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Technologies for Future Precision Strike Missile Systems -
Missile Aeromechanics Technology

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Abstract/Executive Summary

This paper provides an assessment of the state-of-the-art of new aeromechanics technologies for future precision strike missile systems. The aeromechanics technologies are grouped into specific discussion areas of aerodynamics, propulsion, and airframe materials technologies. Technologies that are addressed in this paper are:
- **Missile aerodynamics technologies**. Assessments include aerodynamic configuration shaping, lattice tail control, split canard control, forward swept surfaces, bank-to-turn maneuvering, and flight trajectory shaping.
- **Missile propulsion technologies.** Assessments include supersonic air breathing propulsion, high temperature combustors, low drag ramjet inlets, ramjet inlet/airframe integration, higher density fuels, rocket motor thrust magnitude control, high thrust motor, and reaction jet control.
- **Missile airframe materials technologies.** Assessments include hypersonic structure materials, composite structure materials, hypersonic insulation materials, multi-spectral domes, and reduced parts count structure.

Introduction

Missile aeromechanics technologies have benefits that include enhanced flight performance, reduced weight, increased Mach number, reduced cost, higher reliability, and reduced observables. Figure 1 summarizes new aeromechanics technologies for precision strike missiles. Most of the technologies in the figure are covered in this paper, however there was not sufficient time to address them all. A summary of other new aeromechanics technologies is presented in the Introduction/Overview paper of this lecture series.

Missile Aerodynamics Technologies

This assessment of missile aerodynamics technologies addresses six new enabling technologies. These are aerodynamic configuration shaping, lattice tail control, split canard control, forward swept surfaces, bank-to-turn maneuvering, and flight trajectory shaping.

Aerodynamic Configuration Shaping. Figure 2 illustrates aerodynamic configurations that are highly tailored, using aerodynamic shaping of lifting body configurations. An advantage of a tailored lifting body missile is higher aerodynamic efficiency (lift-to-drag ratio) for extended range cruise performance and enhanced maneuverability. Also shown in Figure 2 is the synergy of tailored missiles with reduced radar cross section. Tailored missiles are also synergistic with ramjets for areas such as inlet integration and liquid hydrocarbon fuel packaging. Disadvantages of tailored missiles include their relative inefficiency for solid subsystems packaging and an adverse impact on launch platform integration, due to a larger span. Improved methods and tests are required for the prediction of the aerodynamics and the structural loads of non-axisymmetric weapons. This includes more extensive wind tunnel tests, computational fluid dynamics (CFD) predictions, and finite element modeling (FEM) of structural integrity.

Lattice Tail Control. Another example of new aeromechanics technology is lattice tail control. Lattice fins have advantages of lower hinge moment and higher control effectiveness at supersonic Mach number. Figure 3 shows a comparison of lattice tail control with two conventional approaches to tail control - all movable control and flap control. Except for radar cross section, lattice tail control has good-to-superior performance for supersonic missiles. Also shown in the figure are examples of supersonic missiles with tail control alternatives of lattice tail control (Adder AA-12), all movable tail control (ASRAAM AIM-132), and flap tail control (Hellfire AGM-114). The smaller chord length of the lattice has less variation in the center of pressure, resulting in lower hinge moment for lattice tail control. Lattice fins are most appropriate for either subsonic or high supersonic missiles. At subsonic Mach number the drag of lattice fins is comparable to that of traditional flight control. At transonic Mach number, lattice fins have higher drag and lower control effectiveness than traditional flight control. At a low transonic free stream Mach number less than 1, the local flow through the lattice accelerates to Mach 1, choking the flow (see Figure 4). For a transonic free stream Mach number slightly greater than 1, the flow through the lattice remains choked. A detached, normal shock wave in front of the lattice spills excess air around the lattice. The lattice remains choked until the supersonic Mach number is sufficiently high to allow the lattice to swallow the shock. An oblique shock is then formed on the leading edge of each surface of the lattice. At low supersonic Mach number the oblique shock angle is large. Each oblique shock is reflected downstream, off an adjacent lattice surface, resulting in increased drag. At higher Mach number the oblique shock angle is smaller, passing through the lattice without intersecting a lattice surface. In summary, lattice fins have their best application at low subsonic and high supersonic Mach number, where they have low drag and high control effectiveness.

Split Canard Control. Modern highly maneuverable missiles are using split canards for flight control. Split canard control has a fixed surface in front of the movable canard. Figure 5 is a schematic of the local flow that illustrates the advantage of split canards. The incremental normal force coefficient, ΔC_N, in the figure is the difference between the normal force coefficient of the deflected control surface and the normal force coefficient of an undeflected control surface. Note that the forward surface reduces the local effective angle of attack (α'). Because the trailing canard control surface has a smaller local angle of attack, it is more effective at higher control surface deflection, δ, and higher angle of attack, α, operating without stall. All modern canard control missiles use split canard control including Kegler AS-12, Archer AA-11, Aphid AA-8, Magic R-550, Python 4, and U-Darter.

Forward Swept Surfaces. Forward swept surfaces are an alternative to the traditional aft swept surfaces for missile canards, tails, and wings. Forward swept surfaces are particularly beneficial for missiles that require low radar cross section (RCS) or have small span requirements for aircraft compatibility. A forward swept wing has low frontal RCS because the wing sweep and the attenuation of backscatter bouncing off the adjacent body. Figure 6 is a comparison of a forward swept leading edge surface with conventional planform surfaces that are triangular (delta), trapezoidal with an aft swept leading edge, and rectangular. In addition to a low RCS and smaller span, forward swept surfaces have good-to-superior characteristics of low variation in aerodynamic center, low bending moment, low supersonic drag, and high control effectiveness. An inherent disadvantage of a forward swept surface is increased potential for aeroelastic instability. Composite structure is synergistic with forward swept surfaces because the higher stiffness of composites mitigates aeroelastic instability. Composite material may also be used in radar absorbing structure. The U.S. AGM-129 Advanced Cruise Missile and the Russia AA-10 are examples of missiles with a forward swept wing.

Bank-to-turn Maneuvering. Figure 7 compares bank-to-turn maneuvers with maneuver alternatives of skid-to-turn and rolling airframe. Missiles using bank-to-turn will first roll until the wings or the major axis of a lifting body are oriented perpendicular to the target line-of-sight. Following the roll maneuver, the missile then maneuvers in pitch, maintaining the preferred roll orientation. A benefit of bank-to-turn maneuvering is higher maneuverability for a lifting body with noncircular cross section or for a missile with wings. Another benefit is smaller sideslip angle for missiles with inlets. Bank-to-turn is particularly suited for mid-course guidance maneuvers prior to seeker lock-on to the target. A disadvantage of bank-to-turn maneuvering is slower response in terminal maneuvers and larger variation in dome error slope that could degrade guidance accuracy, increasing the missile miss distance. Alternative approaches to alleviate this problem include faster

actuators for roll control, faceted or multi-lens dome, and switching from bank-to-turn maneuvering to skid-to-turn maneuvering for terminal flight.

Flight Trajectory Shaping. Figure 8 illustrates the extended range advantage of precision strike missiles that use flight trajectory shaping. Flight trajectory shaping is particularly beneficial for high performance supersonic missiles, which have large propellant or fuel weight fraction. To take advantage of flight trajectory shaping, the missile must rapidly pitch up and climb to an efficient cruise altitude. During the climb, the missile angle-of-attack should be small, to minimize drag. The missile initial thrust-to-weight ratio should be relatively high (~10) for safe separation, followed by a relatively low thrust-to-weight ratio (~2) during climb. A climb thrust-to-weight ratio greater than about two will result in high dynamic pressure, increasing drag. After reaching higher altitude, the missile benefits from cruising at improved lift-to-drag ratio, or aerodynamic efficiency. Dynamic pressure for efficient cruise of a low aspect ratio missile is of the order of 500 to 1,000 pounds per square foot. Following burnout, the missile can also have extended range through glide at a dynamic pressure of about 700 pounds per square foot.

Missile Propulsion Technologies

The assessment of missile propulsion technologies addresses eight enabling technologies. These are supersonic air breathing propulsion, high temperature combustors, low drag ramjet inlets, ramjet inlet/airframe integration, higher density fuels, rocket motor thrust magnitude control, high thrust motor, and reaction jet control.

Supersonic Air Breathing Propulsion. Ramjets, scramjets, and ducted rockets have high payoff for precision strike missiles operating at supersonic/hypersonic Mach number. A comparison of the specific impulse performance of ramjet, scramjet, and ducted rocket propulsion, along with that of solid rocket and turbojet propulsion, is given in Figure 9.

Turbojet and turbofan propulsion is a relatively mature technology for precision strike missiles. Turbojets/turbofans are most suited for subsonic cruise missiles, providing high efficiency to deliver a warhead at long range against non-time-critical targets. The operating regime is to about Mach 3. However, beyond Mach 2, increasingly complex inlet systems are required to match delivered inlet airflow to compressor capacity, and expensive cooling is required to avoid exceeding material temperature limit at the turbine inlet.

Solid rockets are capable of providing thrust across the entire Mach number range. Although the specific impulse of tactical rockets is relatively low, of the order of 250 seconds, rockets have an advantage of much higher acceleration capability than air-breathing propulsion. Solid rocket boosters are used to boost ramjets to their take-over Mach number of about 2.5, for transition to air-breathing propulsion.

The maximum specific impulse of a liquid hydrocarbon fuel ramjet is about 1,500 seconds, much higher than the specific impulse of a solid rocket. An efficient cruise condition for a ramjet is about Mach 4, 80K feet altitude. Above Mach 5, the combustor material maximum temperature limits the achievable exit velocity and thrust. Also, the deceleration of the inlet airflow to subsonic velocity results in chemical dissociation of the air, which absorbs heat and negates a portion of the energy output of the combustor. Liquid fuel ramjets are synergistic with noncircular, lifting body airframes because ramjet fuel can be stored in noncircular tanks. Liquid fuel ramjets can be throttled, for efficient matching of the fuel with the inlet airflow. Throttling provides higher thrust and specific impulse over a broader flight envelope of Mach number and altitude. A rocket booster is required to boost the ramjet up to a speed where the ramjet thrust is greater than the drag of the missile. Ramjet takeover speed is about Mach 2.5.

Above Mach 6, a supersonic combustion ramjet (scramjet) provides higher performance than a ramjet. The minimum sustained flight Mach number of a scramjet, based on providing sufficient thrust to overcome missile drag, is greater than about Mach 4.0. The maximum Mach number, based on engine material temperature limit, is about Mach 8 to 9. An efficient cruise condition for a scramjet is about Mach 6, 100K feet altitude. A key technical challenge is fuel mixing for efficient supersonic combustion. There are

extremely short residence times for supersonic combustion. An enabling technology to enhance supersonic combustion is endothermic fuels. Endothermic fuels decompose at high temperature into lighter weight molecular products that burn more readily, providing higher specific impulse and permitting shorter combustor length. An endothermic fuel also acts as a heat sink, cooling the adjacent structure. Like the ramjet, the scramjet is rocket boosted to a supersonic takeover speed. Takeover speed of a scramjet is higher than a ramjet, about Mach 4.5, requiring a larger booster. For a weight-limited system, a hypersonic scramjet missile will have less available fuel than a supersonic ramjet missile.

Referring again to Figure 9, note that the maximum specific impulse of ducted rocket propulsion is about 800 seconds, intermediate that of a solid rocket and a liquid fuel ramjet. Ducted rockets are most efficient for a Mach number range from about 2.5-4.0. Ducted rockets have advantages of higher acceleration capability (higher thrust) than liquid fuel ramjets and generally have longer range capability (higher specific impulse) than solid rockets. A ducted rocket is particularly suited for the suppression of long range, high performance SAMs. The acceleration and fast response to Mach 3+ provides a short response time for an anti-SAM engagement. Ducted rockets utilize a gas generator to provide fuel-rich products to the combustor. The gas generator flow rate can be controlled, providing a throttle capability for thrust magnitude control. Air from the inlet mixes with the fuel-rich products from the gas generator, providing additional burning. The relatively high acceleration capability of the ducted rocket is due to the momentum of the gases from the gas generator. A disadvantage of the ducted rocket is lower specific impulse than a liquid fuel ramjet. Because the gas generator includes an oxidizer, the total energy stored in the gas generator is less than that of a ramjet or scramjet fuel tank of the same volume. In addition to a relatively high thrust capability of a ducted rocket compared to a ramjet or scramjet, a solid ducted rocket has advantages of lower maintenance requirements and better shipboard compatibility than a ramjet or scramjet.

Figure 10 shows a history of the state-of-the-art advancement for supersonic/hypersonic air breathing missiles over the last fifty years. A number of liquid fuel ramjet demonstrations have been conducted over the years. As shown in the figure, the cruise Mach number demonstrations have provided higher confidence in the capability for efficient hypersonic cruise. Ramjets have demonstrated supersonic and hypersonic cruise up to Mach 4.5. A future flight demonstration of a scramjet plans to demonstrate Mach 6.5 cruise in the year 2004 time frame.

High Temperature Combustors. Higher combustion temperature has payoff in improving the specific impulse and thrust of ramjet missiles, enabling flight at higher Mach number. Figure 11 shows the ideal combustion temperature for maximum specific impulse and thrust of an ideal ramjet as a function of Mach number. Results are based on an assumption of isentropic flow and nozzle expansion to atmospheric pressure. As an example, assume that a ramjet baseline missile is operating at 80,000 feet altitude with a combustion temperature of 4,000 degrees Rankine and a fuel-to-air ratio of 0.02. The ratio of the combustion temperature to the free stream temperature is 10.2 and the ratio of specific heat is 1.29. As shown in the figure, for a combustion temperature of 4,000 degrees Rankine, maximum specific impulse for a ramjet is produced at a Mach number of about 4.2. Also shown is the Mach number for maximum thrust per unit frontal area. The maximum thrust per unit frontal area for a combustion temperature of 4,000 degrees Rankine is produced at a Mach number of about 4.5. Improvement in the technology for maximum allowable temperature of insulated combustor materials allows ramjets to operate at higher Mach number. Also shown in the figure are examples of the ideal Mach number at a specific heat ratio of $\gamma = 1.4$, corresponding to a low value of the combustion temperature. The ideal Mach numbers are lower for a low combustion temperature with $\gamma \approx 1.4$.

Low Drag Ramjet Inlets. Examples of low drag inlet alternatives for ramjets are shown in Figure 12. Current operational ramjets have either a nose inlet (United Kingdom Sea Dart) or aft axisymmetric inlets (France ANS and ASMP, Russia AS-17/Kh-31, Kh-41, SS-N-22/3M80, and SA-6). A nose inlet has an advantage of lower drag, while aft axisymmetric inlets have advantages of lighter weight, lower volume, and they do not shroud/degrade warhead effectiveness.

Ramjet Inlet/Airframe Integration. Because ramjet combustion is subsonic, there must be a normal shock in the inlet to provide subsonic flow into the combustor. Small oblique shocks prior to the normal shock alleviate the problem of total (stagnation) pressure loss across the normal shock. Figure 13 compares a single,

normal shock total pressure recovery with that of one, two, and three oblique shocks prior to the normal shock. Note that three oblique shocks prior to the normal shock provide a relatively high stagnation pressure recovery. Ramjet inlet/airframe integration through external forebody compression (such as a chin inlet), an optimized inlet cowl lip angle, and internal turning provide higher specific impulse and higher thrust. At hypersonic Mach number a mixed compression inlet (external compression from oblique shock(s) on the forebody, followed by internal oblique shock(s) inside the inlet) is often required. A mixed compression inlet may be desirable to avoid excessive flow turning away from the axial direction. An example is shown of a chin inlet ramjet, which has mixed compression consisting of three oblique shocks. There are two external oblique shocks (from a conical forebody half angle of 17.7 degrees and an inlet ramp angle of 8.36 degrees) plus an internal oblique shock of 8.24 degrees. As shown in the example, the stagnation pressure recovery ratio at Mach 3.5 is 83 percent if there are three oblique shocks. This stagnation pressure recovery is much higher than that for the case of one oblique shock prior to the normal shock or for the case of a single normal shock. Ramjet inlet/airframe integration through forebody compression (such as a chin inlet) and an optimized inlet cowl lip angle provides higher specific impulse and higher thrust.

High Density Fuels. Another area of new propulsion advancement is that of higher density fuel. Higher density fuels provide high volumetric performance for volume limited missiles (Figure 14). Current fuels for turbines such as JP-5, JP-7, and JP-10 have relatively low density, of the order of 0.028 pounds per cubic inch, and low volumetric performance, of the order of 559 BTU per cubic inch. Liquid fuel ramjet hydrocarbon fuels such as RJ-4, RJ-5, RJ-6, and RJ-7 have somewhat higher density and higher volumetric performance. Slurry fuels, such as JP-10 with carbon slurry, and solid hydrocarbon fuels have much higher volumetric performance, at the expense of somewhat higher visual observables. Even better performance is achievable with high density, solid metal fuels such as magnesium, aluminum, and boron. For example, solid boron fuel, with a theoretical solids loading of 100%, would provide over three times the volumetric performance of a liquid hydrocarbon fuel. However, disadvantages of solid metal fuels are high visual observables from their plumes and reduced volumetric efficiency from the hollow center grain core that is required for the inlet airflow.

Rocket Motor Thrust Magnitude Control. An approach to energy management for a solid rocket is thrust magnitude control. Alternatives include pulsed and pintle motors (Figure 15). The solid pulsed motor uses thermal or mechanical barriers to separate two or more pulses. The time delay between pulses can be controlled to optimize the flight trajectory profile. As a result, a boost-coast-boost-coast pulsed motor can have longer range and reduced aerodynamic heating compared to conventional single burn boost-coast or boost-sustain-coast motors. The second approach to thrust magnitude control, a solid pintle motor, has a pintle plug that is moved in and out of the throat area. Moving the pintle into the throat area provides increased chamber pressure and higher thrust, while moving the pintle out of the throat area decreases the chamber pressure and thrust. Pintle motors have demonstrated maximum-to-minimum thrust ratios of up to ten-to-one. However, larger thrust ratio is at the expense of reduced specific impulse. A third potential alternative for thrust magnitude control is a gel propellant motor. Gel propellants have not yet been accepted for tactical missile applications, particularly for naval platforms, due to concerns of toxicity.

High Thrust Motor and Reaction Jet Control. Photographs of the US Army Line-of-Sight Anti-Tank (LOSAT) kinetic kill precision missile are shown in Figure 16. Shown are launches from the Bradley Infantry Fighting Vehicle (IFV) and the High Mobility Multipurpose Wheeled Vehicle (HMMWV). LOSAT has no warhead charge - the kinetic energy of the hypersonic missile provides the kill mechanism. LOSAT provides kinetic energy on target that exceeds that of a tank round, without requiring the heavy weight of a tank gun. It is particularly suitable for rapidly deployed, light forces. The LOSAT system can be deployed using a C-130 aircraft, while an M-1 tank cannot be carried on a C-130 aircraft. Aeromechanics technologies include high thrust motor and reaction jet control. Rapid acceleration to hypersonic speed is provided by a high thrust motor, which has rapid burn propellant. Hit-to-kill accuracy is provided by the launch platform projecting a narrow beam laser spot on the target, laser beam rider guidance, and reaction jet control.

Missile Airframe Materials Technologies

The assessment of missile airframe materials technologies addresses five new enabling technologies. These are hypersonic structure materials, composite structure materials, hypersonic insulation materials, multi-spectral domes, and reduced parts count structure.

Hypersonic Structure Materials. Examples of structure materials that are cost effective for precision strike missiles are shown in Figure 17. The materials are based on consideration of weight, cost, and maximum temperature capability. Composite materials are a new technology that will find increased use in new missile airframe structure. High temperature composites have particular benefits for hypersonic missiles, providing weight reduction. Titanium alloy technology also enables lighter weight missiles in a hypersonic, high temperature flight environment.

As shown in the figure, at subsonic and low supersonic Mach number, graphite epoxy and aluminum or aluminum alloys are attractive choices for lighter weight structure. Graphite epoxy and aluminum alloys have high strength-to-weight ratio, are easily fabricated, have good corrosion resistance, and are low in cost. For higher Mach number, graphite polyimide composite structure has an advantage of high structure efficiency at higher temperature for short duration flight Mach numbers to about Mach 4. For flight at about Mach 4.5, without external insulation, titanium structure and its alloys are preferred. A disadvantage of a titanium structure is higher material and machining cost. However, the cost to cast a part made of titanium is comparable to the cost to cast an aluminum part. At Mach 5, although it is heavy, a steel structure would probably be used. Up to Mach 5.7 without external insulation (about 2,000 degrees Fahrenheit), super nickel alloys such as Inconel, Rene, Hastelloy, and Haynes must be used. Above Mach 5.7 the super alloys require either external insulation or active cooling. The Mach number and temperature application relationships are somewhat dependent upon the temperature recovery factor. At a stagnation region, such as the nose or leading edges, the recovery factor is about 1, resulting in the highest (stagnation) temperature. A turbulent or laminar boundary layer downstream of the nose or leading edge will have temperature recovery factors of about 0.9 and 0.8 respectively, with local temperatures less than stagnation.

Composite Structure Materials. The strength-to-weight capability of advanced composites is very high. For example, as shown in Figure 18, the unidirectional tensile strength of a small diameter graphite (carbon) fiber is more than 400,000 pounds per square inch. In addition to small diameter fibers, advanced composite structures have long, continuous fibers and a fiber/matrix ratio that is greater than 50% fibers by volume. Fibers can be graphite (carbon), kevlar, glass, boron, ceramic, silicon carbide, quartz, polyethylene, and others. As an example of strength at the structure level, 50% volume graphite composite structure can have a strength in a tailored laminate that is above 200,000 pounds per square inch, much greater than that of aluminum, or even steel. Also the low density of composites further reduces the weight compared to metals. Graphite fiber composite materials have extremely high modulus of elasticity, resulting in low strain and deflection compared to metals. However, a note of caution, unlike metals that generally yield gracefully before ultimate failure, composite fibers generally fail suddenly without yield.

Figure 19 shows the structural efficiency advantage of composites compared to conventional materials. For short duration temperatures up to about 400 degrees Fahrenheit, graphite epoxy is a good candidate material, based on its characteristics of high strength and low density. Graphite polyimide can be used at even higher temperatures, up to about 1,100 degrees Fahrenheit short duration temperature. Above 1,100 degrees Fahrenheit, titanium and steel are the best materials based on strength-to-weight ratio.

Hypersonic Insulation Materials. An area of enabling capability for hypersonic precision strike missiles is short duration insulation technology. Because hypersonic precision strike missiles have stringent volume and weight constraints, higher density external airframe and internal insulation materials are in development. Higher density insulation materials permit more fuel/propellant, resulting in longer range. Thermal insulators are used to provide short duration protection of structural materials from either the aerodynamic heating of a hypersonic free stream or from propulsion heating of the combustion chamber and exhaust gases of the nozzle. Figure 20 shows the maximum temperature and short duration insulation efficiency of candidate insulation materials.

Note that composite materials are good candidates for lighter weight insulation. For high-speed precision strike missiles, medium density plastic composites, such as fiberglass reinforced phenolic resins containing nylon, silica, graphite, or carbon are often used. These have good resistance to erosion, allow high surface temperatures (over 5,000 degrees Rankine) and exhibit good insulation performance. Medium density plastic composite materials char at high temperature, but generally maintain their thickness and aerodynamic shape. They are usually fabricated by wrapping fiberglass tape over a metal form mandrel, so that the grain of the finished unit is oriented for minimum erosion. Cross flow orientation, or other grain directional orientation, is optimized to minimize the amount of the material that is required. After winding, the tape is cured, machined as necessary, and assembled with other components using adhesives and sealants. Another example of a good insulator at somewhat lower temperatures is lower density composites. Lower density composites such as quartz beads/paint, glass cork epoxy or silicone rubber may be used for temperatures up to about 3,000 degrees Rankine. Quartz beads/paint is a spray-on insulation of about 0.015 inch per coat. A third approach based on lower density plastics is rarely used for hypersonic missiles. A disadvantage of low density plastics is that at high temperatures they decompose into gases and sublime, resulting in decreased thickness and changes in the aerodynamic shape. Lower density plastics are also relatively soft, requiring periodic maintenance touch-up.

Ceramic refractory materials and graphite materials are also candidate insulators for high speed airframes, engines, and motor cases. Although ceramic refractory materials and graphites have high temperature capability, the insulation efficiency for a given weight of material is not as good as that of plastic composite materials. An example of a porous ceramic, with a maximum temperature up to about 3,500 degrees Rankine, is resin impregnated carbon-silicon carbide. At high temperatures the resin melts, providing cooling for the structure. Examples of bulk ceramics are zirconium ceramic and hafnium ceramic. Bulk ceramics are capable of withstanding temperatures up to 5,000 degrees Rankine, but like porous ceramics, they have relatively poor insulation efficiency. Finally, graphite insulators provide the highest temperature capability. Graphites are capable of withstanding temperatures greater than 5,000 degrees Rankine. However, graphites have relatively poor insulation efficiency.

Airframe structure/insulation trades include hot structure/internal insulation versus external insulation/"cold" structure versus a one-piece self-insulating composite structure. A consideration for a volume-limited missile is the total thickness of the airframe/insulation. Large thickness means less volume for fuel, resulting in less range.

Multi-spectral Domes. Shown in Figure 21 is a comparison of alternative dome materials for missile seekers. The dome materials are grouped based on their best applicability to multi-mode (RF/IR), RF-only, and mid-wave IR-only seekers. Measures of merit are dielectric constant, combined mid-wave/long wave infrared bandpass, transverse strength, thermal expansion, erosion resistance, and maximum short duration temperature. Dome materials that are especially suited for combined radar and infrared seekers are zinc sulfide and zinc selenide. Zinc sulfide has advantages in dielectric constant, transverse strength, and rain erosion. Zinc sulfide is generally the multi-mode dome material of choice for Mach numbers up to 3. For Mach number greater than 3, new materials are required for multi-mode seekers. Candidate materials include spinel/sapphire, quartz/fused silicon, and silicon nitride. These materials are more expensive than zinc sulfide and zinc selenide. A new candidate dome material that is under development for missile defense applications is diamond. Obviously cost is very high for a diamond dome. In addition to high material cost, diamond dome assembly cost is high. Diamond domes must be assembled as a built-up mosaic because the present manufacturing processes produce relatively small size diamonds.

For RF-only seekers, two popular radome materials are pyroceram and polyimide. Pyroceram is commonly used in supersonic missiles. Polyimide radomes are used on relatively low speed, low cost missiles such as the millimeter wave (mmW) Brimstone. Polyimide radomes have excellent dielectric characteristics. For MWIR-only seekers, additional dome materials include magnesium fluoride and Alon. Although both are suitable for supersonic missiles, Alon is less susceptible to rain and dust erosion and is capable of operating at higher Mach number. Multi-spectral dome materials may also be used for MWIR-only and RF-only seekers. Zinc sulfide is suitable for MWIR seekers at supersonic Mach number. Spinel or sapphire domes may be used

with MWIR seekers at high supersonic/low hypersonic Mach numbers. Silicon nitride is suitable for RF and mmW seekers at low hypersonic Mach number.

Reduced Parts Count Structure. Airframe cost and producibility are important considerations for precision strike missiles. New airframe technology is in development that will reduce the cost of precision strike weapons. Examples of recent precision strike weapons that include low cost technologies include JDAM and JASSM. Technologies to reduce cost are also being introduced into existing weapons, with large savings. An example is Tactical Tomahawk. It has a simple low cost airframe with extruded wings. It also uses low cost commercial parts for G&C and propulsion. The current Tomahawk has 11,500 parts, 2,500 fasteners, 45 circuit cards, 160 connectors, and requires 610 assembly/test hours. Tactical Tomahawk will have 35% fewer parts, 68% fewer fasteners, 51% fewer circuit cards, 72% fewer connectors, and 68% fewer assembly/test hours – resulting in a 50% reduction in cost (Figure 22). Tactical Tomahawk also has superior flexibility (e.g., shorter mission planning time, capability for in-flight targeting, capability for battle damage indication/battle damage assessment, modular payload) and higher reliability at the same launch weight as the current Tomahawk.

Examples of manufacturing processes that reduce the parts count include vacuum assisted resin transfer molding (RTM), filament winding, pultrusion, casting, vacuum bag/autoclave forming, metal forming, strip laminate, and compression molding. Examples of low cost manufacturing process that are particularly applicable to complex shapes are precision casting, vacuum assisted RTM, filament winding, and pultrusion. Precision casting is particularly suitable. It has high payoff for reducing the cost of high temperature metal airframes with complex shape. A historical limitation in applying castings to complex configurations is the tight manufacturing tolerances required for the complex configurations. However, new technology such as ceramic tooling allows low cost precision castings suitable for complex airframe configurations such as ramjets. Castings reduce the parts count, with a resulting cost savings. Large precision cast structures are in development for complex missile shapes, such as ramjets. A one-piece cast airframe design integrates all of the secondary structure to minimize parts count. Precision casting minimizes subsequent machine and hand finishing of mating surfaces, by achieving a precision surface finish "as-cast." Fuel cells can be an integral part of the structure and not require bladders. Structural attachment points (e.g., ejector attachments, payload supports, booster attachments) and self-indexing/aligning features can be integral to the structure. This minimizes or eliminates mating/alignment/assembly tooling and test/inspection requirements. Precision castings have been demonstrated for missile aluminum, titanium, and steel airframes, motor cases, and combustors.

Dome
◆ Facted / Window
◆ Multi-spectral
◆ Multi-lens

Aerothermal Insulation
◆ Hypersonic
◆ High Density

Airframe
◆ Lifting Body
◆ Neutral Static Margin
◆ Split Canard
◆ Lattice Fins
◆ Low Drag Inlet
◆ Single Cast
◆ Vacuum Assisted RTM
◆ Pultrusion / Extrusion
◆ Filament Wind
◆ Composite
◆ Titanium Alloy
◆ Low Observable

Propulsion
◆ Liquid Fuel Ramjet
◆ Variable Flow Ducted Rocket
◆ Scramjet
◆ High Density Fuel
◆ Endothermic Fuel
◆ Composite Case
◆ Pintle / Pulsed / Gel Motor
◆ Low Observable
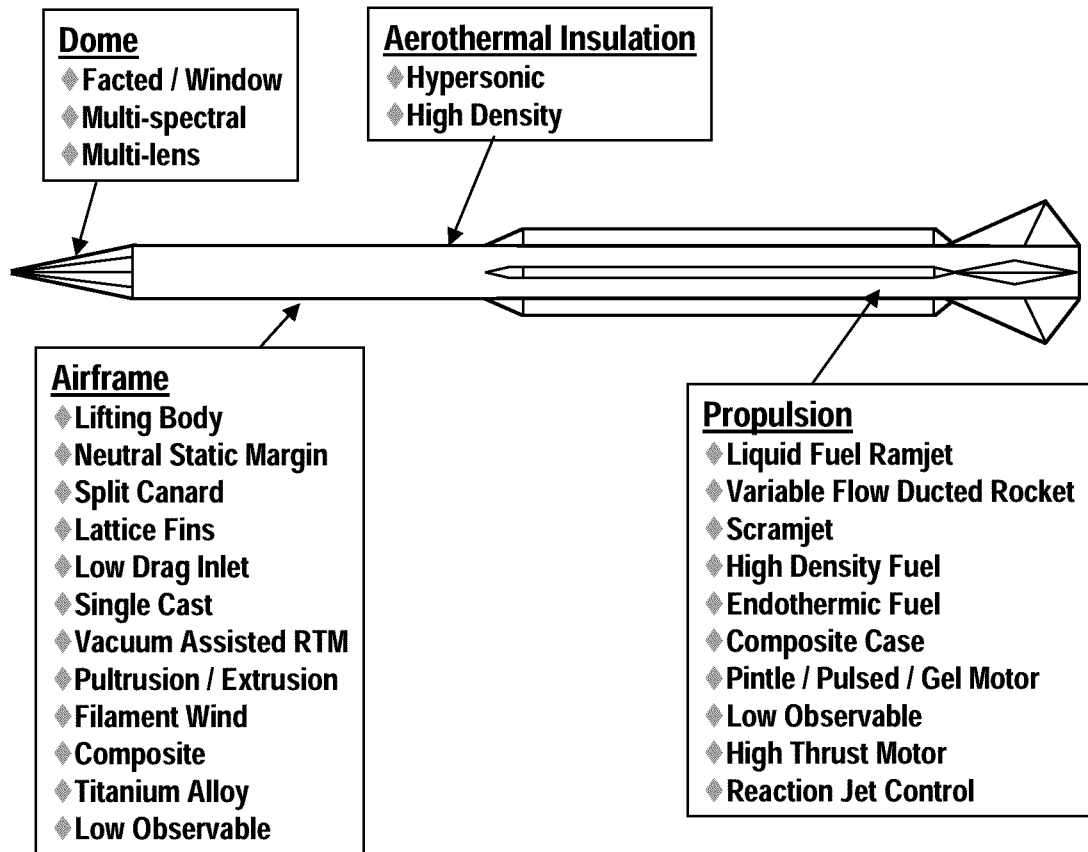◆ High Thrust Motor
◆ Reaction Jet Control

Figure 1. New Aeromechanics Technologies for Precision Strike Missiles.

Tailored Weapons | Advantages:
· $(L/D)_{Max}$
· Low RCS

Conventional Weapons | Advantages:
· Payload
· Aircraft Integration

Lower ↑

Radar Cross Section

x-axis: Planform Area / $(Volume)^{2/3}$, values 2, 4, 6, 8, 10

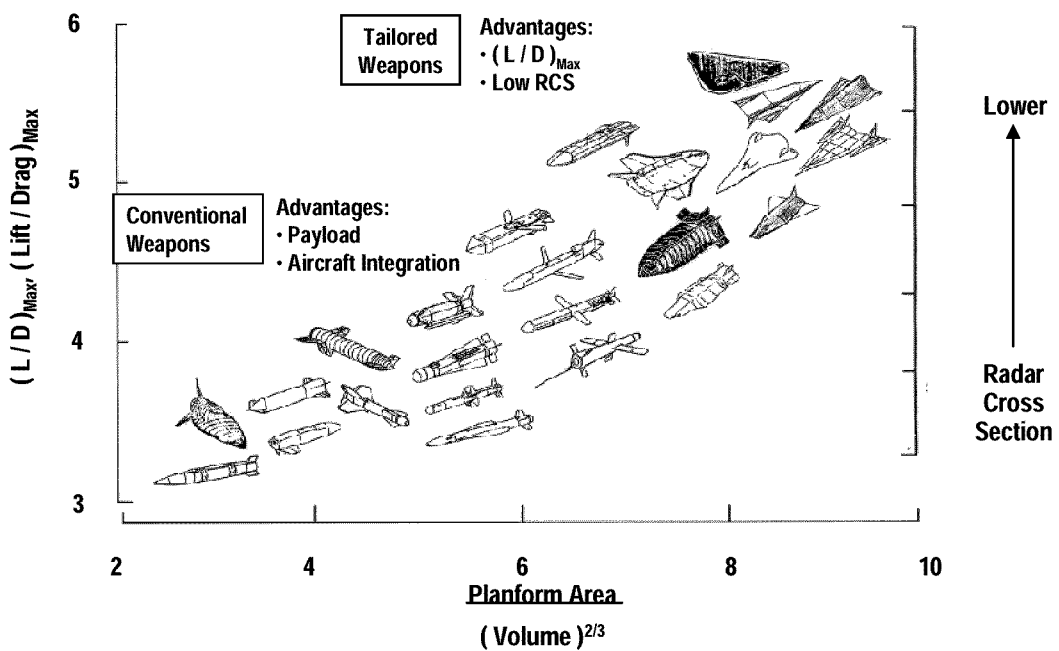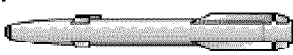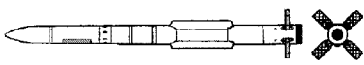y-axis: $(L/D)_{Max}$, (Lift / Drag)$_{Max}$, values 3, 4, 5, 6

Figure 2. Aerodynamic Shaping Provides Reduced Observables and Higher $(L/D)_{Max}$.

Type of Tail Control	Control Effectiveness	Drag	Hinge Moment	RCS
◆ All Movable (Example: ASRAAM AIM-132)	◒	●	◒	◒
◆ Flap (Example: Hellfire AGM-114)	○	◒	–	●
◆ Lattice (Example: Adder AA-12)	●	◒	●	–

Note:	● Superior	◒ Good	○ Average	– Poor

Figure 3. Lattice Tail Control Provides High Control Effectiveness and Low Hinge Moment.

◆ Advantages

◆ High control effectiveness at low subsonic and high supersonic Mach number

◆ Low hinge moment

◆ Short chord length

◆ Disadvantages

◆ High RCS

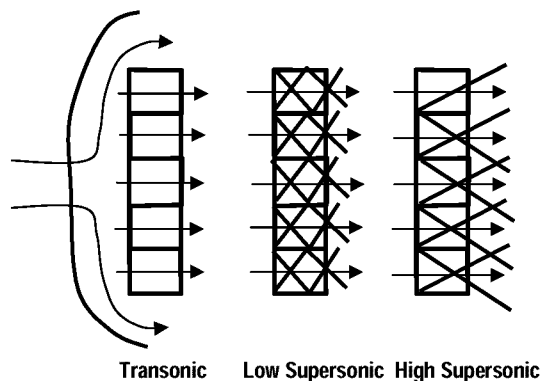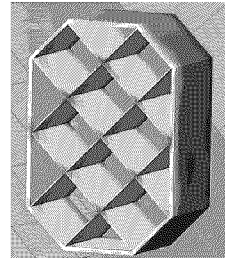### ◆ High drag at transonic Mach number (choked flow)

Transonic   Low Supersonic   High Supersonic

Figure 4. Lattice Fins Have Advantages for Low Subsonic and High Supersonic Missiles.

Note: α' = Local angle of attack

Kegler AS-12   Archer AA-11   Aphid AA-8

Magic R 550   Python 4   U-Darter

Note: Forward fixed surface reduces local angle-of-attack for movable canard, providing higher stall angle of attack.
Python 4 has free-to-roll tails to alleviate induced roll at high α .
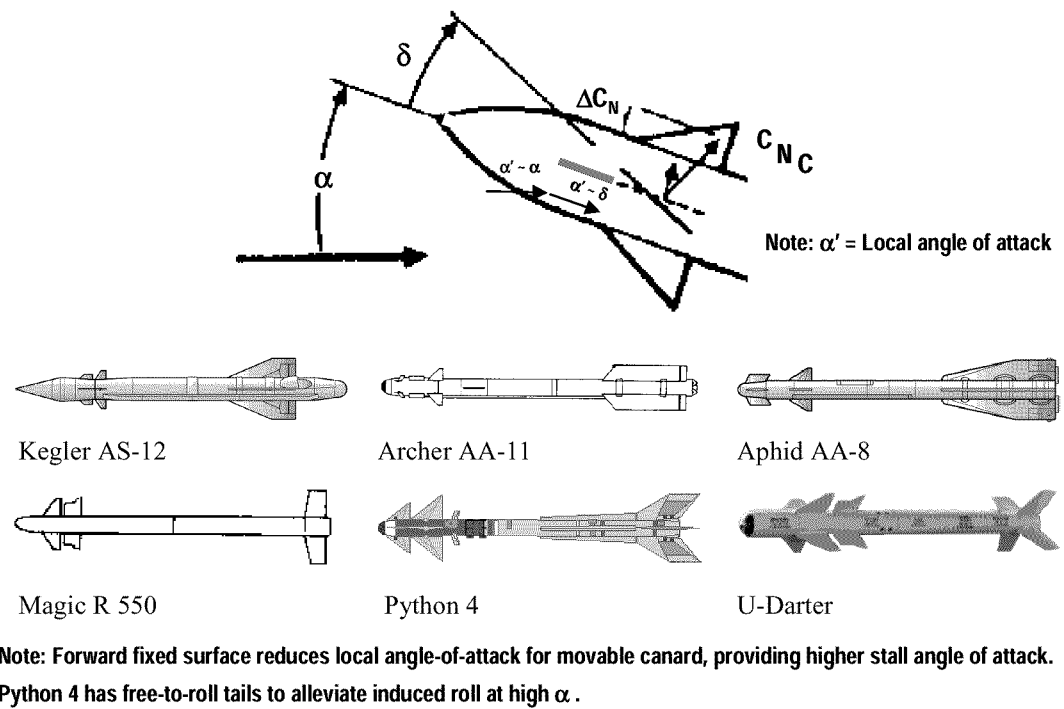
Figure 5. Split Canards Provide Enhanced Maneuverability at High Angles of Attack.

Parameter	Triangle (Delta)	Trapezoid	Forward Swept Trapezoid	Rectangle
Variation x_{AC}	●	◓	◓	○
Bending Moment	◓	○	●	–
Supersonic Drag	●	◓	◓	–
RCS	●	◓	●	–
Required Span	–	◓	●	◓
Control Effect.	○	●	◓	–
Aeroelastic Stab.	●	◓	–	○

λ = Taper Ratio = C_T / C_R
A = Aspect Ratio = 2 b / [(1 + λ) C_R]
y_{CP} = Outboard center-of-pressure location = (b / 2) / (3 - λ)
c_{MAC} = Mean aerodynamic chord = (2 / 3) C_R (1 + λ + λ^2) / (1 + λ)

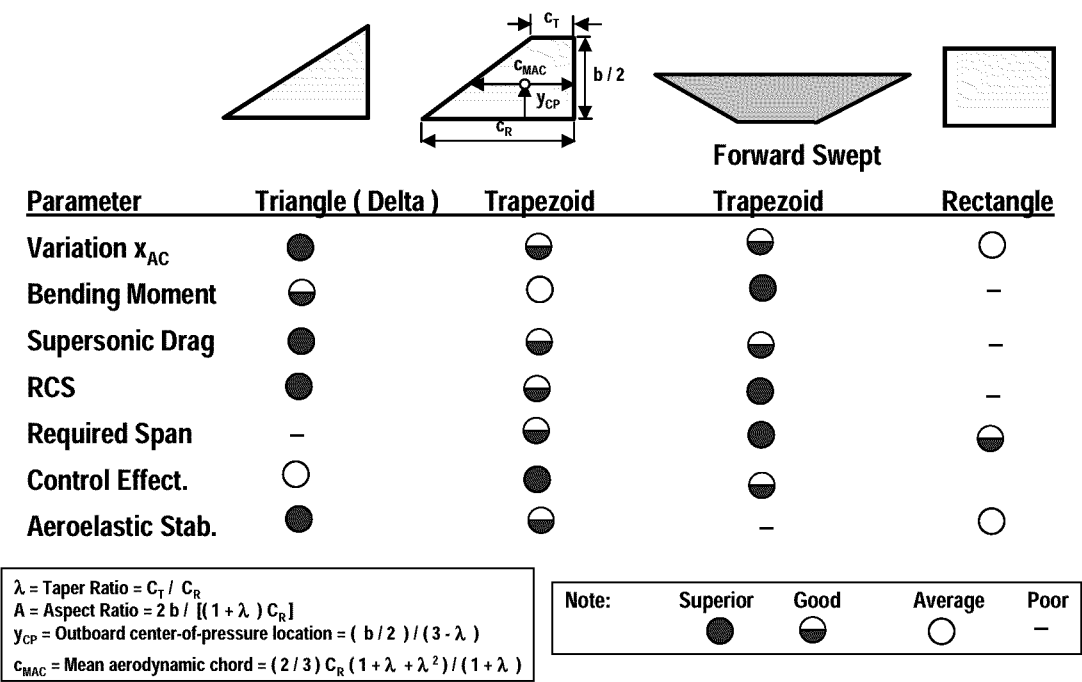| Note:	Superior	Good	Average	Poor
	●	◓	○	–

Figure 6. Forward Swept Surfaces Allow Small Span, Have Low RCS, and Have Low Bending Moment.

◆ **Skid-To-Turn (STT)**
  • Advantage: Fast response
  • Features
    – No roll commands from autopilot
    – Works best for axisymmetric cruciform missiles
◆ **Bank-To-Turn (BTT)**
  • Advantage: Provides higher maneuverability for wings, noncircular / lifting bodies, and airbreathers
  • Disadvantages
    – Time to roll
    – Requires fast roll rate
    – May have higher dome error slope
  • Features
    – Roll attitude commands from autopilot
    – Small sideslip
◈ **Rolling airframe (RA)**
  • Advantage: Requires only two sets of gyros / accelerometers / actuators
  • Disadvantages
    – Reduced maneuverability
    – Potential for roll resonance
  • Features
    – Aileron bias / constant roll rate command from auto pilot
    – Can use impulse steering
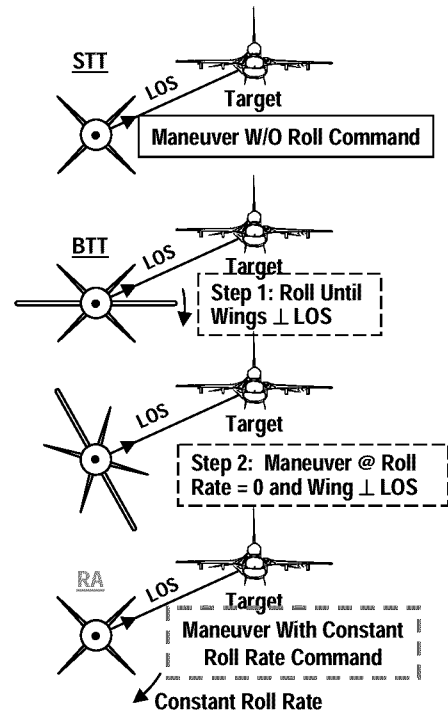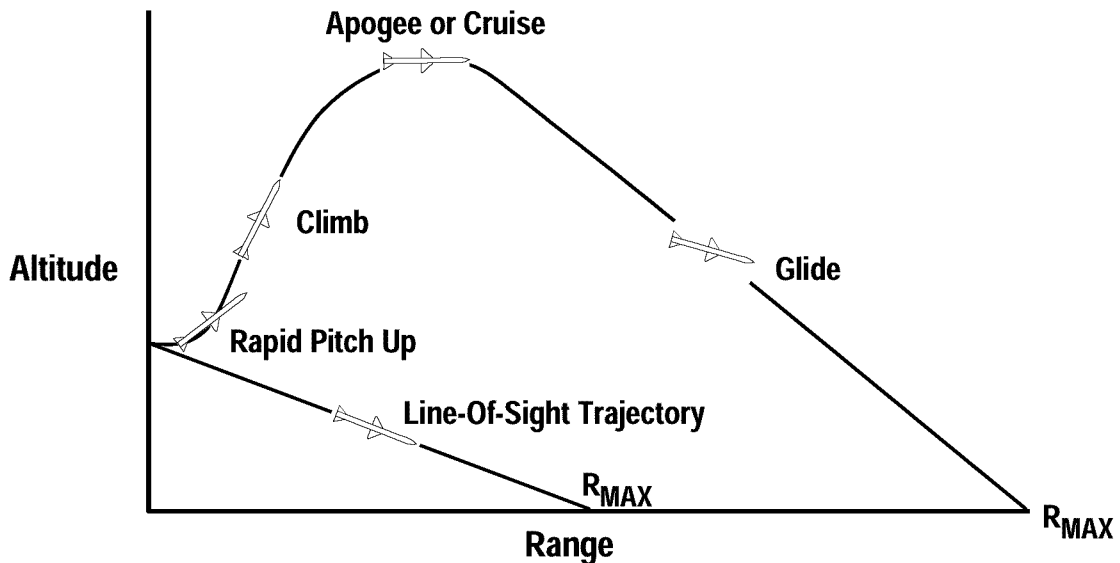   – Compensates for thrust offset

STT
Target
Maneuver W/O Roll Command

BTT
Target
Step 1: Roll Until Wings ⊥ LOS

Target
Step 2: Maneuver @ Roll Rate = 0 and Wing ⊥ LOS

RA
Target
Maneuver With Constant Roll Rate Command
Constant Roll Rate

Figure 7. Bank-to-Turn Provides Higher Maneuverability

Apogee or Cruise

Climb

Altitude

Glide

Rapid Pitch Up

Line-Of-Sight Trajectory

R_{MAX}

Range

R_{MAX}

Design Guidelines for Horizontal Launch:
  – High thrust-to-weight ≈ 10 for safe separation
  – Rapid pitch up minimizes time / propellant to reach efficient altitude
  – Climb at a ≈ 0 deg with thrust-to-weight ≈ 2 and q ≈ 700 psf minimizes drag / propellant to reach efficient cruise altitude for $(L / D)_{MAX}$
  – High altitude cruise at $(L / D)_{MAX}$ and q ≈ 700 psf to maximizes range
  – Glide from high altitude at $(L / D)_{Max}$ and q ≈ 700 psf provides extended range

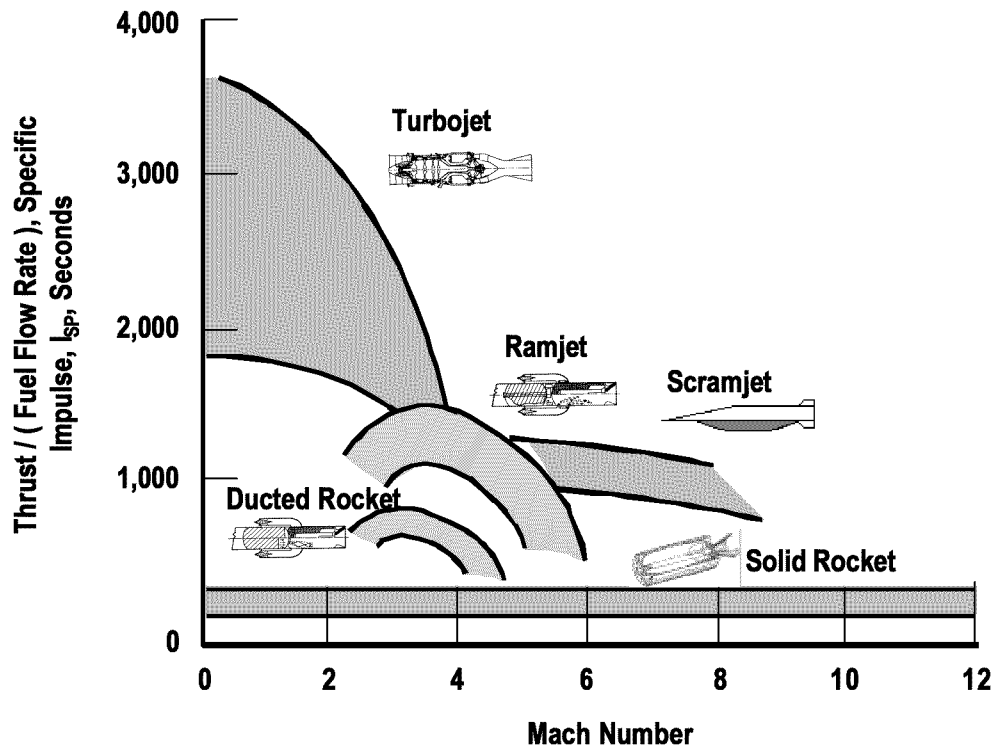**Figure 8. Flight Trajectory Shaping Provides Extended Range.**

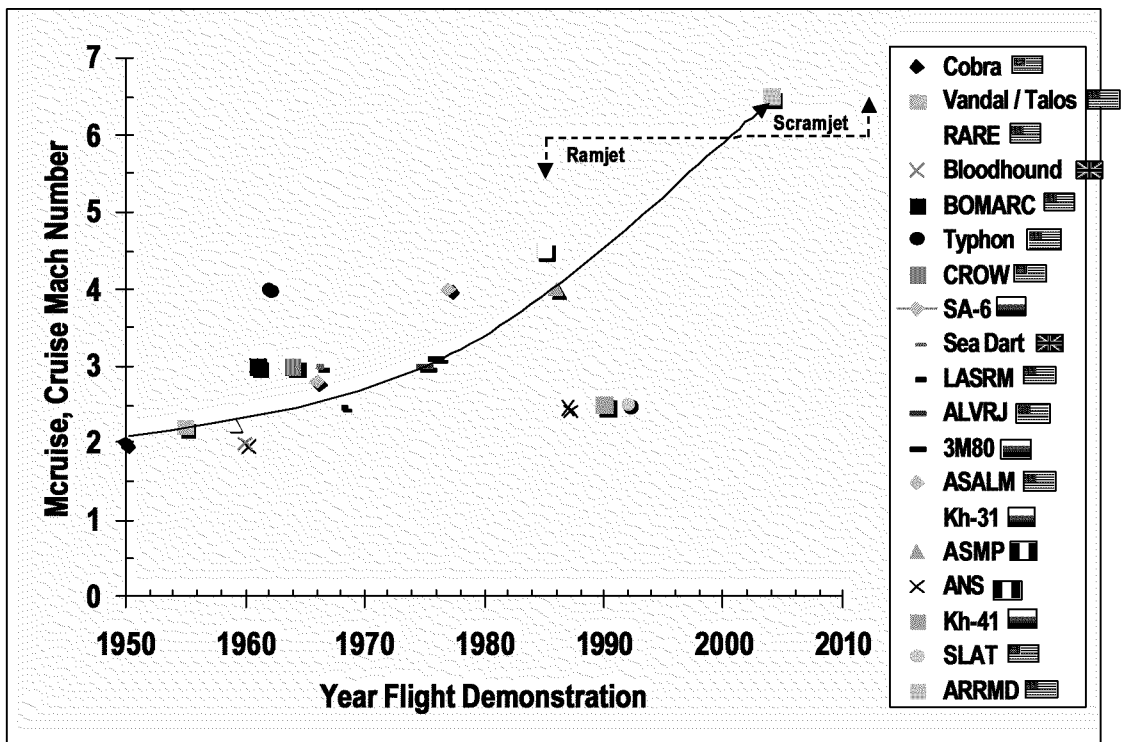Figure 9. Ramjets and Scramjets Have High Payoff at Supersonic/Hypersonic Mach Number.

Figure 10. State-of-the-Art Evolution in Supersonic/Hypersonic Air Breathing Missiles.
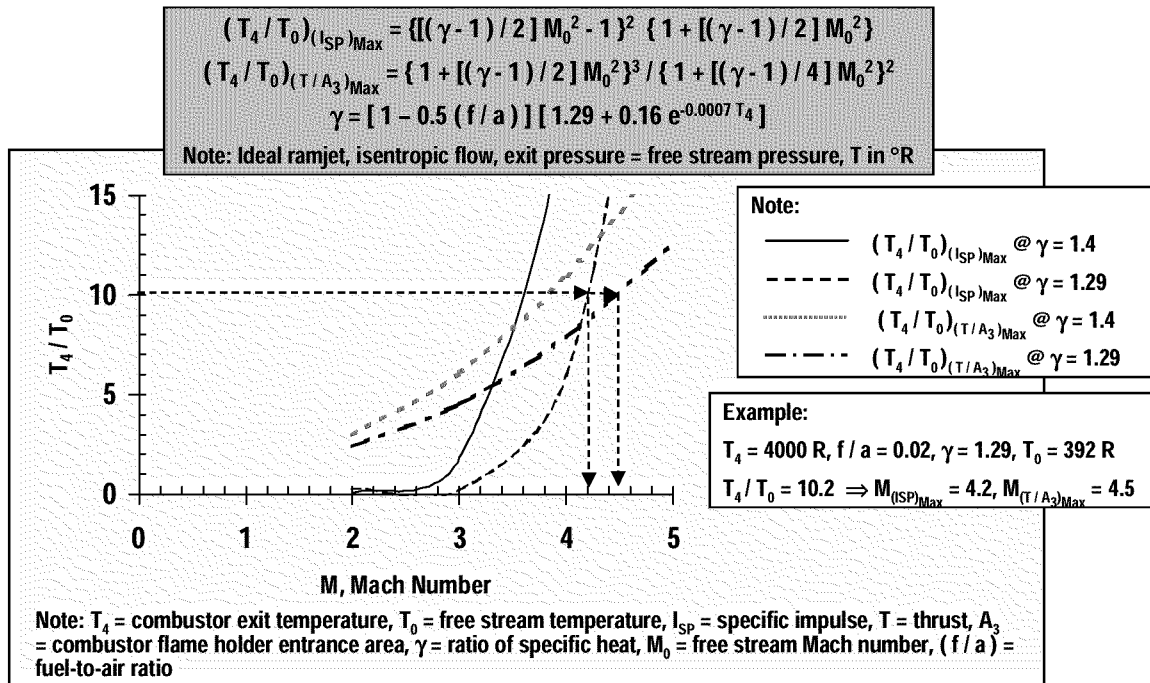
$$(T_4 / T_0)_{(I_{SP})_{Max}} = \{[(\gamma - 1)/2] M_0^2 - 1\}^2 \{1 + [(\gamma - 1)/2] M_0^2\}$$

$$(T_4 / T_0)_{(T/A_3)_{Max}} = \{1 + [(\gamma - 1)/2] M_0^2\}^3 / \{1 + [(\gamma - 1)/4] M_0^2\}^2$$

$$\gamma = [1 - 0.5 (f/a)][1.29 + 0.16 e^{-0.0007 T_4}]$$

Note: Ideal ramjet, isentropic flow, exit pressure = free stream pressure, T in °R

Note:

————— $(T_4 / T_0)_{(I_{SP})_{Max}}$ @ $\gamma = 1.4$

– – – – $(T_4 / T_0)_{(I_{SP})_{Max}}$ @ $\gamma = 1.29$

············· $(T_4 / T_0)_{(T/A_3)_{Max}}$ @ $\gamma = 1.4$

—·—·· $(T_4 / T_0)_{(T/A_3)_{Max}}$ @ $\gamma = 1.29$

Example:

$T_4 = 4000$ R, $f/a = 0.02$, $\gamma = 1.29$, $T_0 = 392$ R

$T_4 / T_0 = 10.2 \Rightarrow M_{(ISP)_{Max}} = 4.2$, $M_{(T/A_3)_{Max}} = 4.5$

Note: T_4 = combustor exit temperature, T_0 = free stream temperature, I_{SP} = specific impulse, T = thrust, A_3 = combustor flame holder entrance area, γ = ratio of specific heat, M_0 = free stream Mach number, (f / a) = fuel-to-air ratio

Figure 11. High Combustor Temperature Has High Payoff at Hypersonic Mach Number.

◆ **United Kingdom**
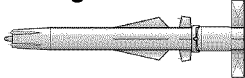
Sea Dart GWS-30

◆ **France**
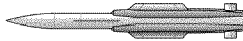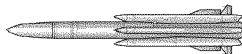
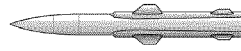**ASMP**   **ANS**
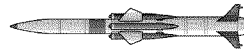
◆ **Russia**

AS 17 / Kh-31   **Kh-41**   **SS-N-22 / 3M80**

SA-6

Aft Inlets versus nose inlet:

◆ Aft inlets have lower inlet volume and enhanced warhead lethality.

◆ Nose Inlet has higher pressure recovery, smaller carriage envelope, and lower drag.

Figure 12. Current Ramjet Inlets Are Either Nose Inlet or Aft Axisymmetric Inlets.
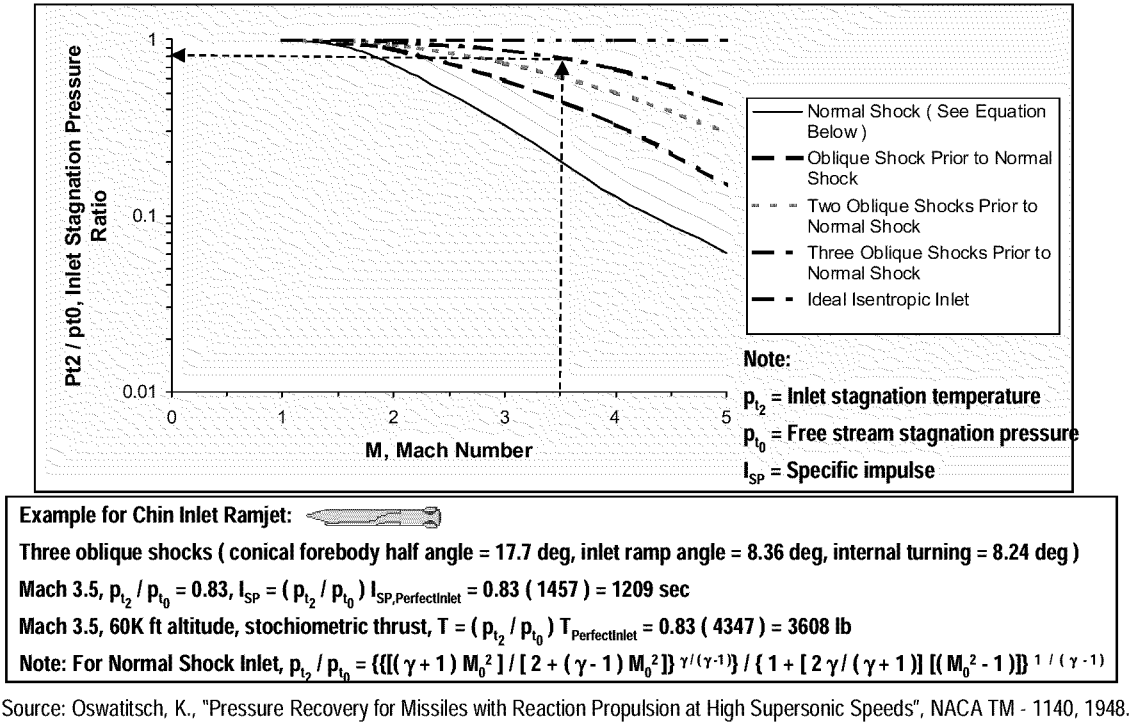
Figure 13. Ramjet Inlet/Airframe Integration Has Payoff.

Type	Volumetric Performance, BTU / in³	Low Observables
Turbine (JP-5, JP-7, JP-10), ρ ~ 0.028 lb / in³	○ 559	●
Liquid Ramjet (RJ-4, RJ-5, RJ-6, RJ-7), ρ ~ 0.040 lb / in³	○ 581	●
Slurry (40% JP-10 / 60% carbon), ρ ~ 0.049 lb / in³	◒ 801	○
Solid Hydrocarbon, ρ ~ 0.075 lb / in³	● 1132	○
Slurry (40% JP-10 / 60% aluminum), ρ ~ 0.072 lb / in³	◒ 866	–
Slurry (40% JP-10 / 60% boron carbide), ρ ~ 0.050 lb / in³	● 1191	–
Solid Mg, ρ ~ 0.068 lb / in³	● 1300	–
Solid Al, ρ ~ 0.10 lb / in³	● 1300	–
Solid Boron, ρ ~ 0.082 lb / in³	● 2040	–

● Superior ◒ Above average ○ Average – Below average

Figure 14. High Density Fuels Provide Higher Volumetric Performance.

2-16

Solid Pulsed Motor

Thermal or Mechanical Barriers

Insulation

Propellant

Igniters

First Igniter

Solid Pintle Motor

Struts

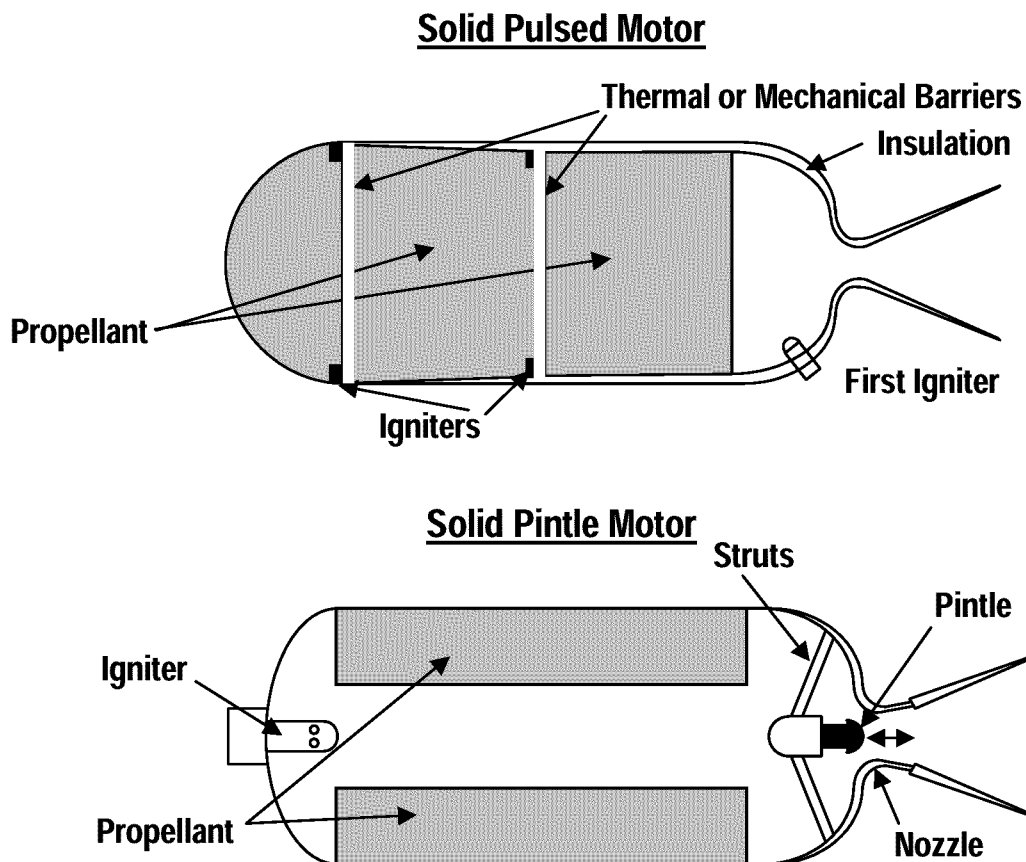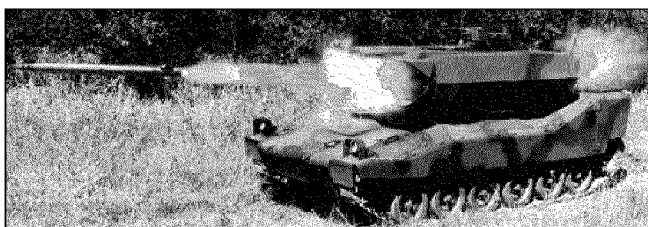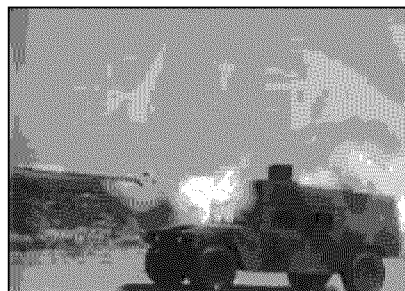Pintle

Igniter

Propellant

Nozzle

Figure 15. Thrust Magnitude Control Provides Efficient Thrust Management.

LOSAT Launch from Bradley Armored Combat Vehicle

LOSAT Launch from HMMWV

LOSAT Launch from HMMWV

LOSAT Loadout on HMMWV

Figure 16. Enabling Technologies for Hypersonic Precision Strike Kinetic Kill Missiles
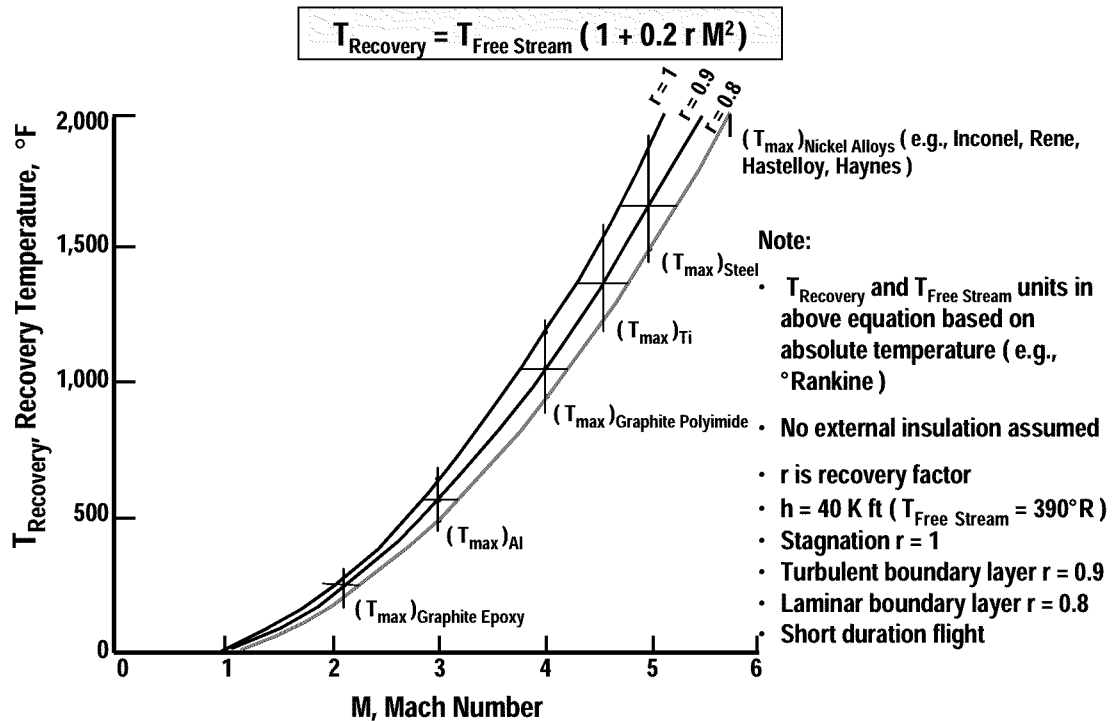Include High Acceleration Motor and Reaction Jet Control.

$$T_{Recovery} = T_{Free\ Stream} (1 + 0.2\ r\ M^2)$$

$r = 1$ $r = 0.9$ $r = 0.8$

$(T_{max})_{Nickel\ Alloys}$ (e.g., Inconel, Rene, Hastelloy, Haynes)

$(T_{max})_{Steel}$

$(T_{max})_{Ti}$

$(T_{max})_{Graphite\ Polyimide}$

$(T_{max})_{Al}$

$(T_{max})_{Graphite\ Epoxy}$

Note:
- $T_{Recovery}$ and $T_{Free\ Stream}$ units in above equation based on absolute temperature (e.g., °Rankine)
- No external insulation assumed
- r is recovery factor
- h = 40 K ft ($T_{Free\ Stream}$ = 390°R)
- Stagnation r = 1
- Turbulent boundary layer r = 0.9
- Laminar boundary layer r = 0.8
- Short duration flight

$T_{Recovery}$, Recovery Temperature, °F

M, Mach Number

Figure 17. Hypersonic Missiles Require High Temperature Structure.

$$F_t = P / A = E\ \varepsilon$$

Kevlar Fiber w / o Matrix

Glass Fiber w / o Matrix

Graphite Fiber w / o Matrix (400 – 800 Kpsi)

High Strength Steel

Titanium Alloy

Aluminum Alloy

F_t, Tensile Stress, 10^3 psi

ε, Strain, 10^{-4} in / in

Note:
- High strength fibers are:
  - Very small diameter
  - Unidirectional
  - Very elastic
  - No yield before failure
  - Non forgiving failure

- Metals:
  - Yield before failure
  - Allow adjacent structure to absorb load
  - More forgiving failure

E, Young's Modulus, psi
P, Load, lb
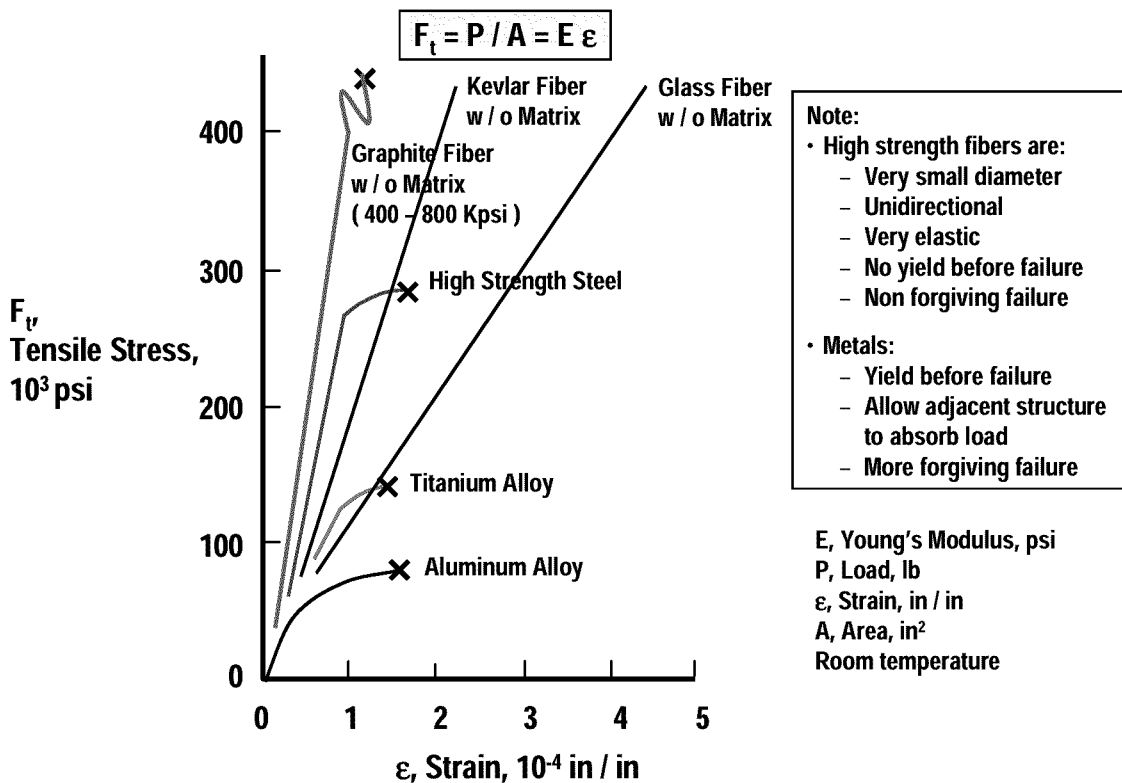ε, Strain, in / in
A, Area, in^2
Room temperature

Figure 18. Composites Have High Strength.
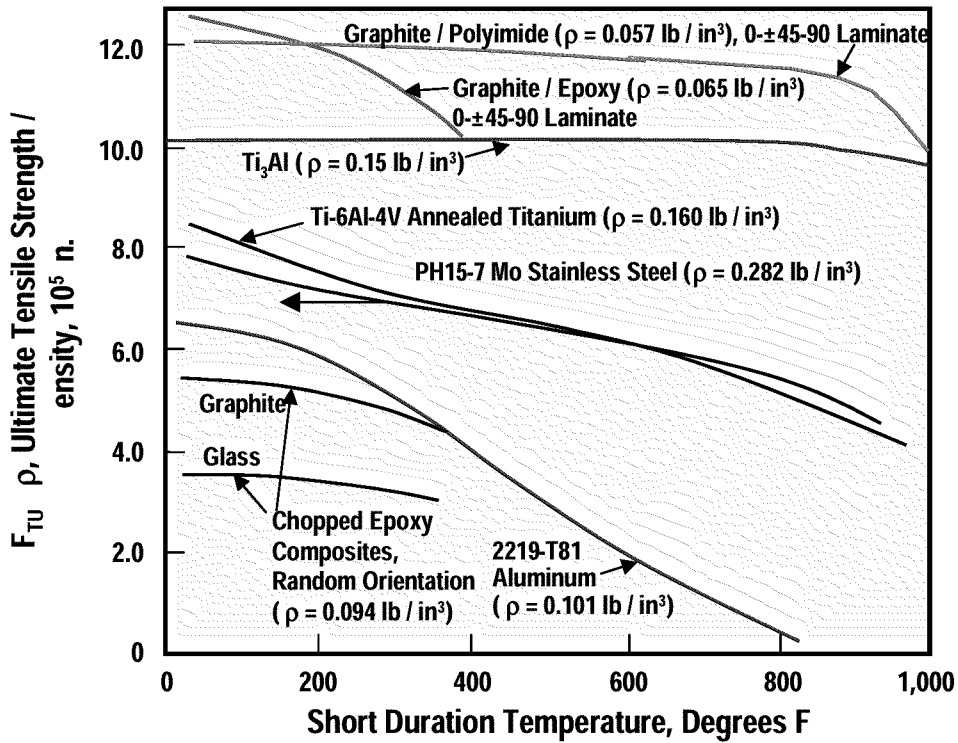
Figure 19. Composites Have High Structural Efficiency.

Insulation Efficiency, Minutes To Reach 300°F at Back Wall
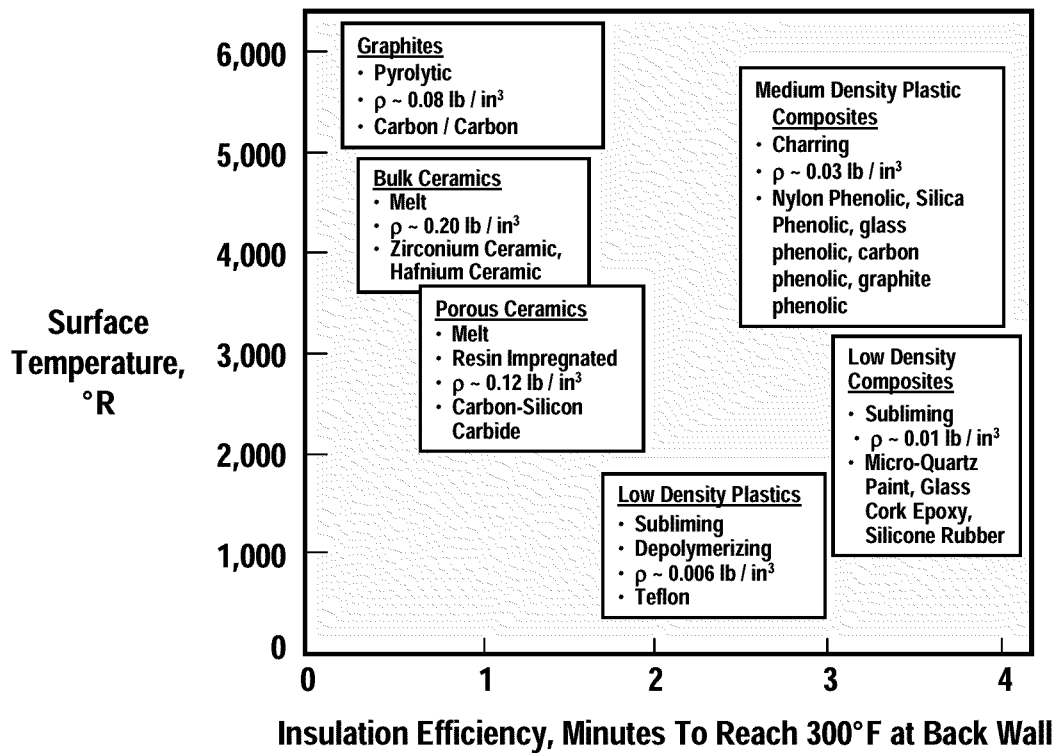
Note: Assumed Weight Per Unit Area of Insulator / Ablator = 1 lb / ft²

Figure 20. Composites Provide Light Weight Insulation.

Seeker Dome Material	Density (gm / cm³)	Dielectric Constant	MWIR / LWIR Bandpass	Transverse Strength (psi)	Thermal Expansion (10⁻⁶ / °F)	Erosion, Knoop (kg / mm²)	Max Short-Duration Temp (°F)
RF / IR							
Zinc Sulfide (ZₙS)	4.05	◯ 8.4	⬤	◯ 18	◯ 4	◯ 350	◯ 700
Zinc Selenide (ZₙSₑ)	5.16	⌣ 9.0	⬤	⌣ 8	◯ 4	◯ 150	◯ 600
Spinel (MgAl₂O₄)	3.68	◯ 8.5	◕	◯ 28	◯ 3	⬤ 1650	⬤ 1800
Quartz / Fused Silicon (SₗO₂)	2.20	⬤ 3.7	◯	⌣ 8	⬤ 0.3	◕ 600	⬤ 2000
Silicon Nitride (Si₃N₄)	3.18	◕ 6.1	⌣	⬤ 90	◕ 2	⬤ 2200	⬤ 2700
Diamond (C)	3.52	◕ 5.6	⌣	⬤ 400	⬤ 1	⬤ 8800	⬤ 3500
RF Only							
Pyroceram	2.55	◕ 5.8	⌣	◯ 25	◯ 3	◕ 700	⬤ 2200
Polyimide	1.54	⬤ 3.2	⌣	◯ 17	⌣ 40	⌣ 70	⌣ 200
MWIR Only							
Mag. Fluoride (MgF₂)	3.18	◕ 5.5	⬤	⌣ 7	⌣ 6	◕ 420	◕ 1000
Alon (Al₂₃O₂₇N₅)	3.67	⌣ 9.3	◕	◕ 44	◯ 3	⬤ 1900	⬤ 1800

⬤ Superior   ◕ Above Average   ◯ Average   ⌣ Below Average

Figure 21. Broad Bandpass Domes Support Multi-Mode/Multi-Spectral Seekers.
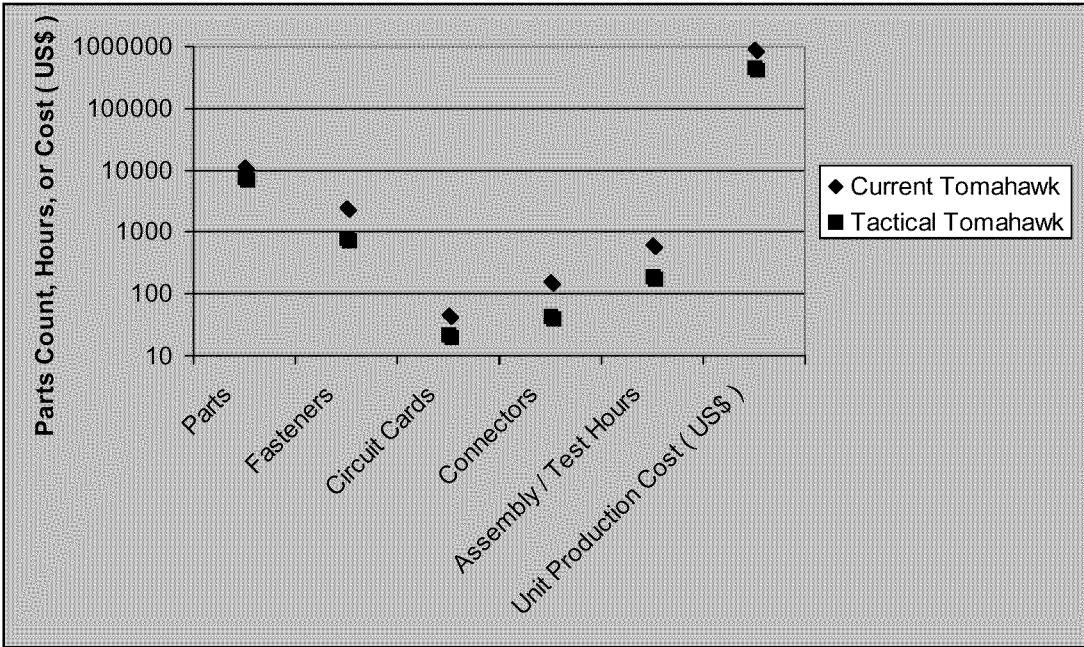
Note: Tactical Tomahawk has superior flexibility (e.g., shorter mission planning, in-flight retargeting, BDI / BDA, modular payload) at lower parts count / cost and higher reliability. Enabling technologies for low parts count include: casting, pultrusion / extrusion, centralized electronics, and COTS.

Figure 22. Low Parts Count Reduces Missile Cost.

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