Gauging the Influence of Technology on Tactical Missiles of the Future

Mark L. Bundy, Gene Cooper and Edward Kennedy

US Army Research Laboratory, Aberdeen Proving Ground, MD–21005-5066

ABSTRACT

Tactical missiles, carrying kinetic energy, high explosives, or multiple submunitions are an integral part of the current and future US Army weapons inventory. Naturally, the number of missiles that can be stowed on any mobile launch platform depends on the size of the missile. Advances in rocket propulsion efficiency and improvements in guidance systems may make it possible to reduce missile size without a proportionate decrease in effectiveness. A primitive 1-DOF computer model is used here to show how advances in missile technology might allow smaller missiles in the future to carry out the mission of today's larger missiles. A scaled-down version of a typical current generation missile is taken as the next generation missile. Hypothetical improvements in this smaller missile are then chosen in four basic areas–propellant impulse, burn time, weight fraction, and aerodynamic drag–with the effects on lethality reported in a nondimensional format.

Keywords: Tactical missiles, projectile design and analysis system, PRODAS, computer model, next generation missiles, advanced missiles system technologies

1. INTRODUCTION

The simplest expression governing missile motion in a gravity-free, zero-drag environment is the ideal velocity equation:

$$v_f = v_o + g\, I_{sp}\, ln \frac{M_o}{M_f} \tag{1}$$

where v is the velocity, M is the total missile mass, g is the acceleration due to gravity, I_{sp} is the specific impulse of the propellant, and subscripts 0 and f refer to the pre-burn and post-burn conditions, respectively.

To include the effect of air resistance on the missile, a drag force, $\vec{D}$, must be added, such that if the motion of the missile is partitioned into small time increments, $t_{i+1} - t_i$, the drag modified equivalent of Eqn (1) would be

$$v_{i+1} = v_i + g\, I_{sp}\, ln \frac{M_i}{M_{i+1}} - \frac{\left|\bar{\vec{D}}\right|}{\overline{M}}\{t_{i+1} - t_i\} \tag{2}$$

The average drag and missile mass, from t_i to t_{i+1}, can be defined as

$$\left|\bar{\vec{D}}\right| = \frac{1}{2}\rho\, A\left(\frac{v_{i+1}+v_i}{2}\right)^2 C_D$$

and (3)

$$\overline{M} = \left(\frac{M_{i+1}+M_i}{2}\right)$$

where C_D is the drag coefficient, ρ is the air density, and A is the cross-sectional area of the missile.

2. VALIDATING SIMPLE MODEL

A knowledge of the missile's drag coefficient, $C_D(v)$, depends on the missile's geometry. For instance, Fig. 1 depicts (in a lumped-component format) a typical tactical missile design which carries a long rod penetrator payload. Based on the geometry of

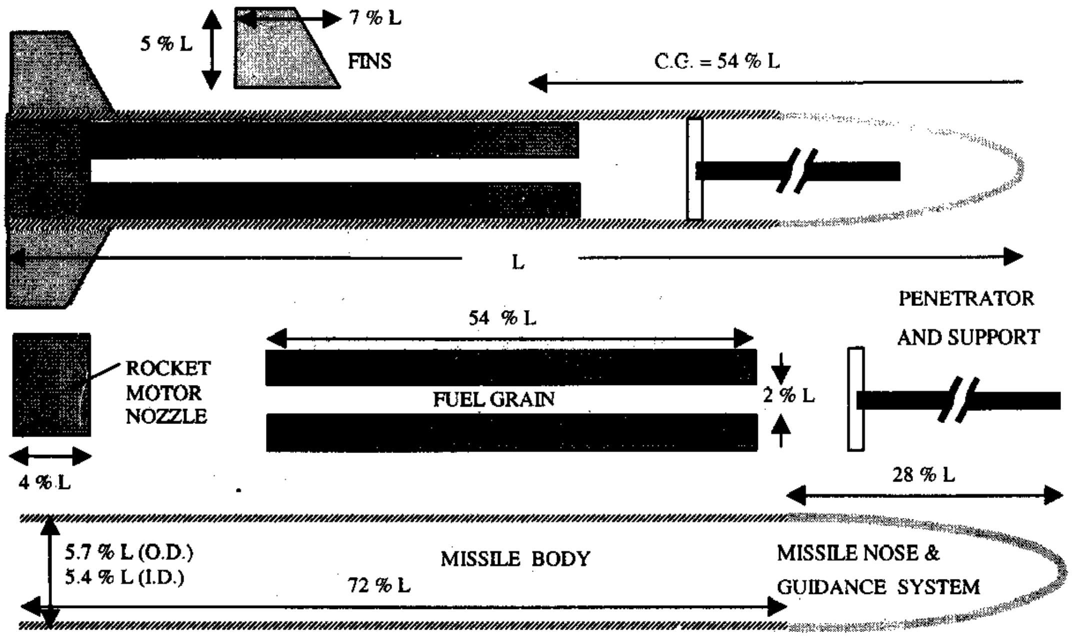

Figure 1. Lumped component depiction of a typical kinetic energy missile

Fig.1, $C_D(v)$ can be computed using the PC-based projectile design and analysis system (PRODAS) of Burnett[1]. The results are shown in Fig. 2.

The change in missile mass with time, $M(t)$, during the propellant burn phase for the typical missile of Fig. 1 is shown in Fig. 3. Putting the data from Figs 2 and 3 into tabular form, Eqns (2) and (3) can be evaluated and plotted using microsoft excel (http://www.microsoft.com), as shown in Fig. 4. Also shown, for comparison, is the outcome if drag was ignored. It can be seen that drag during rocket burn results in about a 5 per cent reduction in the peak (no drag) velocity. Velocity is nondimensionalised, here and henceforth, by the speed, V_{minKE}, deemed necessary to produce the minimum lethal kinetic energy at the target for the particular penetrator mass payload.

The PRODAS is also used to model the missile's trajectory in free flight. In particular, for the missile described in Fig. 1, and the initial free flight velocity (at time t_b) shown in Fig. 4, the PRODAS-estimated downrange trajectory is shown in Fig. 5 (with the lead-in missile burn phase included for reference). Also shown in Fig. 5 is the flight data for the particular (albeit typical) missile on which Figs 1 to 3 are based. As can be seen, this simple PRODAS-based model agrees fairly well with the flight data for the reference missile.

3. NEXT GENERATION MISSILE

3.1 Baseline Design

The number of missiles that can be stowed onboard any launch platform is an important factor. A smaller, but equally lethal missile, is always favoured, how might this be accomplished? A baseline next generation missile might start as a scaled-down version of the current tactical missile, using as much of the current missile technology and components as possible. For example, suppose the baseline next generation missile utilises the same propellant formulation, motor case, guidance control, and missile body material, as the current missile (Fig. 1), but is scaled-down to, say, 75 per cent of its length. Such a design is shown in Fig. 6, where the constraints of a reduced length missile are met by wrapping the propellant grain around a shortened penetrator. Moreover, without the penetrator volume up front, it can be assumed that the guidance system would fit into a shorter nose section, as well. The PRODAS was used to determine the mass and aerodynamic properties (such as C_D) for the baseline next generation

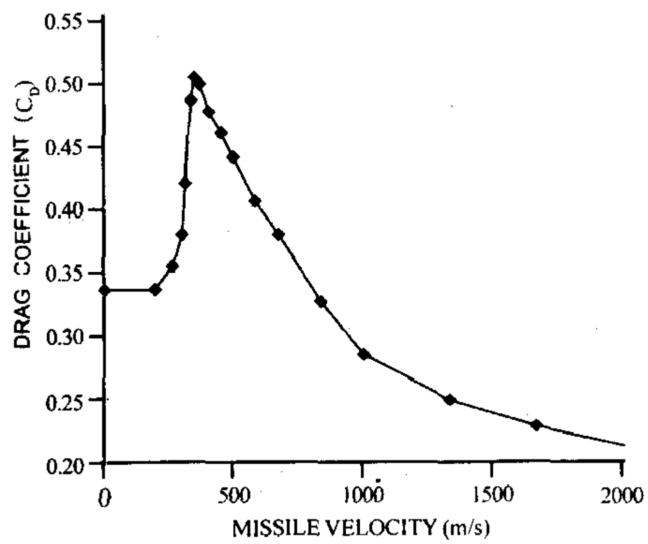

Figure 2. PRODAS-predicted drag coefficient versus velocity for missile geometry of Fig. 1.

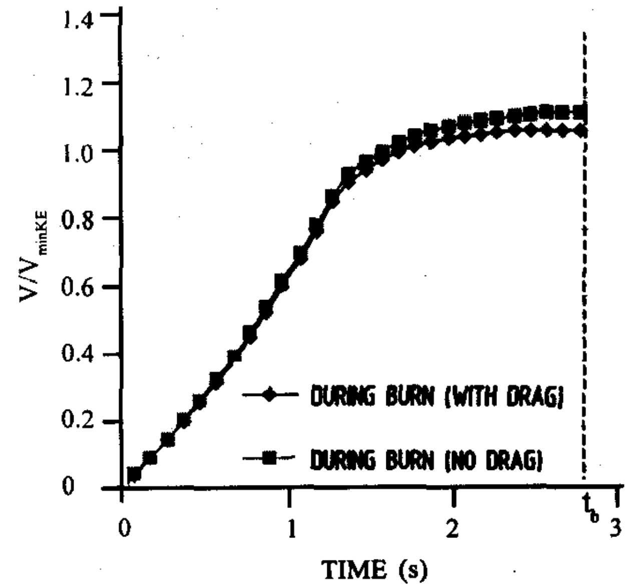

Figure 4. Predicted missile velocity versus time during rocket burn.

missile of Fig. 6. An aerodynamically acceptable design was found to have an overall weigh that was 67 per cent as much as the reference missile of Fig. 1, but accommodated 72 per cent of the fuel weight. Hence, the rate at which propellant is burned in the baseline next generation missile chosen here is assumed to be 72 per cent of the curve shown in Fig. 3. Using the simple (PC-based) computer model, the solution for velocity versus time is shown in Fig. 7. In terms of lethality, the baseline next generation missile is not as effective as the current tactical missile. Given this, what percentage increase (advancement in technology) is needed in the areas of specific impulse, propellant burn time, lighter weight components, andreduced drag, to improve the performance of this baseline next generation missile?

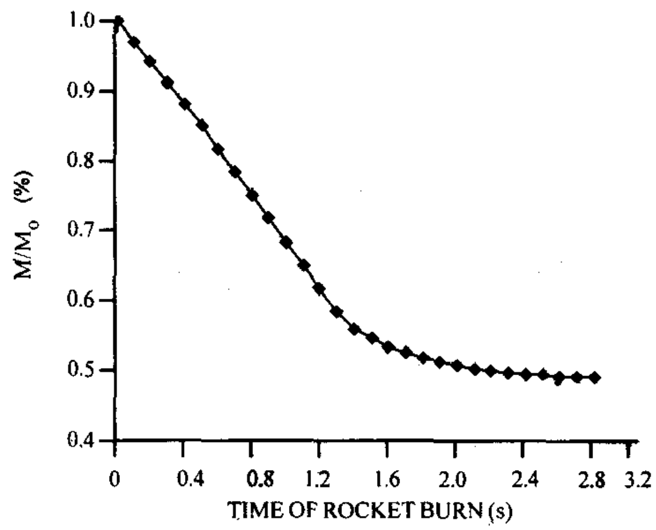

Figure 3. Change in mass versus time during rocket burn for reference missile of Fig. 1.

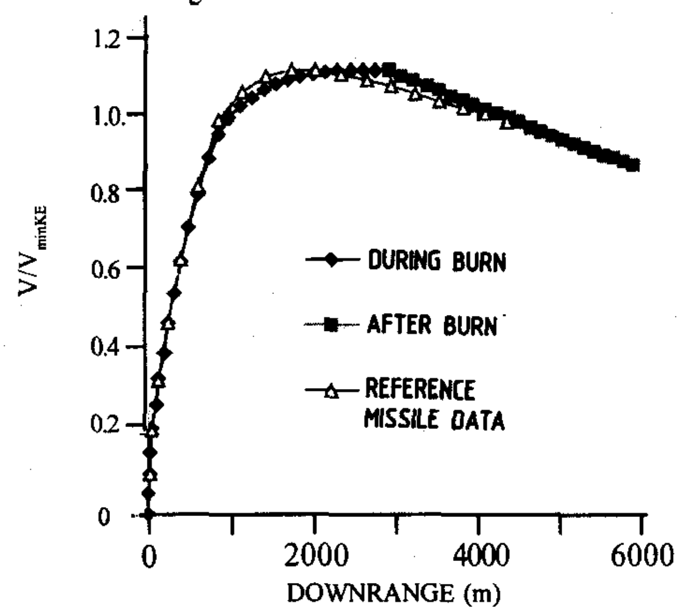

Figure 5. Validation of DIV-PRODAS-predicted trajectory for the reference missile of Figs 1-3.

3.2 Parametric Study for Improved Baseline Performance

Percentage improvements in the four basic areas e.g, propellant impulse, burn time, weight fraction and

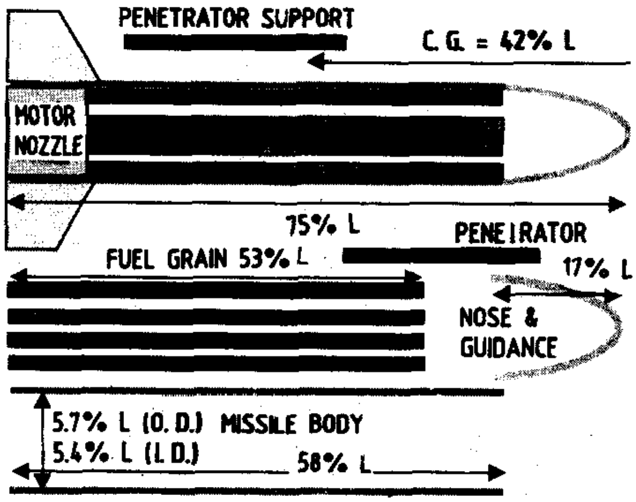

Figure 6. Lumped component illustration of a baseline next generation missile, reference to Fig. 1.

aerodynamic drag, are chosen solely to illustrate how these parameters would influence performance. These are not necessarily an indication of what experts in these areas would agree upon as eminently foreseeable; neither are these considered totally unreasonable.

3.2.1 *Increased Propellant Weight Fraction*

Advances in materials technology may allow a future missile motor case to be made from lighter, stronger materials, in which case the propellant mass would be a higher fraction of the overall missile motor

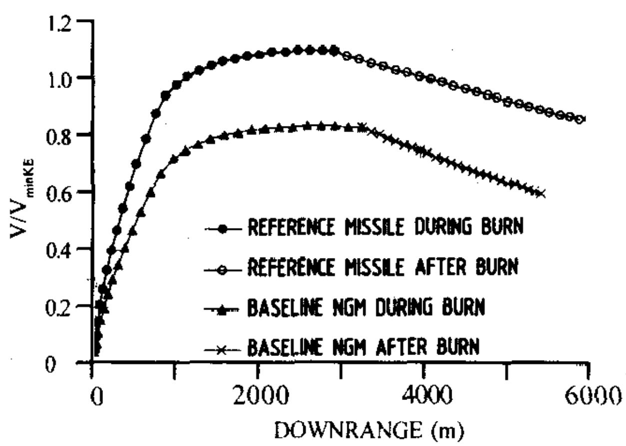

Figure 7. DIV-PRODAS-predicted trajectory for the baseline next generation missile.

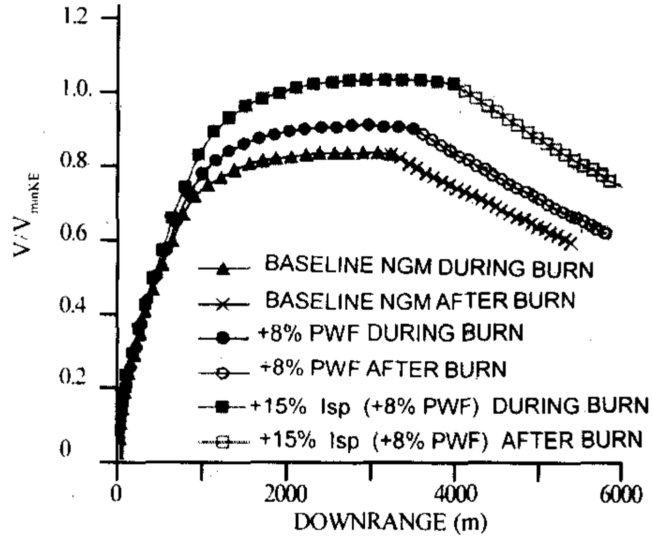

Figure 8. Effects of increased propellant weight fraction and specific impulse on next generation missile velocity.

mass. If the propellant weight fraction were to rise, by say 8 per cent (by simply making the motor case lighter), the overall baseline next generation missile mass would drop, from 67 per cent to 62 per cent that of the reference missile of Fig. 1. Recomputing the next generation missile during and after-burn trajectories for this lighter weight next generation missile would result in a ~ 9 per cent increase in peak velocity over the baseline case, as shown in Fig. 8.

3.2.2 *Increased Specific Impulse of Propellant*

The specific impulse is really the thrust force impulse per unit weight of burned fuel mass. If advances in the propellant formulation, such as creating equally energetic but lighter weight fuel, were achieved, which increased the specific impulse, by say 15 per cent, it would increase the peak velocity by an additional ~14 per cent over that already obtained with an increased propellant weight fraction, as shown in Fig. 8. The combined increase in propellant weight fraction and specific impulse allows the upgraded next generation missile to move above the unit lethality threshold, reaching out to 4 km before reduced burn time, compared to ~3 km at reduced burn time for the baseline next generation missile [and full-scale reference missile (Fig.7)].

3.2.3 *Reduced Burn Time*

Although, the region of lethality ($V/V_{min\ KE} > 1$) for the next generation missile is shown to span ~2 km in Fig. 8, it begins 1 km further downrange than for the reference missile. To increase lethality at shorter range, it is necessary to burn the propellant faster. If the propellant burn time was reduced to only 25 per cent of its current value, the predicted trajectory would appear as indicated in Fig. 9, shifting the lethal velocity to within ~ 400 m of launch.

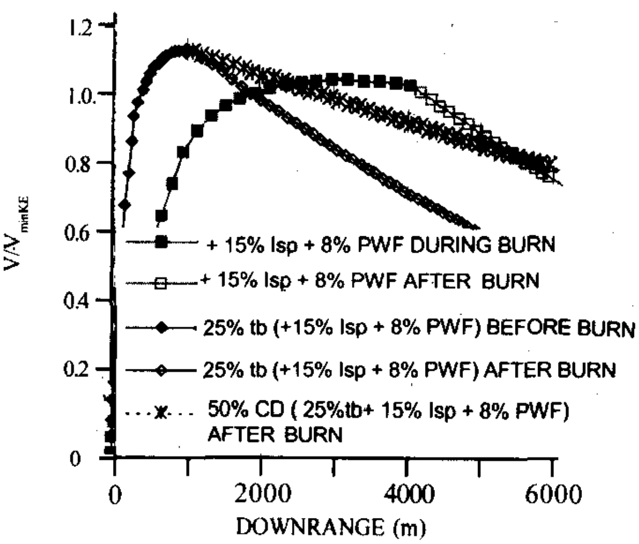

Figure 9. Effects of reduced burn time and drag coefficient on next generation missile velocity.

3.2.4 *Reduced Drag*

although reducing the burn time has the desired effect of making the smaller missile lethal at close range, it also means that the point of burnout is reached sooner (occurring at 1 km as opposed to the prior 4 km in this example). Consequently, aerodynamic drag after burnout condensed the lethal range to only 1500 m (from 400–1900 m). If drag could be reduced, by say 50 per cent, perhaps by shedding the large cross-section surrounding the burned out rocket motor, it 50 per cent, perhaps by shedding the large cross-section surrounding the burned out rocket motor, would extend the lethal range as predicted in Fig. 9. The missile velocity would then stay above the lethal threshold out to 2.8 km. Hence, the combined effect of the four parameter changes is such that the (conceptual) next generation missile of Figs 6 and 9 is smaller, but still lethal, over nearly as long a range (2.4 km versus 3.0 km) as the (conceptual) current generation tactical missile of Figs 1 and 7.

4. CONCLUSION

As demonstrated, a simple 1-DOF computer model can be used by non-experts to examine how advances in technology might allow smaller missiles in the future to perform as well as their larger missile counterparts of today. The model reveals the basic influences (benefits and drawbacks) of each technology on downrange lethality. For example, a shorter burn time moves the region of lethality closer to the point of launch, but it does so at the expense of shortening the range over which the missile remains lethal, unless an in-flight reduction in drag occurs after burnout. Furthermore, the examples demonstrate how the model could be used to estimate the minimum percentage improvement needed in a given technology to bring missile lethality to a desired level. This paper shows how a simple model can provide fundamental answers to cost-versus-benefit questions concerning how best to incorporate, or invest in advanced missile system technologies.

REFERENCE

1. Burnett, J. PRODAS technical manual. Arrow Tech Associates Inc., South Burlington, VT, 1993.