frac{1}{2} M_{sub} V_{sub}^2$$

where N is the total number of perforated rods while N* is the total number of rods that deflect or stop inside a submunition. The velocity of the submunition is

$$V_{sub} = \left\{ \frac{\sum_{i=1}^{N} \left(M_o V_o^2 - M_r V_r^2\right) + \sum_{i=1}^{N^*} \overline{M}_o \overline{V}_o^2}{M_{sub}} \right\}^{1/2}$$

where M_o and V_o are the mass and velocity of the nonperforating rods.

This is the estimated velocity of a submunition which is potentially accelerated into a neighboring submunition that may cause added damage.

Multiple Impact Model

When rods impact close together or with small impact time differentials, there is potentially some increased penetration due to the combined energies or pressure of both rods impacting close together. This combined effect does not occur when rods are spaced far apart. A new penetration damage model is currently being incorporated into RAYSCAN which uses current penetration equations with additional logic that accounts for closely spaced and timed impacting rods. The KE-Rod warhead at small miss distance generates extremely high spray densities making this model essential when computing accurate target submunition damage. Figure 15 is a description of two rods impacting a single submunition. The rod length is L while "a" is the distance between each rod at impact. If a>>L then each rod is treated as a single penetrator. The loading on the submunition wall is modeled as two different impacts. However, there exists an a/L ratio that caused neighboring rods to induce enhanced impact pressure, increasing overall penetration potential. Our model computes all rod impact points and determines rod neighbor as a function of a/L. The difference in impact time is also computed. At this time, the first rod penetrates through the weakened wall of the target. The target material is nearly perforated or detached from the cylindrical wall giving the second rod lower resistance during penetration.

A theoretical probability equation can be used to determine the total number of multiple impact occurrences that may exist. The probability that a rod will impact near another is predicted by

$$P_o = \frac{e^{-\zeta} \zeta^k}{k!}$$

where P_o is the probability of exactly k impacts per crater, ζ equals the number of impacts multiplied by the impact crater area divided by the total rod cloud area.

So, let

$$\zeta = \frac{NA_C}{A_T}$$

and if the crater radius is 1 inch and the deployed cloud radius is 12 inches then given 300 rods the probability of two rods impacting within a rod crater is 27 percent. The probability that three rods impact within a crater is 18 percent.

These models are critical in analyzing and developing optimum rod warheads against TBM payloads. New penetration equation logic considering multiple impacts is being developed to better model rod warhead damage.

8. ROD SIZE SELECTION

The selection of the optimum rod size is driven by target submunition thickness, number of submunitions, material and missile engagement endgame conditions. Also, the total number of submunitions and the manner of how they are packaged in a TBM payload is critical and must be understood before any rod size is selected. Another critical penetration parameter that must be understood is rod yaw at impact. Rods that are explosively deployed from this warhead mechanism generate many difficult yaw orientations. These rods tumble generating many yaw distributions. However, new warhead design concepts are showing promise in keeping the rods aligned for a short period of time. If the yaw could be orientated about the relative velocity vector then much deeper penetration would be expected than if they were randomly tumbling. If we assume a warhead deploys rods that are randomly tumbling then warhead design procedures can design an optimum rod mass and L/D ratio. Obviously, rods that have small yaw are expected to penetrate deeper into the payload compared to rods that have high yaw. The idea is to design a rod that can always penetrate one submunition at high yaw while penetrating two consecutive submunitions at low yaw.

Yawed rod penetration curves by Wollmann are used where total penetration (P) is normalized to cube penetration (P_1) with yaw varying between 0 and 90 deg. This is illustrated in Figure 16.

These curves show total penetration of tungsten cubes into steel, where L/D varied from 2, 3, 4, 5 and 10. On the left of the penetration curves are two consecutive submunitions. Two different penetration shotline paths are selected as potential rod impact points. Path 1 and path 2 impact submunition 1 at different obliquity angles while submunition 2 also sees a different obliquity angle. Based on the total line of sight thickness along both these trajectories the minimum thickness to penetrate the first submunition is plotted on the curve as “a” and “b”. Based on this thickness a 50 gram rod with any L/D less than 10 at any yaw could perforate through the first submunition at 70 deg obliquity. Lines “A” and “B” represent the required penetration to kill two consecutive submunitions. A second submunition is killed if rod yaw is less then 20 deg. The impact velocity of this curve is 2.6 km/sec.

The HULL hydrocode was used to study the effect of rod penetration. Figure 17 is a hydrocode run of an L/D=5 rod and tungsten cube impacting at 2.6 km/sec. The L/D of 5 rod penetrates into the second submunition while the cube stops after the first submunition. The effect at 90 deg yaw was analyzed with a 25 gram tungsten rod. Figure 18 shows a rod of this size and orientation does penetrate through the first wall of the first submunition. These studies provide valuable insight in designing KE-Rod warheads. The major design trade-off of a warhead of this type is whether many small rods or fewer large rods should be selected.

Another critical feature that must be considered in designing an optimum rod is how the submunitions are stacked in side the TBM. If a rod is designed to inflict optimum lethality, a designer must compute the probability that a second submunition is killed by a single rod. If this probability is low, a rod does not need to penetrate two consecutive submunitions. These rods are designed as light as possible to maximize the total number of projectiles on the warhead. However, if the probability of killing a second submunition is high enough, then a rod penetrator design is configured to penetrate two consecutive submunitions. Given specific impact points on the first submunition, a rod could penetrate the first submunition, and if a favorable yaw exists, a second submunition is penetrated.

A generic TBM submunition target is considered that contains 48 steel submunitions. A cloud of 6000 rods with an L/D of 30, weighing 5 lb, is fired into the payload. This cloud of rods was designed to specifically overmatch the target along any shotline in order to determine statistics on number of submunitions that could potentially be killed, given an impact point. The diameter of the spray pattern is equal to the diameter of the payload, ensuring all rods impact the target. The results of this study are shown in Figure 18. The total percentage of shotlines that hit at least one submunition is between 63 and 79 percent. This means that between 21 and 37 percent of the target contains shotlines on which a vulnerable component does not lie. A vulnerable component is defined as the liquid or the fuse. This lack of vulnerable area must be taken into account when considering a total rod warhead weight. The second line on the curve represents the percent of shotlines that contain a second submunition. This is critical because a designer must know whether to design a rod large enough to penetrate a second submunition, or make it smaller and always kill the first. This target shows that 27 to 35 percent of the shotlines contain a second submunition. The curves below show the potential of killing a 3rd and 4th submunition. This would require a very large rod and the probability of impacting these shotlines is low.

9. LETHALITY RESULTS

The lethality of the KE-Rod warhead is compared to a deformable and blast fragmentation warhead. The missile flew 3 ft above the target at a relative velocity of 8000 ft/s with a strike angle of 20 deg.

This analysis compared the results of a rod warhead containing 25 and 50 gram tungsten rods. A cube projectile is compared to a rod with an L/D equaling 5. The kinetic energy warheads were divided into a single and three bay configuration. Figure 19 shows the results for a 50 gram rod. There is an increase in lethality given three wave impacts when compared to one wave. The results do conclude that current raytrace methodologies underpredict overall lethality. This is attributed to the single repetitious firing of rods which do not account for damage generated from previous impacts. These models show that an L/D of 5 rod is a better choice compared to a cube. However, when 600 rods are fired, there is a significant lethality increase with a cube when modeled with three waves. The model also shows that there is a point where lethality is maximized and saturation begins. A warhead designed with 300 rods, performs equal to a warhead with 600 rods. KARPPEN penetration equation were utilized at several different points on the curve showing good agreement with FATEPEN2. The same velocity vector was run using a deformable and blast fragmentation warhead. As expected, these warheads performed poorly perforating much lower than half of the total number of submunitions.

The same analysis is performed with a KE-Rod warhead containing 25 gram tungsten rods. The total number of rods is multiplied by 2 because the total warhead weight is constant. These results generate higher lethality when compared to the 50 gram rods. The same trends held here compared to the 50 gram results. KARPPEN performed well generating similar lethality as FATEPEN2. These results are shown in Figure 20.

These lethality results clearly show that KE-Rod warheads generate high lethality and the effects of waves do significantly change overall lethality.

10. SUMMARY

Studies showed that KE-Rod warheads are highly lethal against submunition payloads. These warheads utilize more total warhead weight as metal penetrators compared to blast fragmentation warheads of today.

A new rod follower model demonstrated that current endgame raytrace methodologies underpredict overall lethality. This model accounts for every impact giving benefit to the second rod on the same shotline.

New KARPPEN penetration equations based on Wollmann and Grabarek were compared to FATEPEN2R showing little difference in overall lethality performance.

This study demonstrated that rod warhead technology is a serious candidate to defeat cluster chemical payloads of the future.

11. REFERENCES

1. R. Lloyd, “Conventional Warhead Systems Physics and Engineering Design,” Progress in Astronautics and Aeronautics, AIAA Book, Volume 179, March, 1998.

2. E. Wollmann, K. Hoog, G. Koerber, B. Wellige, “Performance of Ballistic Terminal Performance at Incidence,” Institut Franco-Allemand De Recherches De Daint-Louis, Deutsh-Franzősisches Forschung Instut Saint Louis, ISL, R110/96, 1996.

3. J.L. Harris, KBM, Private Communication

4. A. Ricchiazzi, C. Brown, "Penetration Equation for Tungsten Fragments, " 2nd International Symposium on Ballistics and Warhead Mechanics, March, 1976

5. S. Bless, "Recent IAT Publications on the Mechanics of Yawed Projectiles," Institute for Advanced Technology, the University of Texas at Austin, IAT.MG 0002, July 1997"

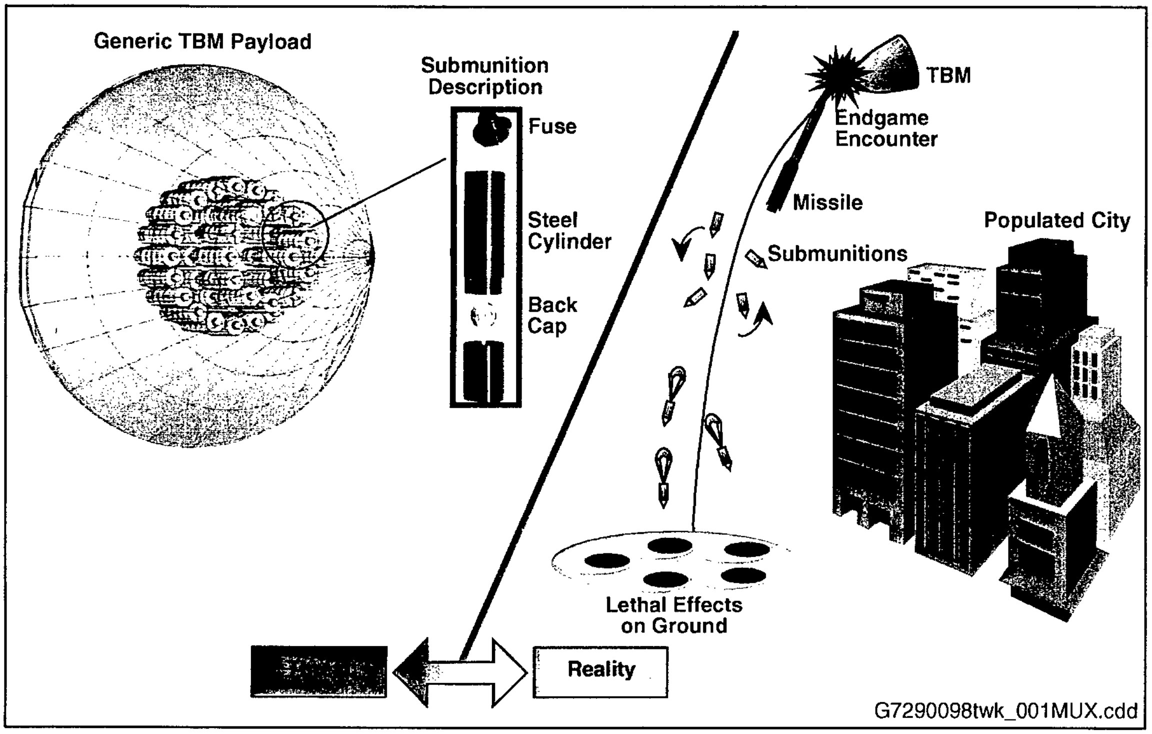


Figure 1. TBM Technology Releases Chemical Agent on Ground Generating Localized Hot Spots

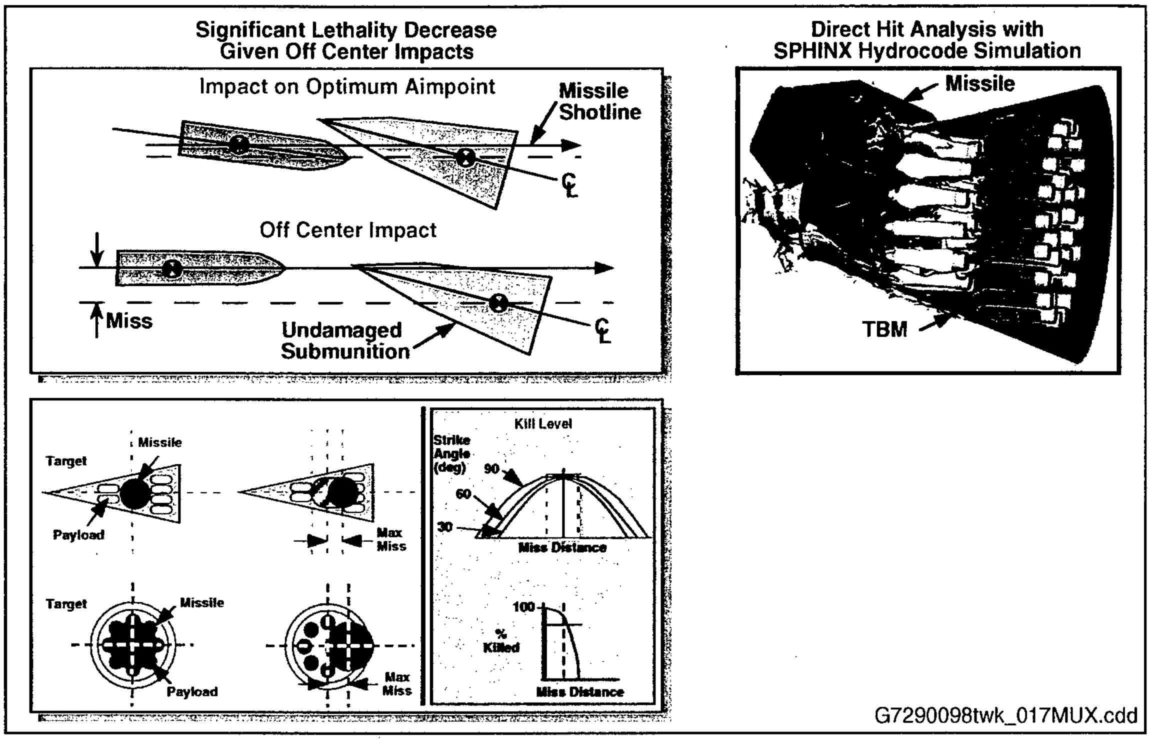


Figure 2. Direct Hit Missile Lethality at "Sweet Spot" Compared to Off-Center with SPHINX Hydrocode Impact

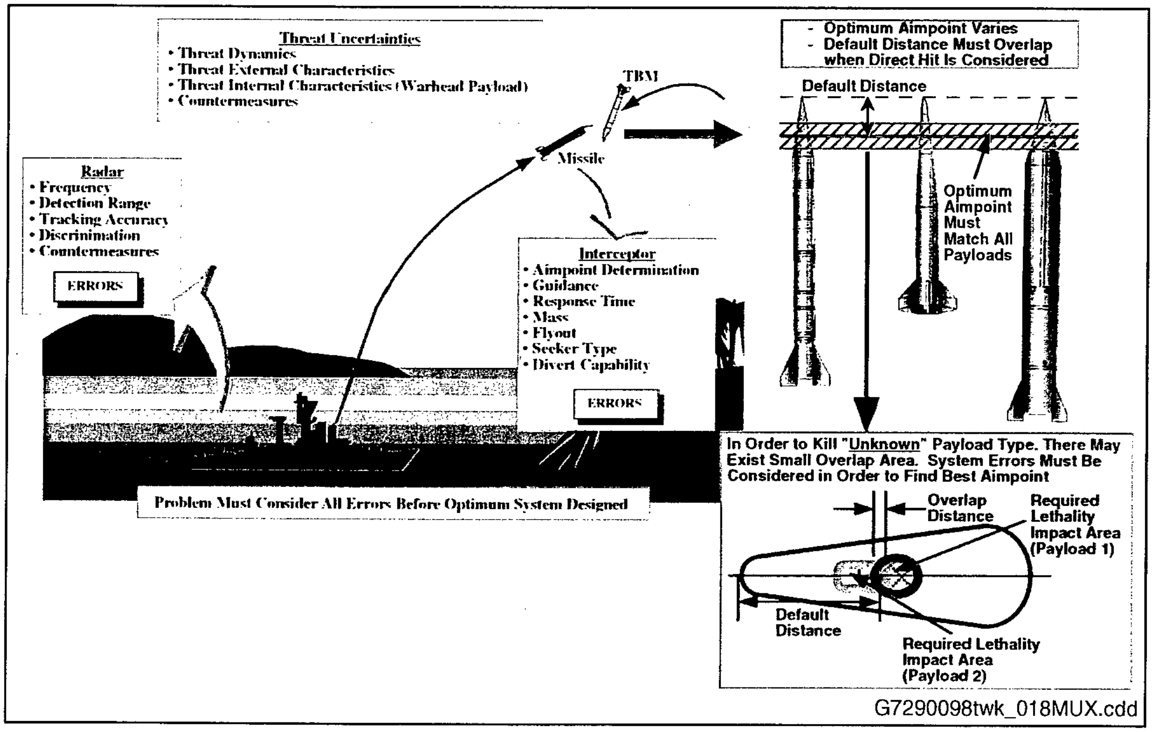


Figure 3. Given a Diverse TBM Threat and Achieving Small Miss "Extremely Difficult" when Threat Uncertainties are Considered

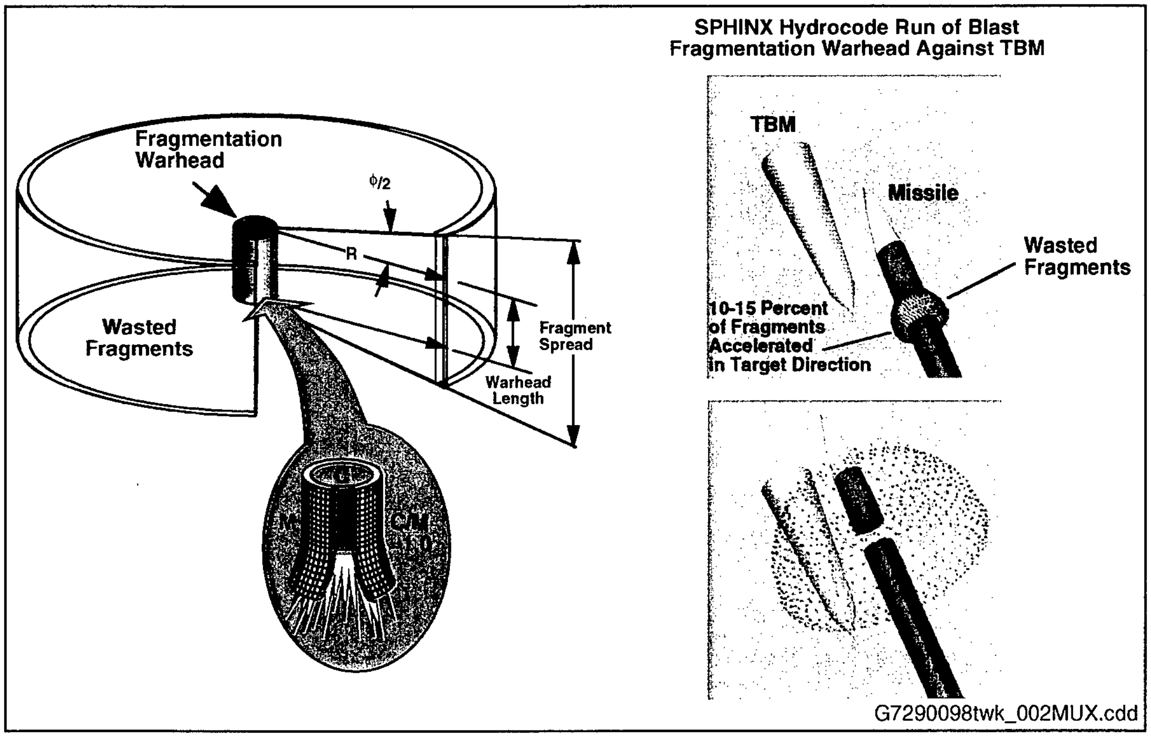


Figure 4. Current Warhead Technology Wastes Most Potential Fragments and Minimal Submunitions are killed

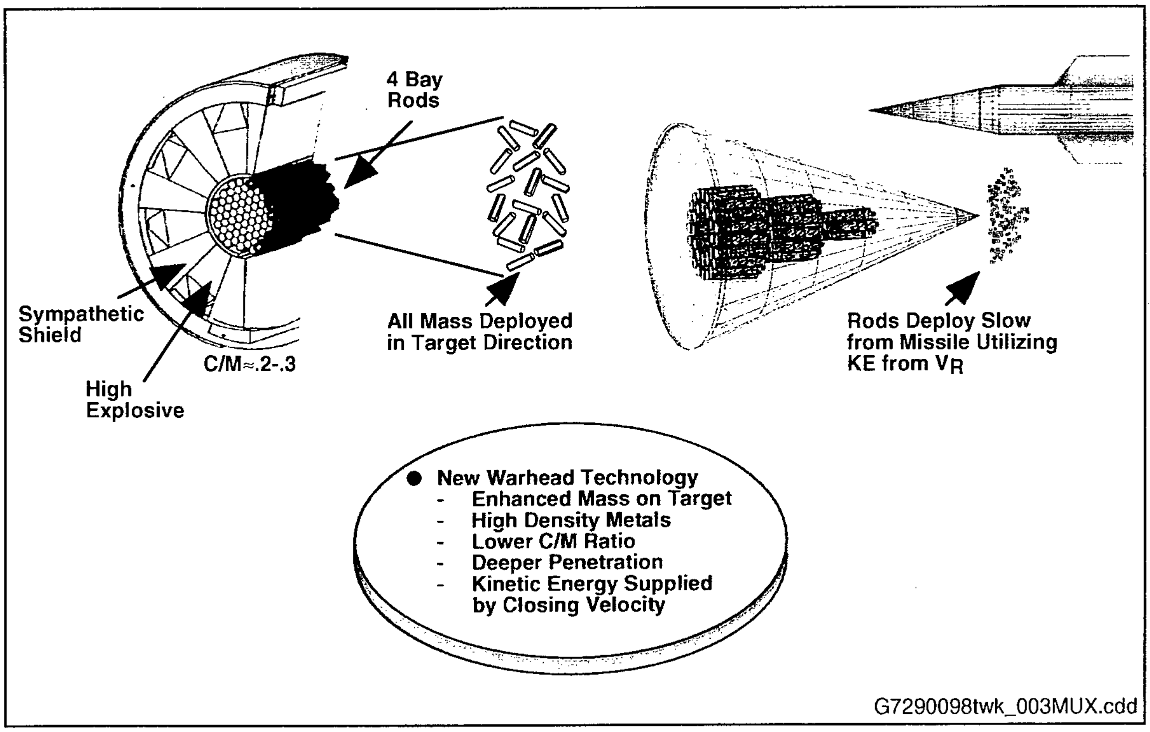


Figure 5. Kinetic Energy Rod Warhead Description

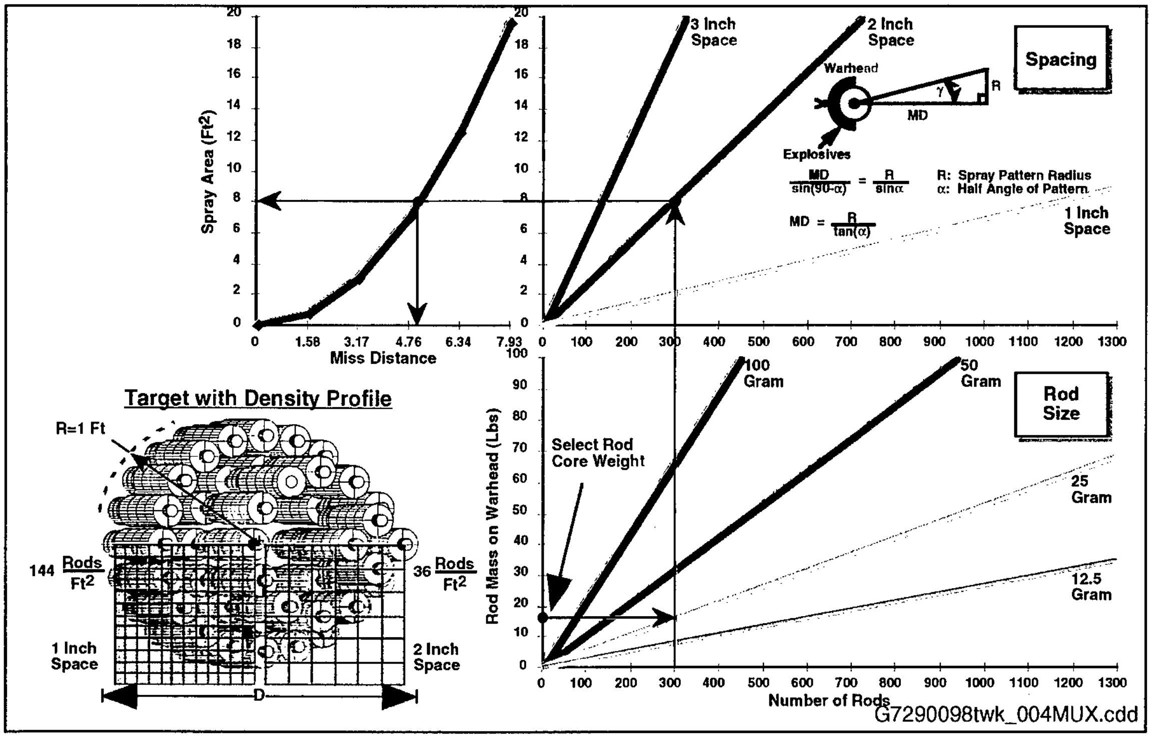
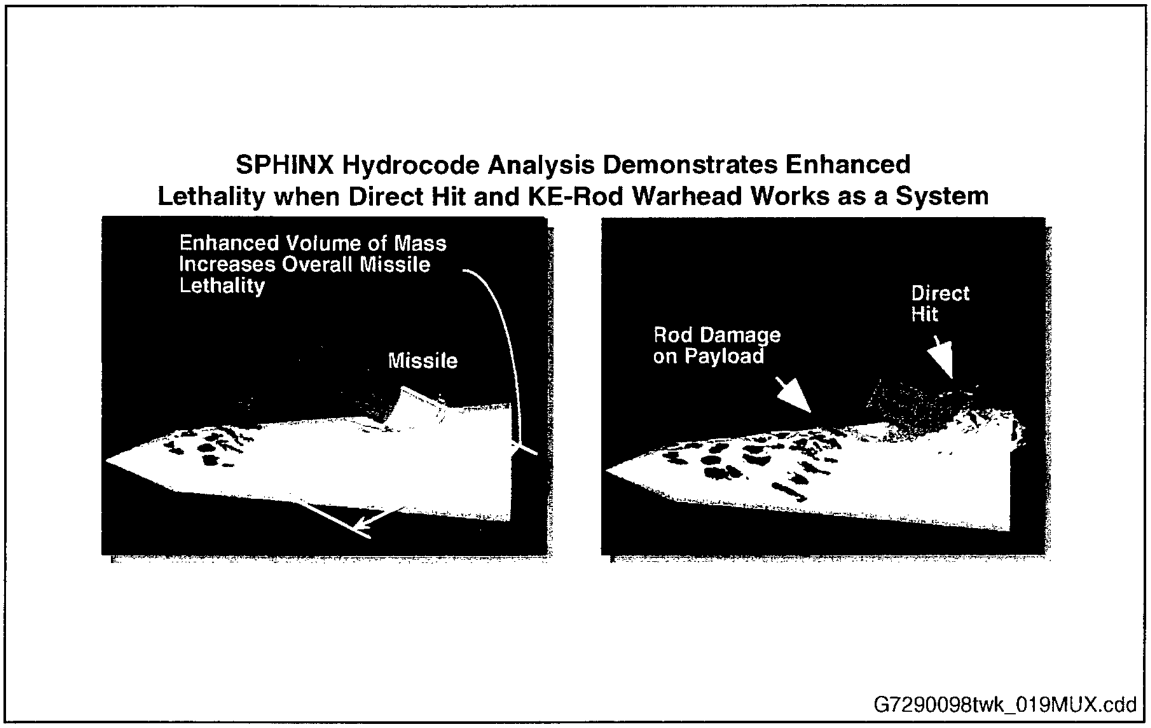


Figure 6. Rod Warhead Design Trades Demonstrate Many Rods Impact Close Generating Flood Loading Phenomena



SPHINX Hydrocode Analysis Demonstrates Enhanced Lethality when Direct Hit and KE-Rod Warhead Works as a System

Figure 7. Direct Hit Combined with Slowly Deployed Rods Creates Enhanced Mass on Target

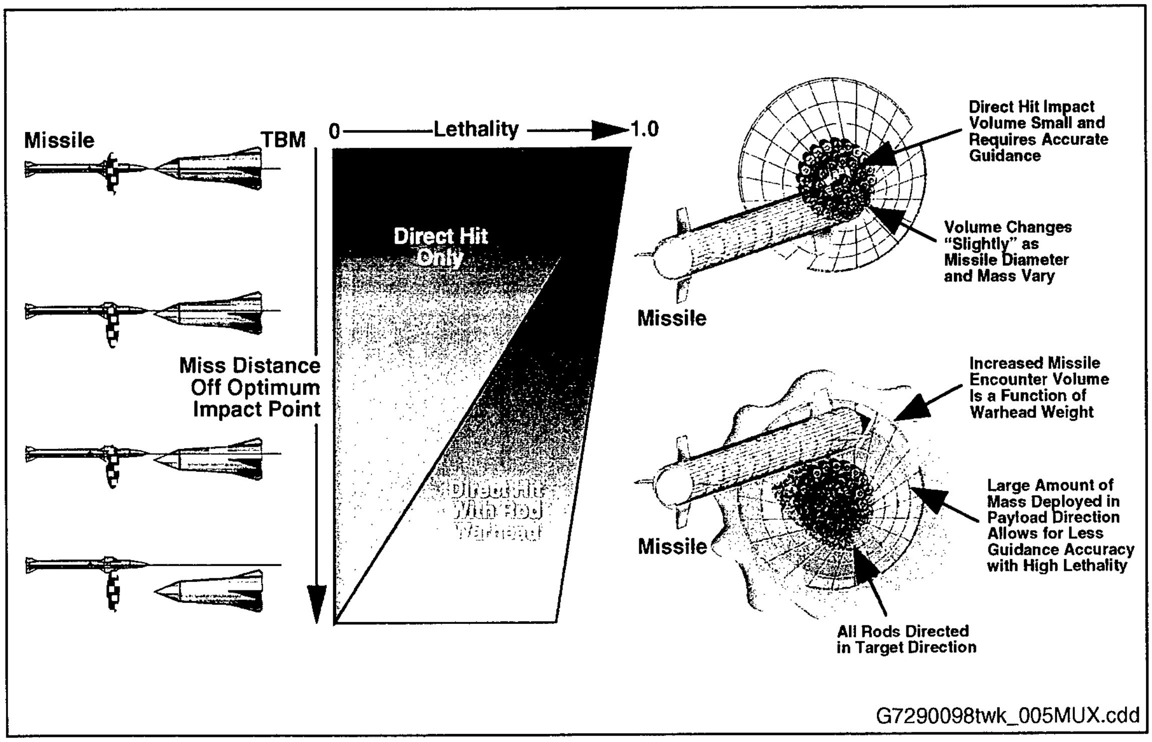


Figure 8. Direct Hit Technology Requires Small Misses While KE-Rod Warhead Combined with Direct Hit Enhances Overall Kill Volume

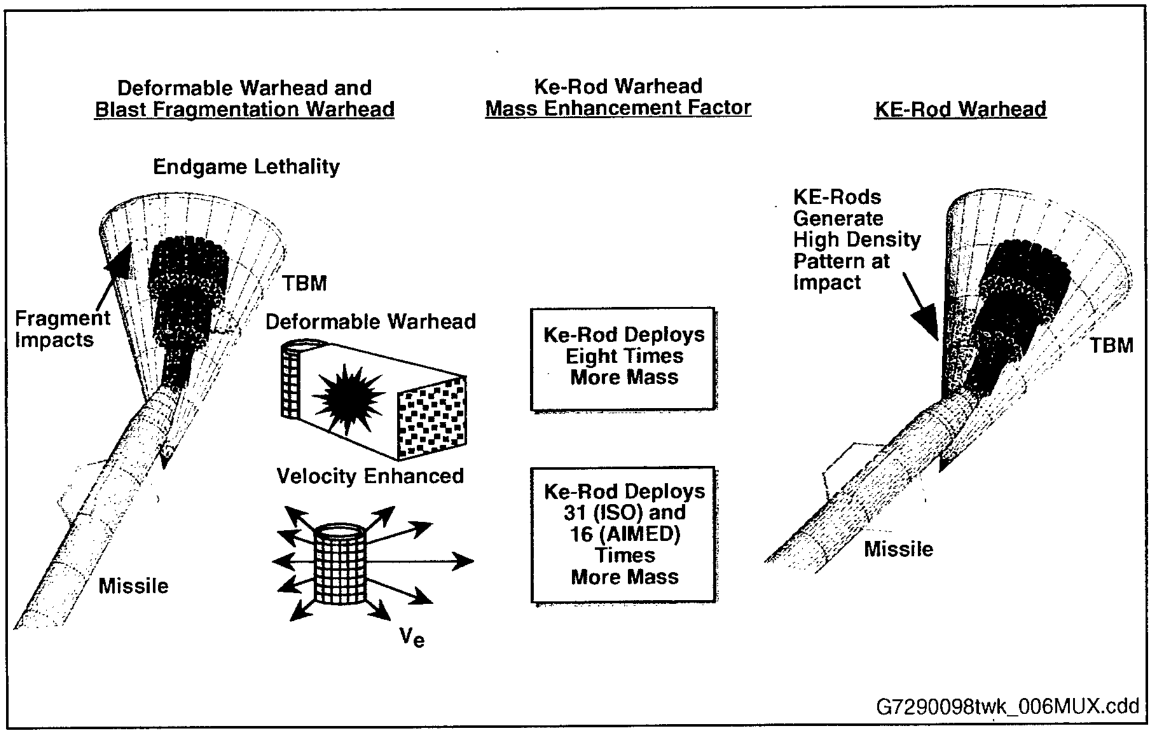


Figure 9. Enhanced Mass on Target Makes KE-Rod Warheads Lethal Against Submunition Payloads Compared to Today's Warheads

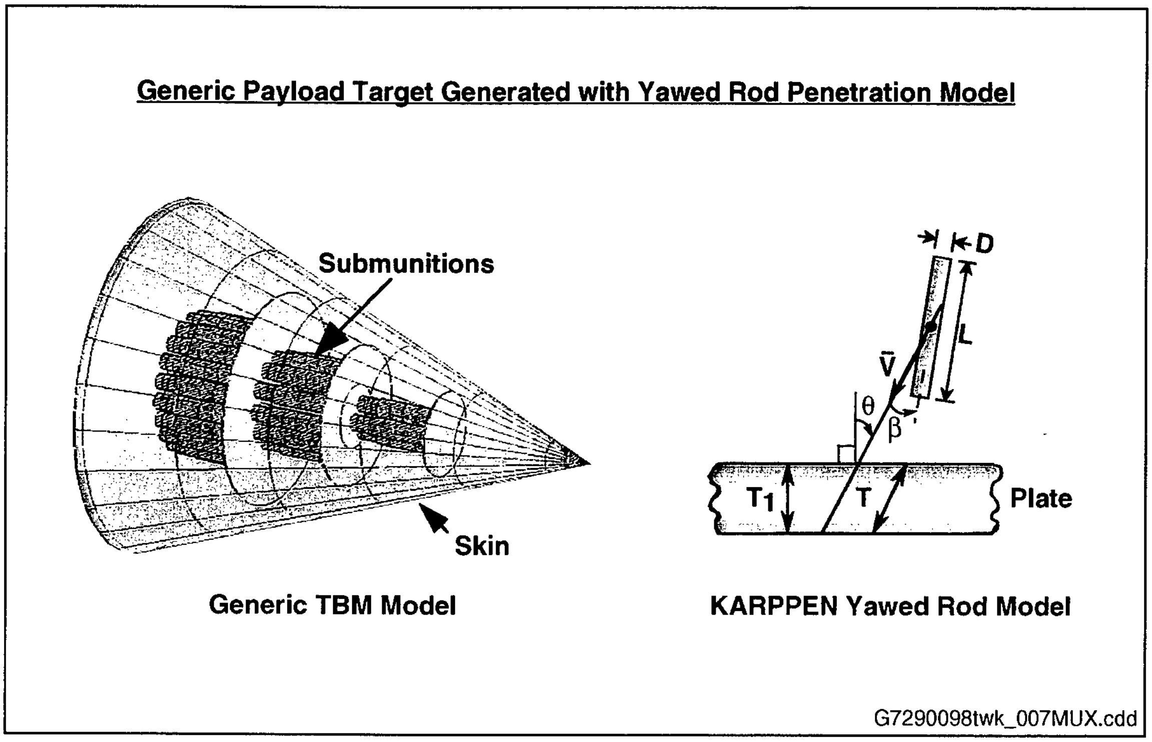


Figure 10. RAYSCAN Endgame Model Used to Assess KE-Rod Warhead Damage Against Submunition Payloads

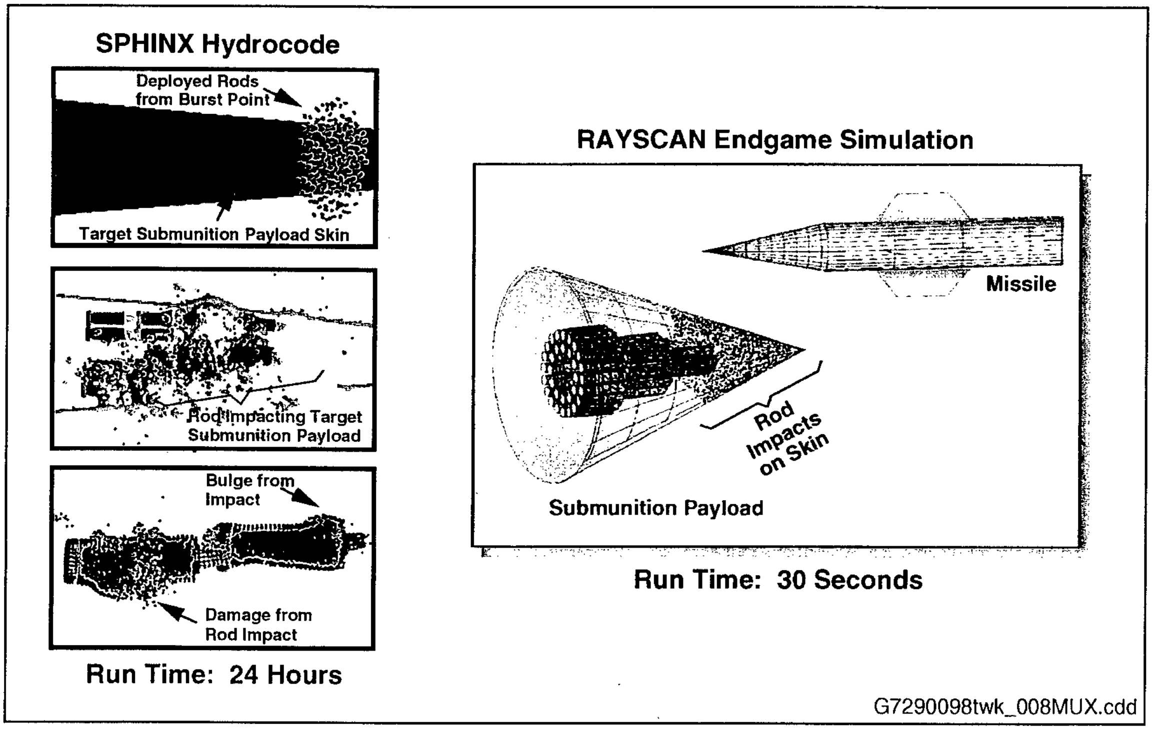
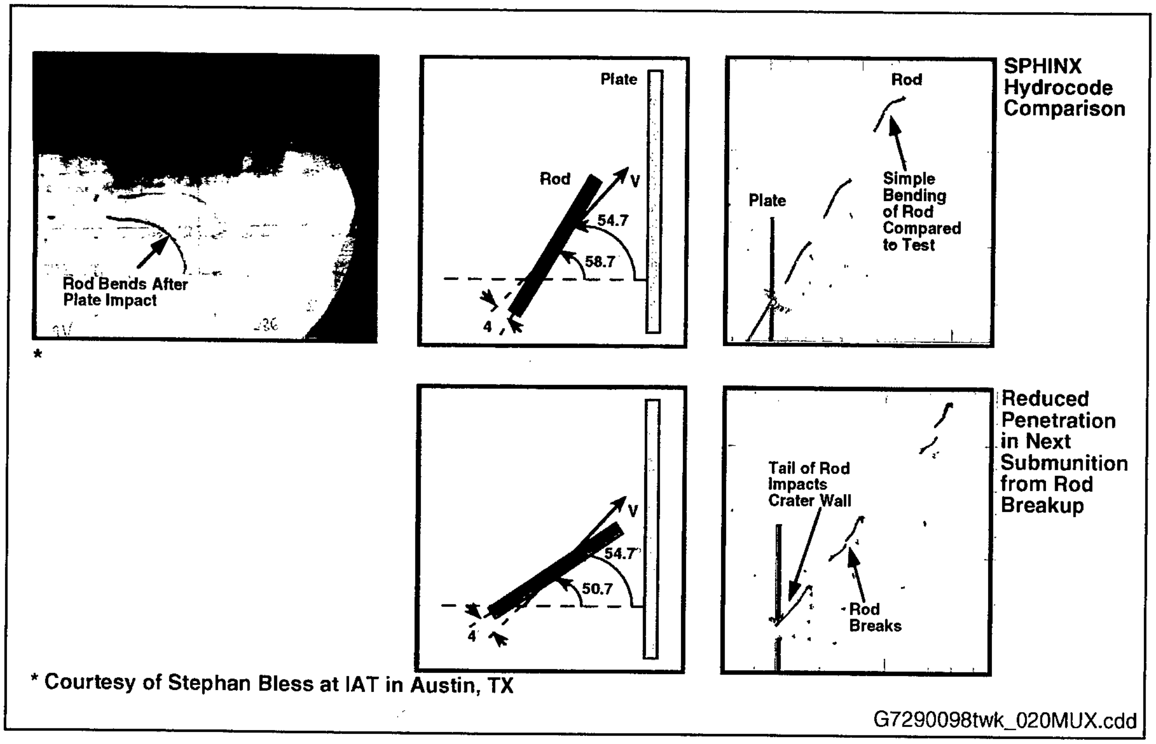


Figure 11. Cumulative Damage from Hydrocode Methodology Adapted to Endgame Simulations



* Courtesy of Stephan Bless at IAT in Austin, TX

Figure 12. Long Rods with Yaw Demonstrate Bending and Fracture Reducing Rod Penetration Performance

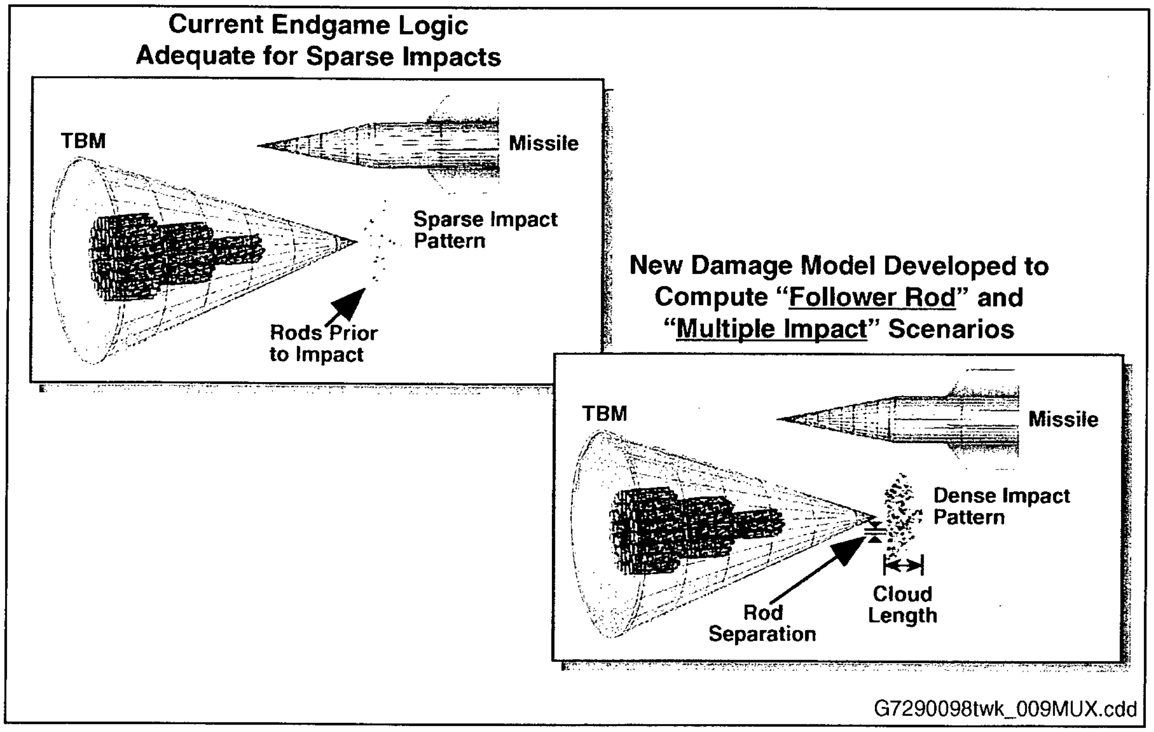


Figure 13. New Endgame Code Methodology Being Developed to Account for Multiple Rod Impacts

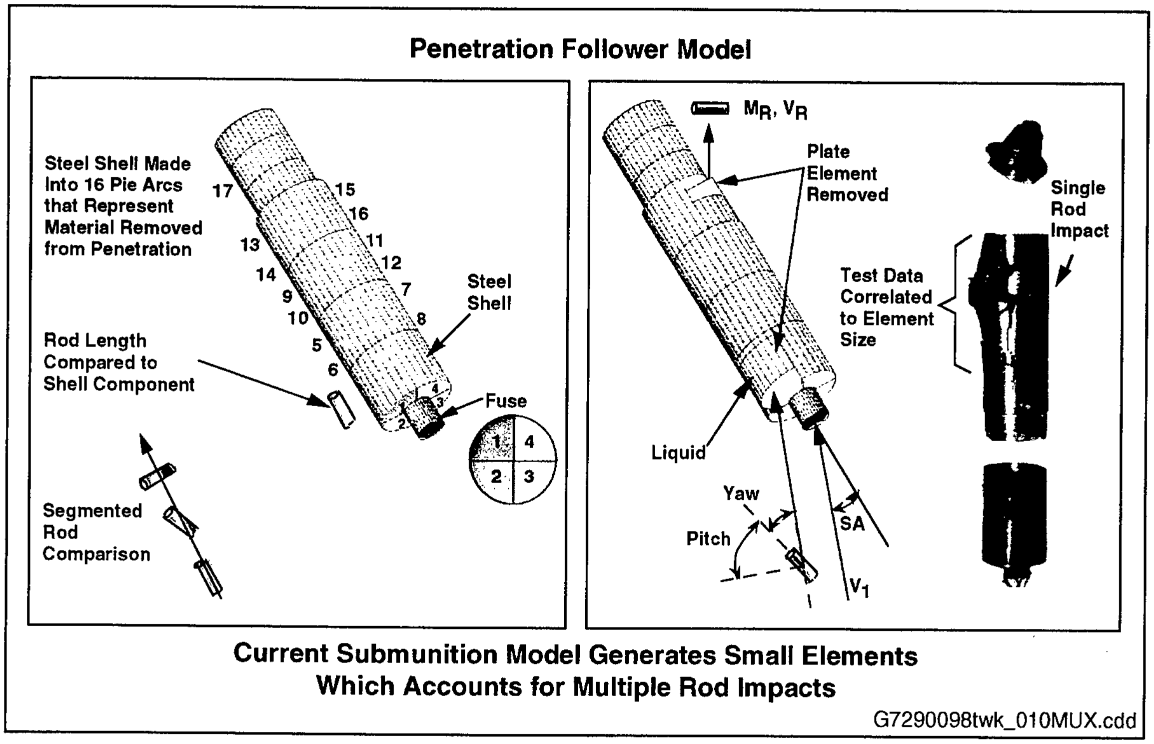
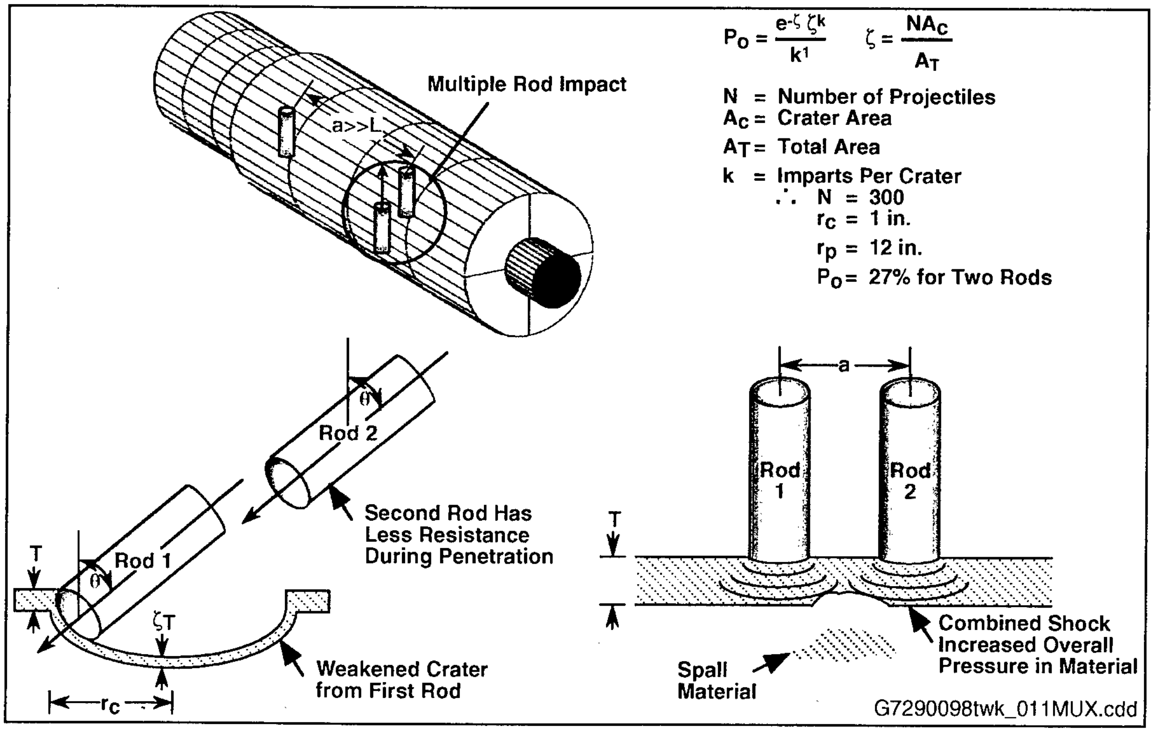


Figure 14. Penetration Follower Damage Models Currently Developed to Accurately Predict Flood's Loading Impact



$$P_O = \frac{e^{-\zeta} \zeta^k}{k^1} \qquad \zeta = \frac{NA_C}{A_T}$$

N = Number of Projectiles
A_C = Crater Area
A_T = Total Area
k = Imparts Per Crater
$\therefore$ $N = 300$
$r_C = 1$ in.
$r_p = 12$ in.
$P_O = 27\%$ for Two Rods

Figure 15. Multiple Loading Damage Models Currently Developed to Accurately Predict Flood Loading Phenomena

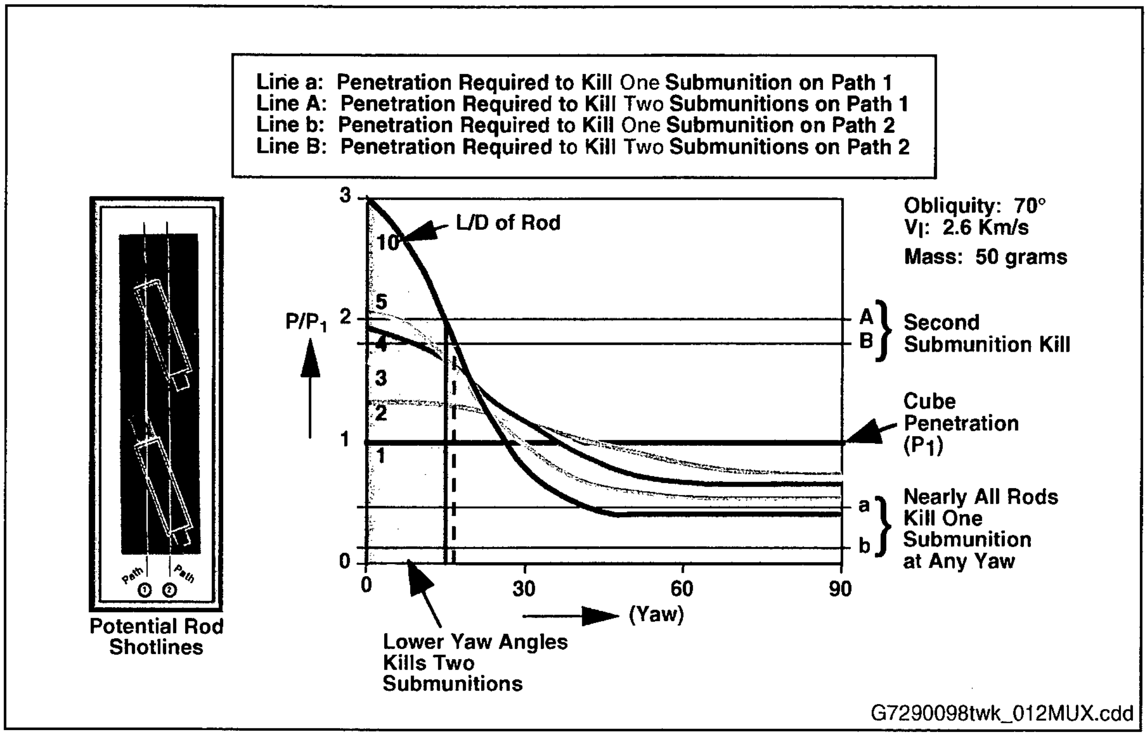


Figure 16. Submunition Penetration Thresholds Plotted Over Wollmann's Curves Demonstrating Single Rod Performance

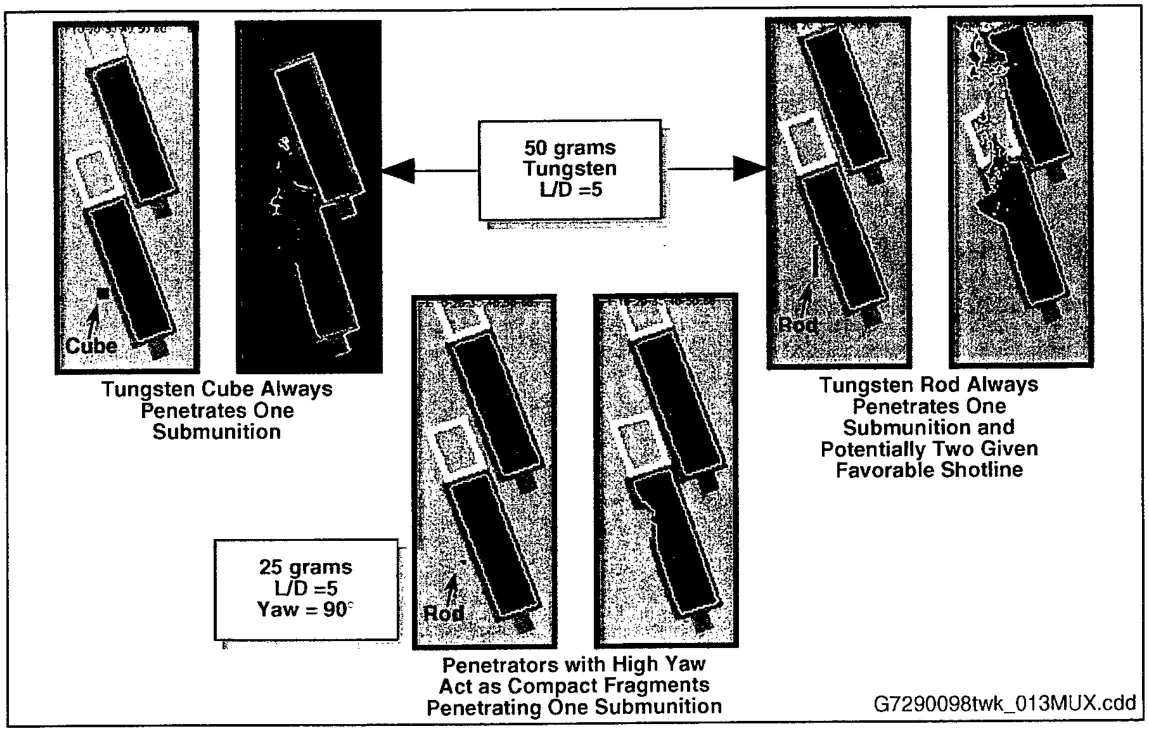


Figure 17. Hull Hydrocode Analysis in Conjunction with Test Data Provides Confidence in Selecting Best Projectile Configuration

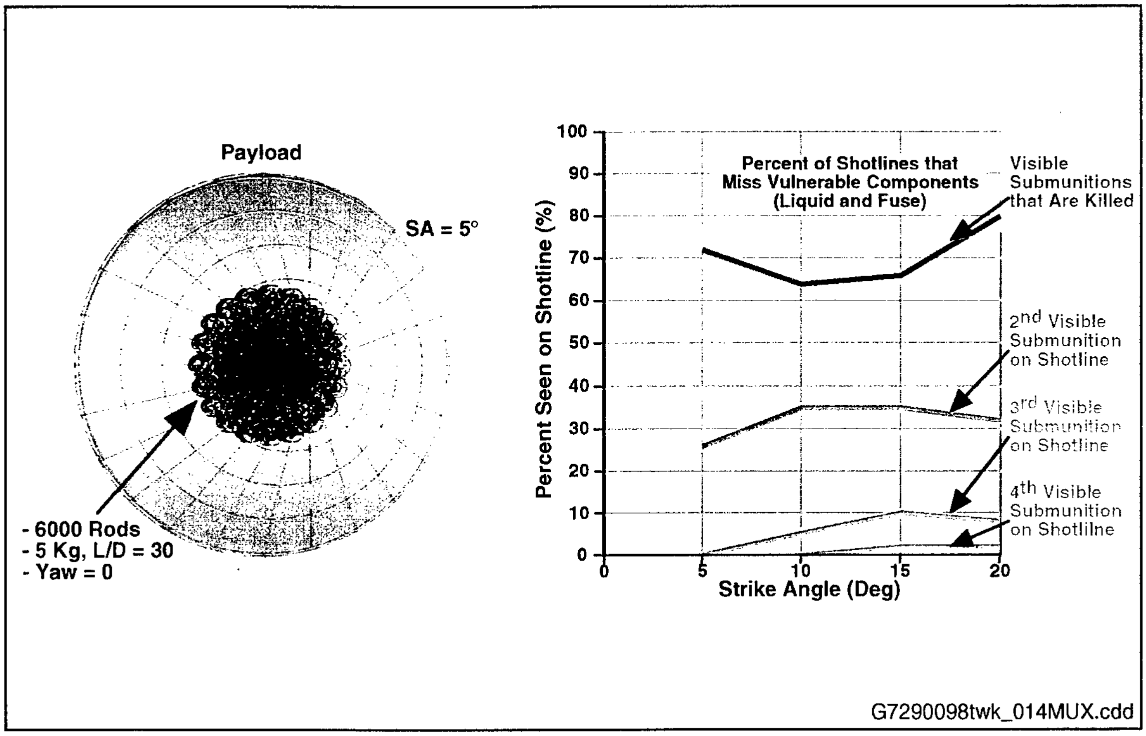


Figure 18. Rod Size Selection Based on Payload Geometric Configuration and Each Rods Penetration Capability

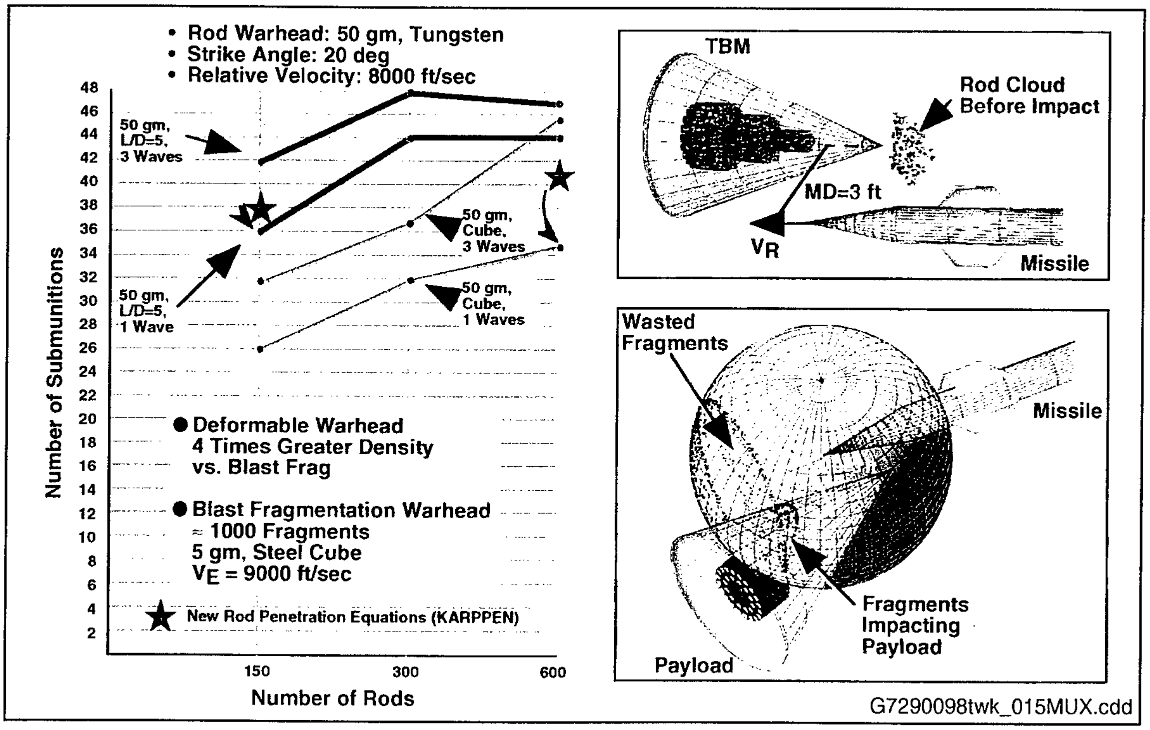


Figure 19. KE-Rod and Blast Fragmentation Warhead Lethality (50 gm)

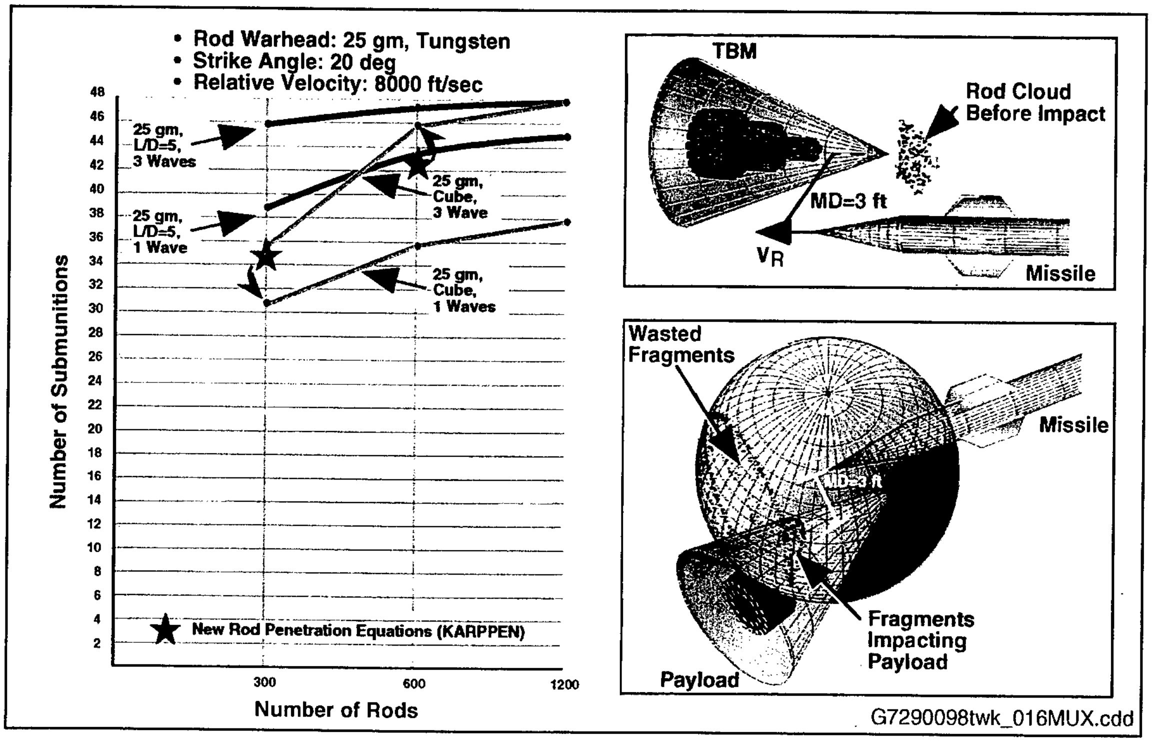


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Figure 20. KE-Rod and Blast Fragmentation Warhead Lethality (25 gm)

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