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Preliminary Design of a Hybrid Propulsion Multimission Missile System

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A preliminary design, prompted by a national design competition, was conducted to select a multimission missile. This missile was expected to replace the Tow, Stinger, and Hellfire missiles, which required it to defeat a diverse target set ranging from hardened bunkers to attacking fixed-wing aircraft. As a result, advanced technologies, which have not been incorporated into any fielded missile system, had to be evaluated, especially, but not limited to, propulsion. Miniature turbojets, air turborockets, pintle solid motors, pulsed solid motors, and gelled bipropellant engines were among the powerplants evaluated. The selected design used a millimeter wave radar seeker with automatic target recognition, a smart shaped-charge tandem warhead, a composite airframe, and a novel, two-stage combustion gelled hybrid propulsion system. The gelled hybrid consisted of a glycidyl azide polymer solid fuel gas generator, which exhausted into the main combustion chamber, where the gas was oxidized using gelled inhibited red fuming nitric acid. The missile weighed 60 lb and had a 6-in. diameter, as well as a 14-s time of flight to a 3-mile target. The hybrid propulsion system, with its flexible energy management and its high performance, was found to uniquely enable the multimission requirements to be met.

Nomenclature

C^* = propellant characteristic velocity, ft/s
I_{sp} = propellant specific impulse, s

Introduction

A MOCK request for proposal (RFP)[1] was released by the AIAA that described a virtual opportunity to develop a new weapon for the U.S. Army and Marine Corps, called the Advanced Combined Arms Missile System (ACAMS). This missile combined the missions currently performed by the Tow antiarmor missile, the Hellfire antiarmor missile, and the Stinger antiaircraft missile into a single, multimission vehicle. The target set required for ACAMS included, but was not limited to, armored combat vehicles, air defense vehicles, radar sites, command posts, bunkers, helicopters, unpiloted air vehicles, and attacking fixed-wing aircraft. Further, ACAMS launch platforms were required to include all ground combat vehicle and helicopter platforms that currently launch Tow, Hellfire, or Stinger missiles.

The objective of this preliminary design was to identify a system that could defeat all of the threats identified and, using measures of merit and comparison to the point design missiles, to refine that system to a viable 21st-century weapon system. Advanced technologies for the warhead, seeker, structures, and propulsion subsystems were identified and evaluated (qualitatively and quantitatively), with the most promising technologies selected for use in the preferred concept.

Thrust management and the impact, which aerodynamics has upon limited energy platforms, were identified early as the two most important design drivers. Consequently, a number of propulsion systems were evaluated. The candidate systems consisted of a solid pintle motor, a solid pulsed motor, an air turborocket, a turbojet engine, a liquid bipropellant engine, a gelled bipropellant engine, and a two-stage combustion gelled hybrid motor. A coarse-gauge optimization procedure was used to reduce this set of propulsion options to three; then detailed trade studies were conducted to determine the system used in the preferred concept.

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Approach

System specifications were provided, and alternative concepts were evaluated and ranked. These measures of merit defined the bounds of the ACAMS question and provided the coarse gauge used to reduce the seemingly infinite possibilities. These specifications, in ranked order of importance, were weight (nominal maximum): 60–70 lb, length (nominal maximum): 48–72 in., launch tube diameter (nominal maximum): 5–6 in., standoff range (sea level, 6-g maneuverability): 5.0–7.5 miles, accuracy [circular error probability (CEP)]: 1.0–1.5 ft, off-boresight footprint (nominal maximum): 30–50 deg, time-to-target (nominal maximum, 5 km or 3 miles): 12–18 s, target vertical impact angle (0.6 mile downrange, 1000-ft altitude): 20–40 deg, launch and flight observables (probability of uncued, unaided observer at 2 miles under typical battlefield conditions): 5–15%, and unit production cost (excluding launchers and fire control systems): $50,000–$150,000.

Common Module

The general design sequence was initiated by determining which subsystems would be involved (the original scope was expanded to include seeker, warhead, and guidance technology) and then by identifying numerous options for each subsystem. Because the scope was voluntarily expanded, emphasis was placed on first selecting common elements to every system simulated. These common subsystems consisted of a millimeter wave seeker; a smart shaped-charge tandem warhead; a midcourse inertial, terminal homing guidance scheme; and an advanced composite airframe. With these subsystem choices frozen, the team was left with the propulsion subsystem and the aerodynamic planform with which to do detailed trade studies.

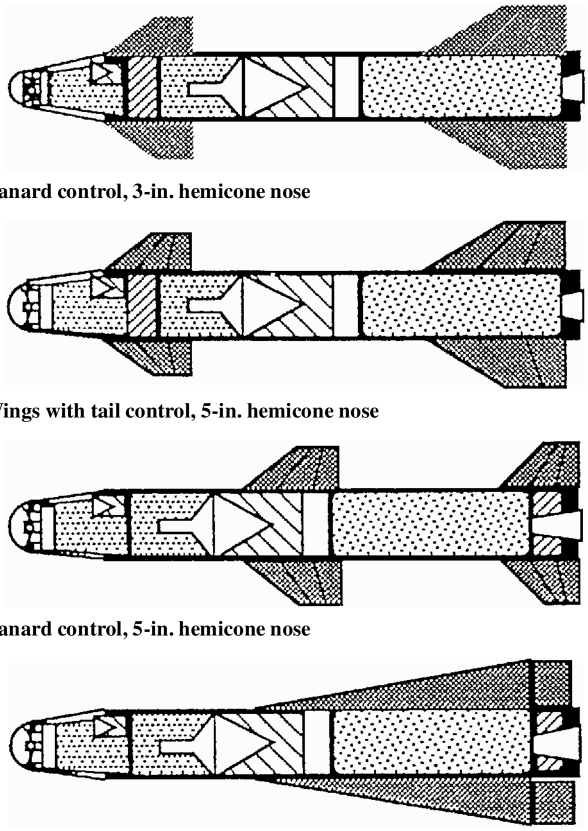
Aerodynamic Planform Options

After the initial coarse screening of planforms, four candidates were selected for mission simulation trade studies. Figure 1 shows these configurations.

For evaluating the aerodynamic planforms, Missile Datcom[2] was the program of choice. The code output lift, drag, and moment coefficients for any configuration at various speeds and angles of attack. The model also gives center of pressure and trim force data over the given flight envelope.

Propulsion Subsystem Options

To reiterate, the candidate subsystems consisted of a solid pintle motor, a solid pulsed motor, an air turborocket, a turbojet engine, a liquid bipropellant engine, a gelled bipropellant engine, and a


Canard control, 3-in. hemicone nose

Wings with tail control, 5-in. hemicone nose

Canard control, 5-in. hemicone nose

Tail only, 5-in. hemicone nose

Fig. 1 Alternative aerodynamic planforms.

two-stage combustion gelled hybrid motor. Early in the evaluation process, all forms of solid propulsion were excluded because, save for using a pintle mechanism, solid motors require a preprogrammed increment of thrust. Arguments can be made for using a pulsed motor, but it was clear that no matter how cleverly the boost/coast phases were programmed, there would never be the flexibility to ensure all mission profiles would be met. Combine this nonflexible energy management with the low performance typified by solid propellants (which would result in large weight penalties due to the amount of propellant carried onboard), and this exclusion is reasonable.

Similarly, air turborockets and turbojets were excluded during the coarse screening, even though they provide far superior energy management and throttleability to the best bipropellant engines. However, these powerplants are better suited to long-range or loitering/autonomous search mission profiles. In addition, these engines would require some type of boost motor for the tube launch, resulting in a heavier and longer missile. These facts also make this exclusion reasonable.

The three remaining choices, liquid bipropellant engines, gelled bipropellant engines, and gelled hybrid motors, were then used for mission simulation trade studies. Each candidate system, outlined in Table 1, was modeled using the Thermochemical Equilibrium Program (TEP),[3] a Windows-based derivative of the NASA Lewis Research Center one-dimensional equilibrium (ODE) thermochemical code. The user selects the oxidizer and fuel combination, the nozzle area or pressure ratio, and the oxidizer-to-fuel ratio, and the program calculates C^*, I_{sp}, and other propellant-specific parameters.

The two bipropellant alternatives were classic, single-stage combustion cycles where both fuel and oxidizer were injected into a main combustion chamber. The hybrid alternative, however, was a unique approach in that a two-stage combustion cycle was used. The first stage consisted of the decomposition of a glycidyl azide polymer (GAP)/carbon-filler monopropellant in a gas generator configuration. The exhaust products were then injected into the second-stage main combustion chamber and oxidized using gelled inhibited red fuming nitric acid (IRFNA).

A propulsion sizing program[4] was incorporated into the mission simulator output routine, which allowed the output of details such as propellant tank length and weight, thrust chamber size, nozzle weight and length, and staging length. To reduce system weight, the propulsion system was designed as a load carrying member in the airframe.

Table 1 Alternative propulsion subsystem

Proplusion subsystem	Propellants	I_{sp}	Minimum signature?
Staged combustion hybrid	GAP/Carbon/IRFNA	~250	Yes
Gelled bipropellant	MMH/IRFNA	~240	Yes, nonmetallized
Liquid bipropellant	MMH/IRFNA	~240	Yes, nonmetallized

Mission Analysis

Fastpass,[5] a vehicle synthesis and trajectory simulation tool, was originally used as a two-dimensional Space Shuttle trajectory simulator. The code was modified to allow for nonballistic trajectories and to allow for ground impact. A vehicle model was first input (the aerodynamic model from Datcom, all nonpropulsive weight, and the propulsion system model from TEP), then a mission sequence requirement was added. Fastpass then optimized the vehicle to satisfy the mission by minimizing system weight, system length, time of flight, or any other parameter specified by the user. For this analysis, the measures of merit were used as simulation constraints, with minimum system weight used as the optimization parameter.

Each of the four aerodynamic planforms (Fig. 1) were then flown with three different propulsion systems (Table 1). The 12 missiles competed in a series of Fastpass flyouts, with inputs from Datcom for each planform, and ODE calculations (C^*, nozzle area ratio, thrust coefficient, and mixture ratio) for each propulsion subsystem used. These combined with the sizing model incorporated into Fastpass allowed each of the 12 systems to be sized and optimized in a single simulation, with each simulation consisting of all of the following mission profiles: 1) maximum standoff range of 6 miles with a minimum impact velocity of 400 ft/s (required for 6-g maneuverability) and an impact angle between 30 and 40 deg, 2) 15-s time of flight to a 3-mile hardened bunker target with a minimum impact velocity of 1675 ft/s (required for bunker penetration) and an impact angle between 30 and 40 deg, and 3) 5-mile air target at 325-ft altitude. Figure 2 shows this process flow.

Evaluation Criteria

A majority of the analysis and design work went into formulating the constraints, boundary conditions, and mission profiles for the Fastpass simulations and into choosing subsystems for the common module. The missile diameter was fixed at 6 in.; the seeker met the off-boresight footprint requirement, and in conjunction with the guidance, navigation, and control electronics, the system had a CEP of 1.6 ft; the low-flight observables requirement was met in choosing the propellants for each of the propulsion systems; the standoff range, time of flight, and target vertical impact angle requirements were all met by the mission profiles in Fastpass. As a result, missile weight, length, and unit production cost were used as measures of merit for system comparison. Therefore, because weight was the highest ranked measure of merit, it was chosen as the optimization parameter for Fastpass, as well as the final gauge for a baseline system selection.

System Refinement

As the analyses became more detailed, the common module just described evolved, requiring updates to the baseline system. Also, the ODE analysis was expanded to reflect the staged combustion by using a two-step procedure. The first stage modeled the GAP/carbon decomposition, with the exhaust species from the first-stage analysis becoming the fuel input for the second-stage IRFNA oxidation. This modeling refinement resulted in lower performance, and so overall these changes increased the missile inert weight from 25 to 37 lb.

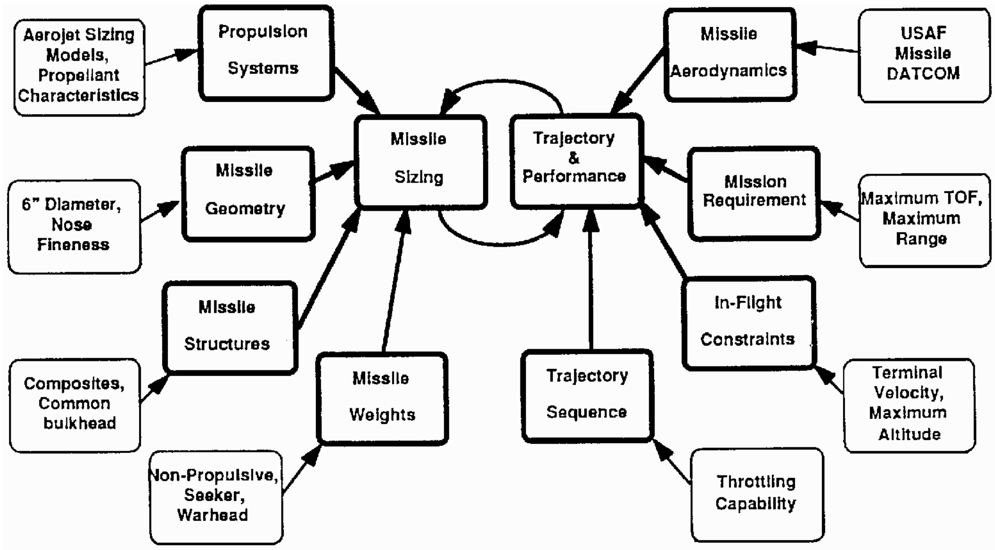


Fig. 2 Mission analysis and vehicle synthesis.

To further refine the selected system, a sensitivity analysis was performed to determine the relationship between time of flight, standoff range, and missile weight and length. The Fastpass missions were changed to first vary time of flight to a 3-mile ground target from 12 to 18 s while holding standoff range constant; then standoff was varied from 6.2 to 7.5 miles while holding time of flight constant. The optimized system required, then, striking a balance between missile performance and size.

Unit production cost (UPC) (not to include fire control or launch platforms) was calculated only for this optimized system using a cost model based on historical weapons program information. A production learning rate was calculated by averaging the learning rates from Chaparral, Hellfire, Maverick, Stinger, and Tow historical production figures. The following subjective factors were incorporated into the model as well: a technology inheritance factor, an estimate of the percentage of each subsystem that consisted of technology already fielded in other weapons systems; a technological readiness factor, a percent estimate of the amount of advanced technology needed in the system; and a complexity factor, another percent estimate of how complex the new technology would be over current state-of-the-art technology. A 38-year average inflation rate of 3% was used in calculating UPC in fiscal year 1993 (FY93) dollars. The spreadsheet was then programmed to maximize the number of missiles built by using a ramped, 10-year production schedule. Total system production budget was $2 billion (FY93 dollars); this figure does not include advanced technology programs or fire control/launch platform retrofit.

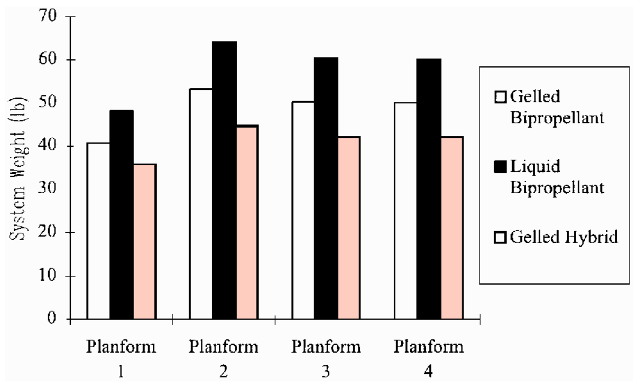


Fig. 3 Alternative concept weight comparison.

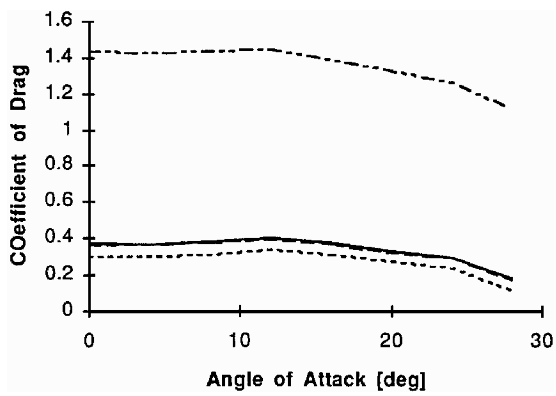


Fig. 4 Influence of nose shape on drag: - - -, Ogive; – – –, 3-in. Hemi-Ogive; ——, 4-in. Hemi-Ogive; and – - - -, 5-in. Hemisphere.

Results

Baseline Selection

Figure 3 shows the results of the 12 flyouts. It can be seen that planform 1 provided the lowest total system weight for all propulsion subsystems flown. The combination of planform 1 and the staged combustion hybrid provided the overall low total system weight.

A number of design factors contributed to these results: the 3-in. hemicone nose cut drag down dramatically at all angles of attack (see Fig. 4); the canard control surfaces tended to be smaller than the other control surface configurations, resulting in lower drag; and the higher density I_{sp} for the staged combustion hybrid system required less fuel and oxidizer and, consequently, smaller tankage.

Using the weight comparisons shown in Fig. 3, the gelled hybrid motor was selected along with planform 1 to complete the baseline common module. This missile, christened battlefield all-weather nighttime sure-hit enemy eliminator (BANSHEE) is shown with exterior and interior details in Fig. 5.

Figure 6 shows the system refinement process results. Recall that the nonpropulsive weight was updated from 25 to 37 lb and that a higher fidelity ODE analysis was completed prior to system refinement.

As shown in Fig. 6, normal and axial accelerations were beyond the anticipated airframe capabilities for times of flight less than 14 s. Also, increasing the standoff range of 6.2 miles used during baseline selection to 7.5 miles (the preferred range) resulted in only a 4-lb weight penalty. Thus, the balance between weight and performance was found at the 7.5-mile range, 14-s time-of-flight design point.

Examining the weight growth between selection and refinement for this system shows an increase of 67.5% with an increase in length of 25.6%. If identical increases were calculated for the remaining 11 systems not chosen for refinement, all but one (the gelled bipropellant option) would be disqualified due to excess weight and length. Even that is misleading, however, because the density of monomethylhydrazine (MMH) is much lower than that of GAP, and so the growth for the other 11 systems would be higher. These

Table 3 BANSHEE, Tow, Hellfire, and Stinger performance comparison[a]

	RWA-clear	RWA-clutter	Attacking FWA	Heavy Armor	Light Armor	Bunker	Radar site	Maximum range, mile	Weight, lb; length, in.; diameter, in.
Tow	S	S	N/A	P	P	S	S	2.3	54, 46, 6
Stinger	P	P	P	N/A	N/A	N/A	N/A	3.7	35, 60, 3
Hellfire	P	P	S	P	P	S	S	4.3	100, 65, 7
BANSHEE	P	P	P	P	P	P	P	7.5	60, 55, 6

[a]Poor performance indicated by bold face outline, marginal performance by light face outline, and good (or not applicable) performance not outlined. RWA, rotary wing aircraft; FWA, fixed-wing aircraft; P, primary; S, secondary; and N/A, no requirement.

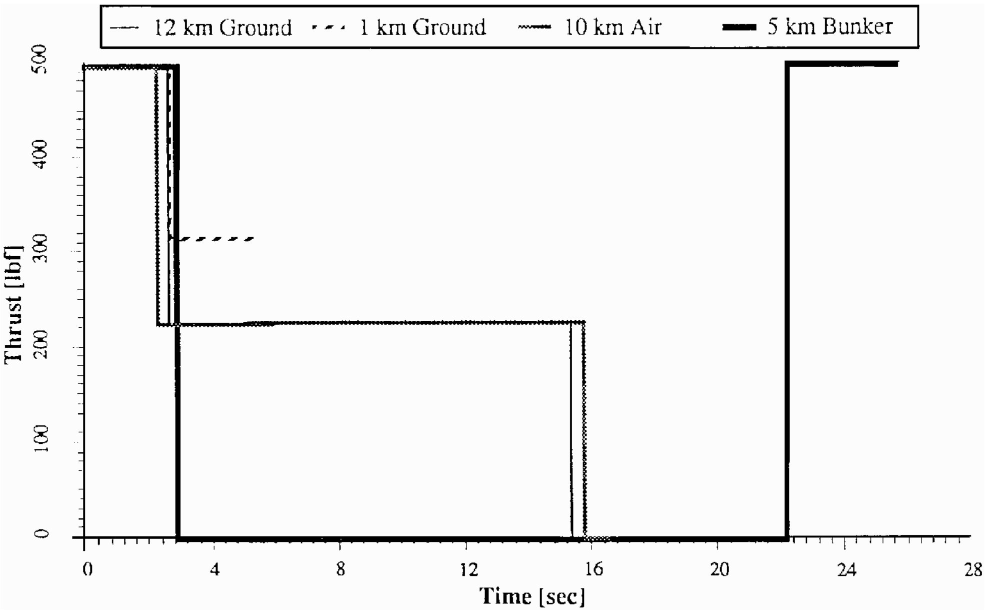


Fig. 7 Hybrid propulsion energy management.

horizontal and vertical and the tail surfaces directly horizontal and vertical. This arrangement ensured that every control surface sees the least turbulent air, resulting in higher control forces at a given speed for excellent maneuverability. As with the rest of the airframe, the control surfaces were constructed of carbon fiber-epoxy composites. To facilitate launch tube storage, the canards were foldover, elongated-hex configurations, whereas the aft fins were rigid, wraparound configurations.

Propulsion

The baseline propulsion[20–22] system is a gelled IRFNA, GAP solid gas generator hybrid. Combustion occurs in two stages: the first stage is the decomposition of the carbon-loaded GAP, with its hot gases injected into the second-stage main combustion chamber and oxidized using gelled IRFNA. The GAP has a high exponent for good burn rate control and is a high-density, high-energy monopropellant. It also has a low-hydrogen content, resulting in an opaque, low-water-content exhaust when oxidized with gelled IRFNA.

The propellant tank was a nested bulkhead design, where one hemisphere of the gas generator outer tank forms an end of the gelled IRFNA tank. The gas generator contained additional propellant to allow a portion of the hot gas to be used as pressurant for the IRFNA. In addition, a rubber bladder in the oxidizer tank was used to expel its contents in a controllable fashion (a 5% ullage was assumed in the system optimization).

Maximum thrust performance parameters for the gelled hybrid were calculated to be thrust: 500 lb, chamber pressure: 520 psi, mixture ratio: 2.12, fixed nozzle area ratio: 5.0, vacuum I_{sp}: 253 s, and throttling ratio: 2:1 (with midflight stop/restart capability).

Figure 7 clearly shows the flexibility of this propulsion subsystem.

Unit Production Cost

After the system was refined and the design iterations were halted, a UPC was estimated to be $70,000. For the $2 billion production contract, 28,500 missiles would be produced. Figure 8 shows the production schedule with acquisition costs.

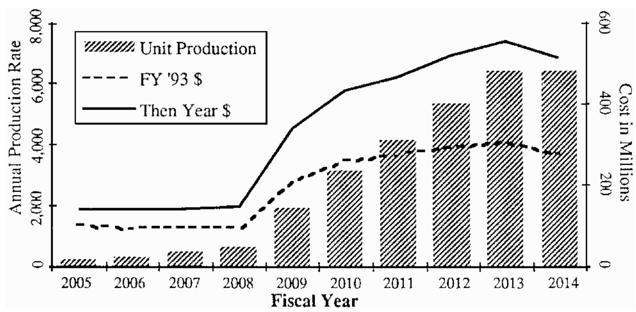


Fig. 8 BANSHEE production schedule.

System Performance

Table 2 shows how the BANSHEE design meets every measure of merit.

BANSHEE performs well against all required targets. Table 3 shows the relative performance of BANSHEE vs Tow, Stinger, and Hellfire, with BANSHEE clearly outperforming the point-design missiles against the entire target spectrum. The Tow, Stinger, and Hellfire capabilities shown are based on a U.S. Army Missile Command mission analysis to support the TACAWS (The Army Combined Arms Weapon System) multimission missile system.[23]

Conclusions

The varied missions specified in the RFP required an advancement of current state of the art to design a single missile system that could defeat every target. Smart subsystems were incorporated into the BANSHEE, as it was found that only with proper lethal effect and propellant energy management could the multimission role be realized. The throttleable gelled hybrid motor with midflight stop/restart capabilities had the highest performance, resulting in the lightest possible missile.

Much of the technology used on BANSHEE would represent significant developmental risk; however, by implementing advanced technology development programs, this risk would be significantly reduced.

Acknowledgments

The weapon system described in this paper represents the work of undergraduate and graduate students at the University of Alabama in Huntsville associated, in part, with the Propulsion Research Center. Without the significant work by Steve Cornelius, Steve Mustaikis, Joseph Parsley, George Story, Joseph Szedula, Michael Smith, and the entire finance team, the missile system described in this paper would not exist. The engineering maturity reflects not only the eminent mentoring by professionals in the field, but the dedication, spirit, and caliber of these students.

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