Affordable Hypersonic Missiles for Long-Range Precision Strike

Michael E. White and Walter R. Price

The United States' current and planned weapons systems for strike warfare are deficient in their ability to attack time-critical targets at long range. Hypersonic air-breathing propulsion may be an enabling technology to remedy this deficiency. A revolutionary strike warfighting capability could be supplied by coupling hypersonic air-breathing propulsion into a long-range missile and incorporating other recent technology advances such as Global Positioning System guidance, greatly improved targeting capability, and improved lethality payloads (e.g., smart submunitions and kinetic-energy penetrators). The Defense Advanced Research Projects Agency has initiated the Affordable Rapid Response Missile Demonstrator Program to develop a concept for an affordable hypersonic long-range cruise missile and to demonstrate it in flight for the first time. A firm program requirement is that the eventual average "unit flyaway" price of the missile concept demonstrated be $200,000 or less. This article discusses the overall program goals and approach and briefly describes the technology being pursued. (Keywords: Hypersonic, Missile, Ramjet, Scramjet.)

INTRODUCTION

The development of a long-range, high-speed missile utilizing hypersonic aeropropulsion technology offers an opportunity to dramatically change the warfighter's ability to respond to a broad range of threats. A hypersonic cruise missile (a missile that flies at speeds greater than 5 times the speed of sound) possesses a unique combination of speed, lethality, survivability, and range. It presents the tactical warfighter with unprecedented capability to respond to long-range threats such as time-critical, hardened, buried, and heavily defended targets. Developers of a long-range, precision-strike weapon system based on a hypersonic cruise missile must consider numerous factors required to conduct a successful mission, including

- Overall missile kinematic performance
- Launch platform compatibility
- Adequate command, control, communications, computers, intelligence, surveillance, and reconnaissance (C^4ISR)
- Targeting requirements
- Accurate guidance and navigation
- Survivability
- Payload lethality

Hypersonic cruise missiles typically fly at altitudes exceeding 90,000 ft, with cruise speeds of 6000 ft/s or more. They can be powered all the way to the target, which allows significant trajectory flexibility and very high impact velocities. Such flexibility and impact velocity give the missile a unique capability against time-critical, heavily defended, and hardened or buried targets. The altitude and speed during cruise make the missile highly survivable and greatly reduce the time of flight relative to subsonic cruise missiles. Furthermore, the survivability permits a simple "up and over" trajectory, dramatically reducing prelaunch timelines for mission planning. High velocities at impact greatly increase the kinetic energy available to defeat hardened or buried targets. For targets that are sheltered from the direction of attack, the ability to strike from any direction improves lethality relative to ballistic missiles.

These missile capabilities raise numerous technical challenges associated with propulsion and aerothermal survivability that are briefly discussed here. White[1] gives more detail on the benefits and the technical challenges of a long-range, precision-strike weapon system based on a hypersonic cruise missile. Two of the most critical issues associated with the development of such a weapon system are the flight test demonstration of a viable hypersonic missile and the affordable production of such a missile.

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PROGRAM DESCRIPTION

The Affordable Rapid Response Missile Demonstrator (ARRMD) Program of the Defense Advanced Research Projects Agency (DARPA) began in fiscal 1998. Its objective is the flight test demonstration of a long-range hypersonic cruise missile concept designed to meet the most effective set of performance objectives while constrained to a firm program affordability requirement.

Design-to-Cost Requirement

The design-to-cost requirement of the ARRMD Program is an average unit flyaway price (AUFP) of $200,000, in FY98 dollars, for a single-lot production purchase of 3000 missiles. The AUFP requirement is firm: the missile design is to be optimized with respect to a list of performance goals and thresholds to maximize weapon effectiveness within the $200,000 cost constraint. To meet the unit cost constraint, the contractor is permitted to employ "best commercial practices" to the extent necessary and to apply a learning curve consistent with experience in past missile production programs. The baseline $200,000 missile price is for air launch of the missile. It includes the air vehicle, all subsystems, and a basic warhead. The AUFP for the ship-launched variant is to be proportionally higher to account for the larger rocket booster needed.

Performance Goals

The missile concept demonstrated in the ARRMD Program must meet the most effective set of program performance goals within the defined AUFP requirement. Within this list of program goals are critical thresholds on range and speed. The missile concepts also must include the use of logistically suitable fuels. The ARRMD performance goals are as follows:

- Powered range of 600 nmi, with a minimum threshold of 400 nmi
- Time to target of less than 7 min at a range of 400 nmi
- Aim-point ground impact error of less than 35 ft
- Ground impact velocity of 4000 ft/s
- Survivability against surface-to-air missile (SAM) threats in 2005 and beyond
- Compatibility with Air Force and Navy tactical fighters; internal carriage on Air Force strategic bombers and on Navy Vertical Launch Systems and Canister Launch Systems
- Mission flexibility in a tactical environment
- Minimum payload weight of 250 lb, with warhead modularity for smart submunitions, unitary munitions, and kinetic energy penetrators
- Use of logistically suitable liquid hydrocarbon fuels
- Capacity for at least 10 years of storage without servicing (i.e., a "wooden round" missile)

Program Execution Strategy

The ARRMD Program is being executed in two phases. Phase 1 is an 18-month risk reduction and concept validation phase. Phase 2 will focus on the flight test demonstration. The purpose of Phase 1 is to reduce risk in the areas of affordability and flight vehicle viability for two candidate missile concepts. A series of component demonstrations is proving the viability of the critical low-cost manufacturing techniques that will enable the candidate missile concepts to meet the $200,000 AUFP requirement. Effort also is being focused on developing cost models and increasing the fidelity of the estimates associated with manufacturing the missile components and integrating the missile system. The missile designs will be evolved through a preliminary design review, and the performance and operability of the candidate flight vehicle concepts will be demonstrated in a series of wind tunnel tests. These tests will measure the operating characteristics of critical engine components, integrated engines, high-temperature materials, and actively cooled structures.

The data gathered in Phase 1 will supply the critical affordability, performance, and operability information required for progressing to the flight test demonstration in Phase 2. Should the Phase 1 data support the viability and affordability of the proposed concepts, DARPA will decide whether to proceed to Phase 2.

At the start of Phase 2, DARPA will select the most promising vehicle concept for the flight demonstration. The program flight test demonstration phase will last 30 months. It will consist of the detailed design of the selected flight vehicle, flight demonstration of the missile's aeropropulsion performance capabilities, and refinement and large-scale demonstration of manufacturability processes. A final affordability assessment will be made to substantiate the $200,000 AUFP, and operational utility of the missile will be assessed.

The ARRMD Team

The DARPA Tactical Technology Office, with Lieutenant Colonel Walter Price as the Program Manager, is executing the ARRMD Program. The Air Force Research Laboratory (AFRL), which is serving as the contracting agent for DARPA, has established a single agreement with the Boeing Company to execute both phases of the ARRMD Program. Boeing has been directed to pursue two candidate missile concepts with equal vigor and has primary subcontracts for propulsion with Aerojet and Pratt & Whitney (P&W) to develop the two candidate vehicle concepts. APL is serving as DARPA's lead technical advisor for program execution and is supporting flight vehicle design, affordability assessment, and warfighting benefit analysis. The AFRL and the Air Force Aeronautical Systems Command are also providing technical program support.

The Candidate Missile Concepts

The Phase 1 activity will bring two candidate missile concepts proposed by Boeing to maturity. Boeing and P&W developed the first concept based on integrating propulsion technology developed by P&W under the Air Force Hypersonic Technology (HyTech) Program.[2,3] The HyTech-based propulsion system is integrated into a flight vehicle based on a "waverider" design (Fig. 1). (A waverider is a vehicle having a high lift-to-drag ratio due to shock wave pressurization effects at supersonic speeds.) The engine is rectangular and integrated into the underside of the flight vehicle, utilizing the underside compression for the inlet. The inlet feeds a rectangular combustor containing innovative air-breathing pilots that allow efficient burning of a hydrocarbon fuel in a predominantly supersonic combustor. The engine's combustor is actively cooled using the liquid endothermic fuel. The engine's nozzle is integrated into the aft portion of the underside of the vehicle. The cruise vehicle is boosted to the Mach number at which the air-breathing engine takes over from the rocket booster. These boosters are side-mounted for integration onto aircraft launch platforms.

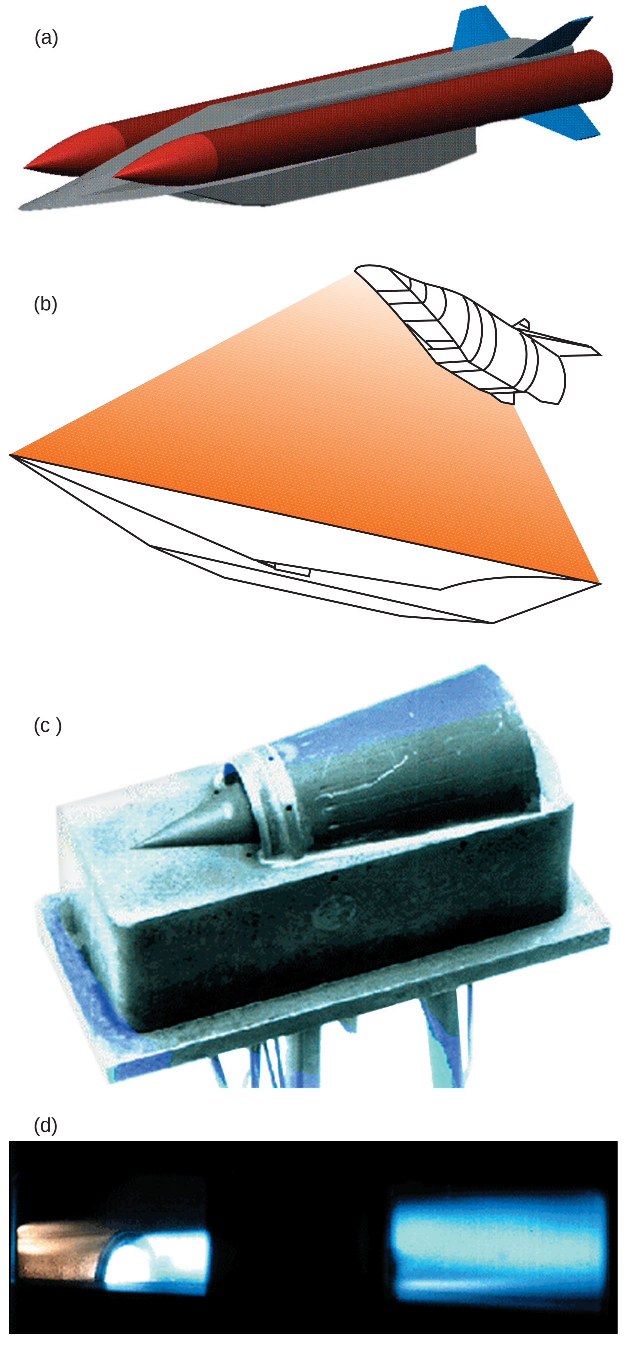

Figure. 1. Waverider-based Affordable Rapid Response Missile Demonstrator. This concept is for a missile that uses endothermic fuel, has an actively cooled structure, and is capable of Mach 4 to 8 operation: (a) vehicle with side-mounted boosters, (b) rectangular integrated engine flow path, (c) air-breathing pilot, (d) pilot operating on hydrocarbon fuel.

When the missile is integrated with naval ship platforms, the side-mounted boosters are replaced by a tandem booster sized to meet the constraints of the vertical and canister launch systems. More details on this concept are presented in the section on Technical Challenges.

The second missile concept was developed by Boeing and Aerojet. It is based on dual-combustor ramjet (DCR) technology originally developed by the Navy for surface-to-air applications under the Navy Surface Launched Missile Technology Program (Fig. 2).[4] This concept is for an axisymmetric missile with multiple inward-turning scoop inlets located in the compression field of a conical forebody. These inlets split the air to feed a subsonic dump combustor and a tandem supersonic combustor. All of the fuel is added to the subsonic combustor, which heats and partially cracks the fuel. The fuel-rich effluent provides the core flow for mixing with the annular supersonic inlet supply in the supersonic combustor. This design burns unprocessed liquid hydrocarbon fuel and relies on high-temperature materials and insulation for the engine and airframe structure. A slip-in booster for the air-launched configuration boosts the missile to a take-over Mach number. A tandem booster is used for ship-launched versions. (See also the section on Technical Challenges.)

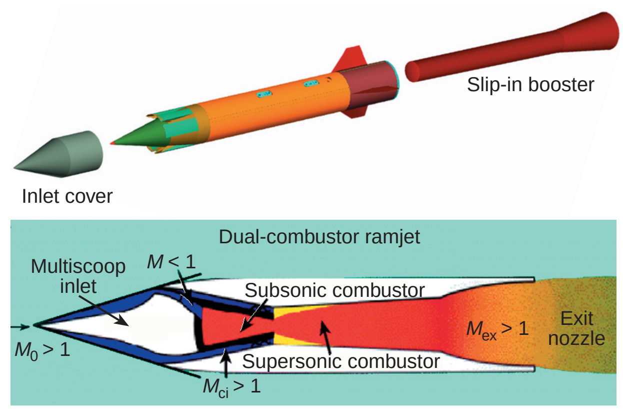

Figure. 2. Dual-combustor ramjet–based Affordable Rapid Response Missile Demonstrator. This concept is for a missile that uses conventional hydrocarbon fuels, has improved low-speed performance and good hypersonic performance, is efficient from Mach 3 to above Mach 6, and is more efficient than a ramjet except at and near the ramjet design point. (M = Mach number, M_0 = freestream Mach number, and M_{ci} = combustor inlet Mach number.)

Coordination with DoD Science and Technology Programs

The ARRMD Program is not a technology development program; rather, it is a program to demonstrate state-of-the-art technology being developed by the Navy and Air Force. The Office of Naval Research (ONR) is executing the Hypersonic Weapon Technology (HWT) Program to mature the suite of critical component technologies that specifically enable a long-range strike missile and to demonstrate them. This program is a coordinated effort between the Naval Air Warfare Center Weapons Division at China Lake, APL, and the Naval Surface Warfare Center at Dahlgren, Virginia. China Lake is responsible for program management, guidance and control, and airframe technologies. APL is responsible for propulsion technologies, and Dahlgren is responsible for ordnance technology. Under the HWT propulsion program, the near-term focus is the DCR engine, and the HWT propulsion tasks have been fully coordinated with ARRMD Program efforts. In addition, HWT ordnance technology being developed for multifunction warheads can be applied to the weapon concepts under the ARRMD Program.

The AFRL has contracted with P&W under the HyTech Program to develop hydrocarbon-fueled scramjet propulsion technology for Mach 4 to 8 applications. Such applications might include a long-range strike missile, global reach aircraft, or even an interim stage for access to space. The broad range of applications for the HyTech technology is enabled by the use of an endothermic hydrocarbon fuel and an actively cooled structure. The Boeing/P&W waverider concept for the ARRMD Program uses this HyTech technology and relies heavily on that program's technology development efforts.

To cover coordination between the Navy and Air Force hypersonic technology programs and the DARPA flight demonstration program, a Memorandum of Understanding has been established. Initially, DARPA and ONR established and signed such a memorandum stating that "their programs are to be integrated in a manner that best permits the accomplishment of the overall objective to field a hypersonic cruise missile." The memorandum notes that "DARPA will look to the ONR Hypersonic Weapon Technology Program to help provide the technology basis to draw from during the execution of the ARRMD program," and provide "continual technology evolution essential to the eventual development of a viable weapon system." It also affirms that the "DARPA program addresses the critical objectives of weapon manufacturability and affordability, and provides an essential near-term opportunity to demonstrate hypersonic missile technologies in flight." This memorandum was recently expanded to include the Air Force HyTech Program. The expanded memorandum states that "DARPA, ONR, and AFRL will coordinate their programs and establish an integrated technology roadmap supporting hypersonic weapons development," and that "program execution strategies for the ARRMD, HWT, and HyTech programs will be pursued that are mutually supportive and integrated." The fully integrated memorandum is currently awaiting signature.

Concept of Operations

The technology being demonstrated under the ARRMD Program will enable the development of an Affordable Rapid Response Missile (ARRM). The ARRM will be compatible with a large range of launch platforms and will be able to use targeting information derived from national and tactical surveillance assets. Utilizing a modular or multifunction warhead, the ARRM is envisioned as having the capability to defeat time-critical, hardened, buried, and heavily defended targets. Figure 3 depicts a baseline concept of operations for employment of a notional hypersonic strike weapon system concept based on the ARRM.

For the baseline concept of operations, the target is identified and located using a variety of potential surveillance assets, either in-theater (e.g., Joint Surveillance and Targeting Attack Radar System [JSTARS], Global Hawk, Dark Star) or spaced-based (e.g., Defense Support Program [DSP], Space Based Infrared System [SBIRS], or Discoverer II). The target location is provided in the form of Global Positioning System (GPS) coordinates to a strike warfare commander via satellite communications links. This GPS target location is uploaded to the missile, and the missile is launched at the threat. During flyout, improved targeting information can be transmitted to the missile using secure satellite communications links, should such information be available from either national space-based or in-theater surveillance assets. The rapid-response missile flyout is done at hypersonic speeds, and once in the target area, the missile terminal maneuver is tailored to the type of target being attacked. For relocatable targets whose location error is such that submunitions are required, the missile slows, descends to deploy an appropriate submunition payload, and attacks the target before leaving the area. For fixed hard or buried targets, the ARRM carries a kinetic-energy penetrator and dives vertically to the target at high speed. For soft targets, the same high-velocity terminal dive is envisioned with deployment of a high-explosive or area munitions payload. Figure 4 shows the critical components of an ARRM weapons system concept.

TECHNICAL CHALLENGES

Hypersonic Missile

A number of critical technical challenges are associated with demonstration of a hypersonic cruise missile. At a top level, many of the challenges are common, regardless of the missile concept being developed, but often the approach to these top-level challenges creates a concept-specific set of technical problems. Again, in the ARRMD Program, affordability is a firm missile design requirement. Thus, ARRMD will focus on demonstrating an affordable flight vehicle to make a long-range hypersonic weapon system possible.

Perhaps the most challenging issue in developing a missile for sustained hypersonic flight is the ability to

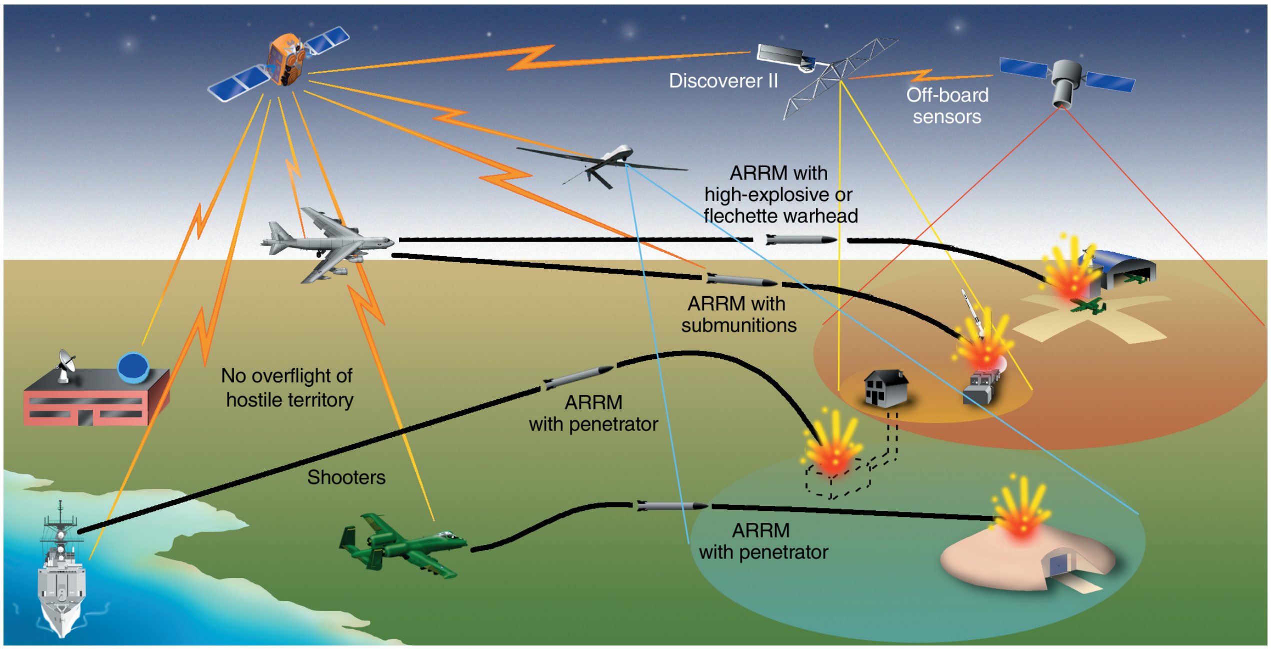

Figure. 3. Concept of operations for a hypersonic strike weapon system based on the Affordable Rapid Response Missile (ARRM) under study. The system holds deep targets at risk and allows a short time of flight to fleeting targets.

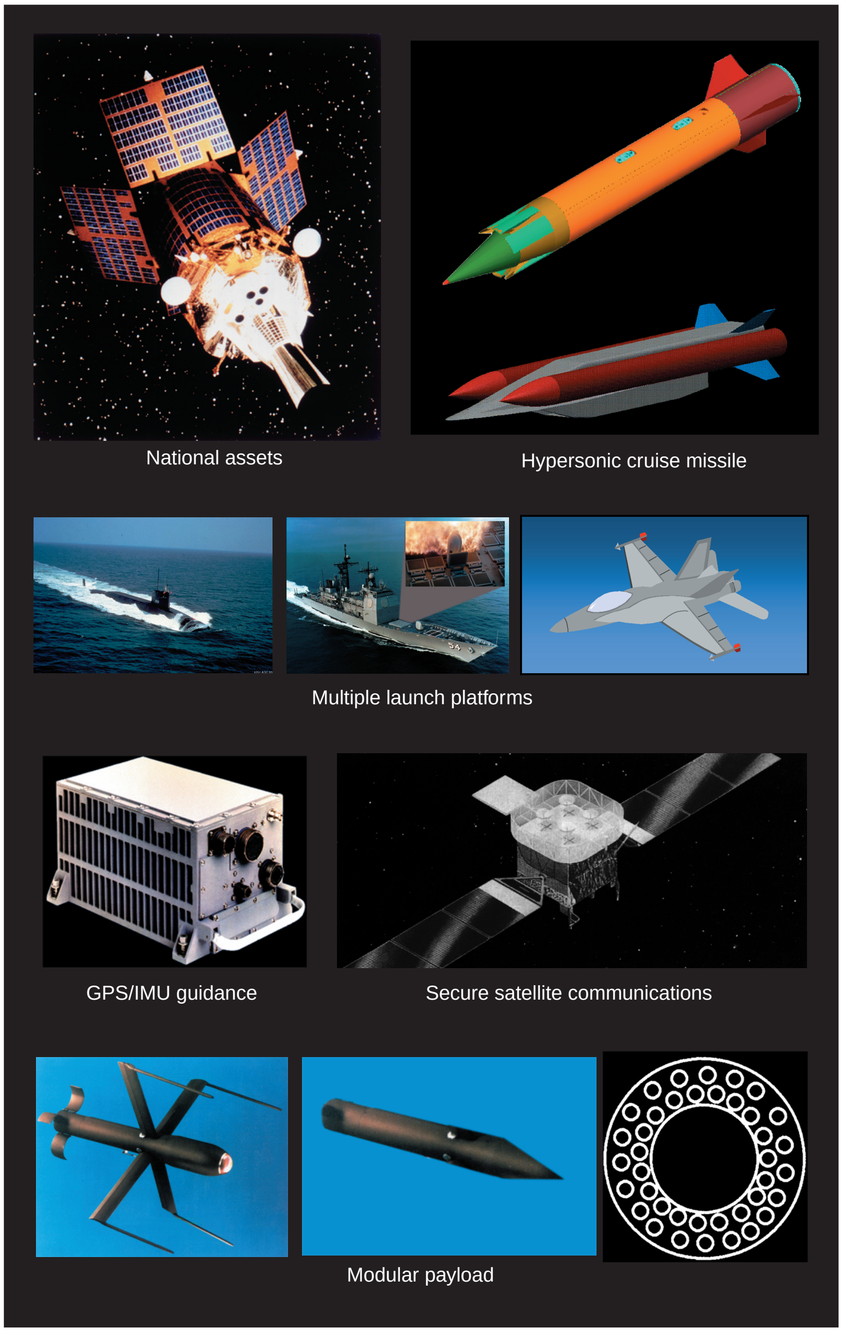

Figure. 4. The hypersonic strike weapons system concept based on the ARRMD. (GPS = Global Positioning System; IMU = inertial measurement unit.)

deal with the extreme thermal environment. Flight at speeds above Mach 6 results in missile skin temperatures that exceed 1000°F, leading edge and inlet duct temperatures that exceed 2000°F, and combustor and nozzle temperatures in excess of 4000°F if there is no active cooling (Fig. 5).[5] The approach to survival in this thermal environment varies depending on the specific missile concept and missile component. For most of the exterior surfaces of the missile, the use of high-temperature materials with or without thermal barrier coatings is generally adequate. Missile components directly exposed to the air stream, such as control surfaces and inlets, need special attention because of swept and unswept leading edges and the resulting shock interactions. Inside the missile, critical subsystems, including payload, electronics, and the fuel system, must either be protected from the extreme temperatures or designed to handle them.

By far the most stressing thermal challenge is the combustor. How the thermal environment is overcome in the combustor is directly linked to another critical technical challenge: getting a logistically suitable liquid hydrocarbon fuel to burn efficiently in a supersonic stream. The two ARRMD concepts approach this problem in dramatically different ways. A brief description of each concept missile's operation illustrates this difference.

The waverider hypersonic missile concept discussed earlier (Fig. 1) incorporates a propulsion approach having its origins in work sponsored by the Navy and involving NASA Langley Research Center and United Technologies Research Center. Researchers at United Technologies developed the rectangular combustor configuration that embeds a small, subsonic combustion, air-breathing pilot on the wall of the combustor. The pilot captures a small amount of flow and burns a small amount of fuel. Its exhaust anchors the supersonic combustion in the primary combustor, where the rest of the fuel is added. This engine configuration requires the liquid hydrocarbon fuel to be vaporized upon injection. An endothermic fuel is used, and backside heat exchanger panels provide a vaporized, partially cracked product to the combustor. This approach also utilizes the heat exchanger to cool the combustor walls.

The actively cooled combustor can control the wall temperature and offers the potential to operate at speeds on the order of Mach 8, but the actively cooled structure and the associated fuel system must be built

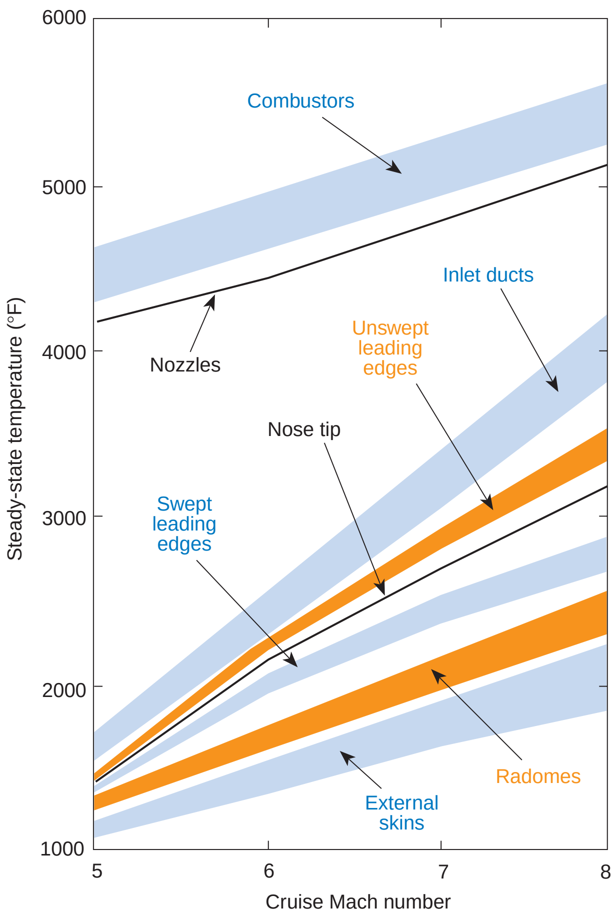

Figure. 5. Steady-state temperature versus cruise Mach number for critical missile components at an 80,000-ft altitude.[5]

affordably. Reasonable combustor performance has been demonstrated under the HyTech Program for Mach numbers ranging from 4 to 8.

The primary technical challenges of the waverider approach include

- Affordable integration of the requisite missile subsystems to permit cold start of the engine, inlet starting, and control of the heated fuel
- Integration and affordability of the rocket boosters
- Controllability of the air vehicle throughout the flight envelope

The ARRMD Program will benefit from continuing development work under the HyTech Program on the engine technology being utilized in the waverider concept. Under the ARRMD Program, the flight vehicle design will be developed to maturity and demonstrated through force and moment wind tunnel testing. Critical low-cost manufacturing approaches for this concept will be demonstrated.

The DCR-powered hypersonic missile concept (Fig. 2) combines features of a ramjet and a scramjet by embedding a subsonic dump combustor in the engine upstream of the supersonic combustor to act as a pilot. This pilot prepares the hydrocarbon fuel for burning in the supersonic combustor. Approximately 25% of the air passing through the engine is captured by two inlets and ducted to an embedded subsonic dump combustor, where it is mixed and burned with all of the fuel. The resulting fuel-rich effluent then burns, with the air stream captured and delivered to the tandem supersonic combustor by four inward-turning scoop inlets. These inlets compress and wrap the flow into an annular dump plane at the same axial station as the subsonic combustor exit. The combustion process that starts in the subsonic combustor is then completed in the cylindrical supersonic combustor and exhausted through the divergent exit nozzle.

This combustor arrangement allows a hypersonic missile to use conventional hydrocarbon fuel with liquid injection. Because the combustion process does not require any additional energy added to the liquid fuel, the entire combustor can be passively cooled for a cruise Mach number of approximately 6.5.

The primary technical challenges of the DCR approach include

- Development and implementation of affordable materials that can withstand the extreme temperatures in the subsonic and supersonic combustors, the surrounding inlet ducts, and the nozzle
- Affordable fabrication of the complex inlet and subsonic combustor assembly
- Engine sizing for operation from Mach 3 to 6.5
- Missile packaging to permit carrying of adequate fuel and an effective warhead

Leveraging the technology development and component demonstration effort for the DCR sponsored by the Navy from 1977 to 1986 and continued under the HWT Program, Phase 1 of the ARRMD Program will demonstrate critical, low-cost manufacturing techniques and integrated propulsion system performance.

Targeting, C^{4}ISR, and the Endgame

Targeting and lethality are essential elements of a viable weapon system. The ARRMD Program is focused on demonstrating a viable hypersonic strike missile. Its product is the flight-test demonstration of a missile that can fly at least 400 nmi to within 35 ft of a defined aim point. Ultimately, however, a successful long-range strike requires the ability to accurately locate and identify the desired target, transmit the targeting information to the shooter in a timely manner, and use the result in a lethal endgame. Targeting accuracy and latency dictate important weapon system requirements for terminal sensors, guidance system accuracy, communications for in-flight target updates, and weapon flyout time. This is particularly true for mobile or relocatable targets that pose the most stressing threat for a number of important system design parameters. Two factors are crucial in establishing the capability to defeat time-critical mobile targets like tactical ballistic missile launchers:

1. The ability to detect and identify the target with enough accuracy to effectively direct a strike
2. The ability to get that information to the shooter within the required time

This targeting ability defines many of the other major weapons system requirements, as well as the overall probability of mission success.

Several options exist for targeting, and the assets available for deployment depend largely on the circumstances of the conflict. Potential targeting assets include satellites, manned aircraft, unmanned aerial vehicles, special operations forces, and unattended ground sensors. This infrastructure is currently being developed independently of high-speed missile development; many resources are being applied to the timely identification of tactical ballistic missile launchers and other critical short-dwell targets.

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At long range, a hypersonic cruise missile permits maximum leverage from this infrastructure. It compresses by a factor of 5 to 6 the time of flight of the weapon for attack of the target. The compression greatly reduces the time that a given sensor suite and communications channel must be dedicated to a single target. It is likely to significantly improve overall warfighting effectiveness.

Certain space-based surveillance assets may be able to identify a tactical ballistic missile launch and establish a projected launch location within the time and accuracy required to meet mission objectives. This type of targeting capability would permit the development of the least-expensive weapon: guidance and navigation could be provided with a GPS-updated inertial navigation system, and the weapon payload could be area munitions or flechettes. However, if assets are not available to provide sufficient launch location accuracy for effective weapon system operation, a terminal sensing capability may be necessary. In that case, either additional off-board, in-theater assets are needed (unmanned aerial vehicles, JSTARS, etc.) to supply more accurate targeting information for terminal guidance, or the missile design must incorporate an active terminal seeker, or a payload with a terminal sensor capability (i.e., smart submunitions) must be used.

To defeat short-dwell relocatable targets, the ARRMD Program's approach is to carry smart submunitions to the target, such as the Brilliant Anti Armor Submunition (BAT) or the Low Cost Autonomous Attack Submunition (LOCAAS). Critical technology challenges include thermally protecting the submunition payload during the mission and deploying it at conditions consistent with the flight envelope of the high-speed missile, which can include terminal speeds as high as Mach 3. For penetrator missions where the target location is relatively well known, the ARRM will be designed to carry a 250-lb kinetic-energy penetrator payload delivered at impact velocities up to 4000 ft/s. For relatively soft area targets whose locations are well known, area munitions will be carried.

Launch Platform Compatibility

Some of the critical constraints imposed on the design of a viable hypersonic weapon concern integration with the launch platform. The ARRMD Program has an objective of compatibility with a wide range of launch platforms. The missile weight is constrained most severely by the F/A-18 aircraft. Its length is constrained most severely by the internal rotary rack on the B-52 and B-1 strategic bombers. Geometric constraints are imposed by the square cells of the Navy Vertical Launch System on surface ships, the circular cross section of the Navy Canister Launch System aboard submarines, and the rotary rack on the bombers. In addition, the rocket boosters must meet insensitive munitions constraints and firing limitations aboard ships.

SUMMARY

The DARPA ARRMD Program is under way to develop, and for the first time demonstrate in flight, a hypersonic cruise missile concept. The concept has as a firm requirement that the eventual AUFP not exceed $200,000. The only firm requirement for the missile design is affordability. Two candidate missile concepts are being developed by Boeing to achieve capability goals that include accuracy (35 ft), long range (600 nmi), minimum time to target (7 min at 400 nmi), survivability, and robust launch platform compatibility. The missile must also be logistically suitable for the complete set of launch platforms and effectively be a "wooden round." The 18-month Phase 1 activity will demonstrate the viability of the air vehicle designs in a series of wind tunnel tests, demonstrate the critical low-cost manufacturing techniques, and refine affordability assessments. Should Phase 1 objectives be successfully accomplished, and should DARPA continue the work, Phase 2 will include selection of a preferred vehicle configuration. The selected configuration will go into a 30-month flight test demonstration phase. The ARRMD Program is being coordinated with, and relies on, Air Force HyTech and Navy HWT Program efforts.

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