

Hypersonic Airbreathing Propulsion

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Hypersonic airbreathing propulsion technology is rapidly maturing to enable flight vehicles with transformational capabilities. APL has a rich history of leading-edge accomplishments in this arena. Laboratory-invented technology is being transitioned to a missile flight demonstration, and APL is contributing to a variety of hypersonic technologies and vehicle system concepts being developed by the DoD. Building from a substantial knowledge base on the operation of these emerging propulsion systems, this article discusses science and technology issues that will enable future performance improvements and expanded operational envelopes for these systems. Critical technology challenges include improving our understanding of the stressing aerothermal environment, achieving the necessary component and integrated engine performance, dealing with the engine system dynamics to achieve robust operation, developing proper scaling laws to enable transition from ground test to flight systems, and developing advanced lightweight, high-temperature materials and cooling techniques to handle the engine environment. We also briefly address the potential warfighting payoff of systems that use high-speed missiles.

INTRODUCTION

Emerging hypersonic airbreathing propulsion systems offer the potential to enable new classes of flight vehicles that allow rapid response at long range, more maneuverable flight, better survivability, and routine and assured access to space. Historically, rocket boosters have been used to propel hypersonic vehicles (i.e., those flying faster than 5 times the local speed of sound) for applications such as space launch, long-range ballistic flight, and air-defense interceptor missiles. Airbreathing propulsion systems currently under development will provide a means for sustained and accelerating flight within the atmosphere at hypersonic speeds. Potential mission areas include long-range cruise missiles for

attack of time-sensitive targets, flexible high-altitude atmospheric interceptors, responsive hypersonic aircraft for global payload delivery, and reusable launch vehicles for efficient space access. Although hypersonic airbreathing propulsion systems have been investigated for the past 40 years without development of an operational system, significant technology advancements have been realized recently, and the development of operational hypersonic systems appears to be within our grasp. In particular, the technology to support a baseline hypersonic propulsion system exists that will allow operation at speeds up to Mach 6 with conventional liquid hydrocarbon fuels.

Hypersonic propulsion systems can be categorized as liquid- and solid-fueled rockets, turbojets, ramjets, ducted rockets, scramjets, and the dual-combustion ramjet (DCR). All existing hypersonic systems use either liquid or solid rockets as their propulsion system. As with liquid-fueled rockets, solid-fueled rockets (Fig. 1a) carry both fuel and oxidizer—either separately in liquid fuel tanks or combined within a solid propellant grain—which are burned within a high-pressure chamber to produce hot gaseous products that are expanded through an exhaust nozzle to produce thrust. Both types of rocket system have drawbacks. Liquid engines typically operate with either cryogenic or toxic storable propellants, while solid propellant systems usually cannot be throttled or stopped and restarted. Some of the drawbacks of pure rocket motors, mainly the inefficiency of carrying all required oxidizers onboard, can be addressed by using a ducted rocket. Figure 1b shows a ducted rocket where the fuel-rich effluent of a rocket motor is mixed in a downstream combustor with air captured from the atmosphere to improve the efficiency of the engine cycle.

Further improvement in efficiency is achieved by using pure airbreathing engines, which capture all of their needed oxygen from within the atmosphere instead of carrying oxidizers. This results in more efficient engine operation (albeit at generally lower thrust levels) and the ability to use conventional hydrocarbon fuels. A key feature of these engines is that in addition to being highly efficient they can be throttled to allow trajectory flexibility.

Pure airbreathing engines can be subdivided into turbojets, ramjets, scramjets, DCRs, and turbo-ramjets. Conventional turbojets (Fig. 1c) use mechanical compression in the inlet, driven by a turbine located

downstream of the combustion process, to provide a portion of the airstream compression. The maximum speed of a turbojet is usually limited to a Mach number of about 3.5 by the allowable turbine blade temperature, although options for higher-speed applications are under investigation. As flight speed is increased, the mechanical compression within a turbojet is not required, so the ramjet cycle (Fig. 1d)—which relies on the compression inherent in capturing and slowing a supersonic airstream to the subsonic conditions where combustion occurs—becomes feasible. At still higher speeds, the losses associated with decelerating the captured airstream to subsonic speeds become large and the supersonic combustion ramjet, or scramjet, cycle is preferred. In the scramjet engine (Fig. 1e), the captured airstream is still compressed by the inlet, but the combustion is allowed to occur at supersonic speeds.

Ramjets and scramjets can operate efficiently at supersonic and hypersonic speeds, but there tend to be limitations to the range of Mach numbers over which they can operate. For instance, the need to have sufficient compression in the inlet ordinarily requires that the ramjet engine operate supersonically. The inefficiencies of slowing the flow down to subsonic speeds makes the ramjet difficult to use for speeds exceeding Mach 5. Scramjets can be used above approximately Mach 5 but below that there is in general insufficient energy in the captured airstream to enable efficient combustion in the supersonic combustor. Both the ramjet and scramjet must be coupled with some additional form of propulsion (for missiles, this is chiefly a rocket) to accelerate the vehicle to its “take-over” Mach number. To overcome these limitations, combined cycle engines have been developed.

Combined cycle engines, such as the DCR (Fig. 1f) and turbo-ramjet, offer design features that enhance engine performance and operability over a wide range of flight conditions. In the DCR, a subsonic combustion ramjet is used as the pilot to a scramjet engine, enabling efficient operation over a wider range of supersonic and hypersonic Mach numbers using logistically suitable fuels. In the turbo-ramjet, an integral turbine-based core engine provides acceleration up to supersonic speeds, at which point the engine transitions to ramjet operation. This engine enables a vehicle to accelerate from a standing start to high supersonic Mach numbers. An example of a vehicle powered by such an engine is the now-retired SR-71 Blackbird spy plane.

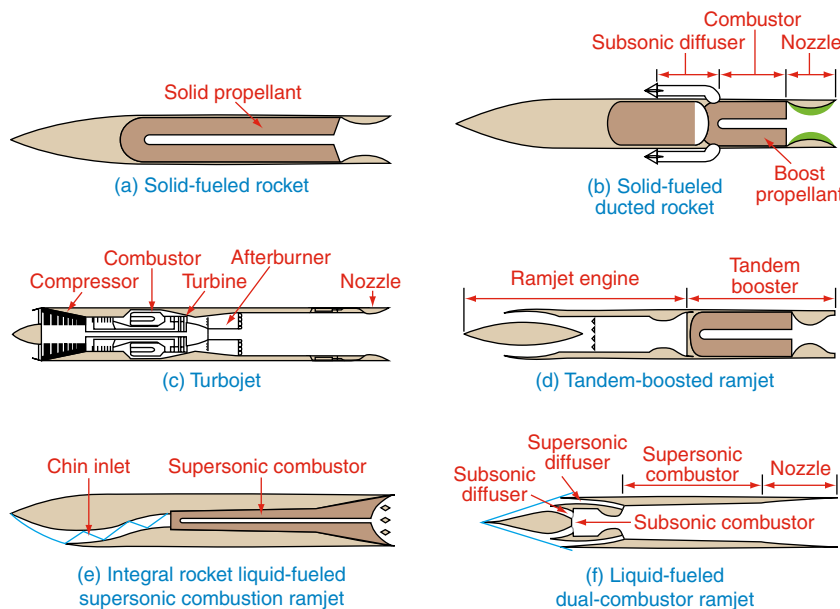


Figure 1. Candidate engine cycles for hypersonic vehicles.

To give a general understanding of the relative efficiency of the various engine cycles described above, Fig. 2 shows the specific impulse, i.e., the pounds of thrust generated per pound of fuel flow used, for the various engine cycles as a function of Mach number. Information is presented for a range of engine cycles, with the airbreathing engines using either hydrogen or liquid hydrocarbon as fuel.

TECHNOLOGY CHALLENGES

Let's now turn our attention to engine technology needed to achieve hypersonic flight (generally considered to be flight at Mach numbers >5). We focus on the use of airbreathing engines because that engine technology will enable a whole new class of flight vehicles capable of achieving hypersonic cruise within the atmosphere.

As mentioned above, the primary airbreathing engine cycle used for flight at speeds approaching hypersonic flight (Mach numbers above ≈5) is the ramjet. At supersonic speeds a ramjet-powered vehicle utilizes an inlet that is designed to capture atmospheric air and compress that air to prepare it for combustion. Once the air is compressed, it is ducted into a combustor where it is mixed with fuel, and the mixture is burned to raise the temperature and pressure inside the engine. The ducting that delivers the air from the inlet to the combustor is called the diffuser (the term commonly used for subsonic combustion ramjets) or isolator (the term commonly used for scramjets). For subsonic combustion ramjet engines the diffuser compresses the captured airstream, slowing the flow from the supersonic flight speeds down to approximately 300 ft/s for delivery to the combustor. Once the fuel/air mixture is burned in the combustor, the mixture is passed through a converging/diverging nozzle and accelerated, exiting the engine once again at supersonic speeds. Above Mach 5 there is a high price to pay for slowing the flow down to subsonic speeds, so for these hypersonic speeds supersonic combustion ramjets (scramjets) are preferred. For scramjet engines, the flow captured by the inlet is still slowed to increase the pressure and temperature prior to combustion, but the flow entering the combustor remains supersonic. The design for both the ramjet and scramjet must be such that the pressure increase in the engine is sufficient to generate enough thrust to overcome the vehicle drag in order to propel the vehicle through the air. Achieving such a design requires that numerous technical challenges first be overcome. These challenges are shown schematically in Fig. 3.

Numerous investigations into the operability and performance

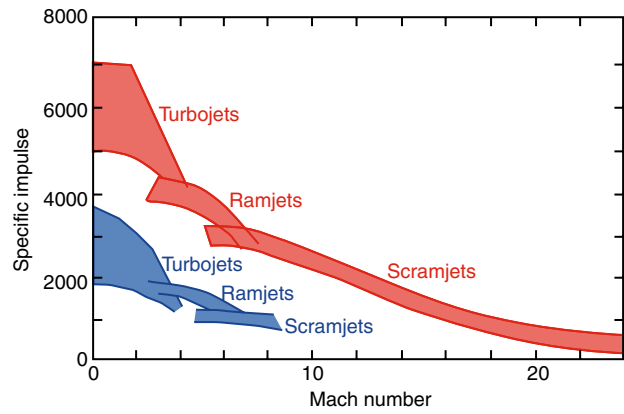


Figure 2. Engine-specific impulse advantages of airbreathing engines (hydrogen fuel, red; hydrocarbon fuels, blue).

of each of the principal engine components (inlet, diffuser/isolator, combustor, nozzle, and fuel control system) have been conducted, providing a solid basis for a future engine development program. Significant empirical design databases exist together with validated analysis tools for the prediction of engine performance (and to a lesser extent, operability). However, until very recently all of the data gathered have been in ground demonstrations, and no realistic system has yet matured to the point of flight demonstration. Remaining science and technology challenges related to hypersonic airbreathing engines are aimed at techniques for improving baseline performance levels, increasing the accuracy of performance predictions, predicting engine operability limits, reducing engine weight for a given thrust level, and demonstrating in flight a viable integrated vehicle concept powered by a hypersonic airbreathing engine.

APL has a long history of high-speed airbreathing engine development with notable achievements^{1,2} including

- The first flight of a ramjet-powered vehicle at supersonic speeds
- Development of the first ship-launched ramjet-powered surface-to-air missile
- Development and flight test demonstration of a Mach 4 surface-to-air ramjet-powered missile

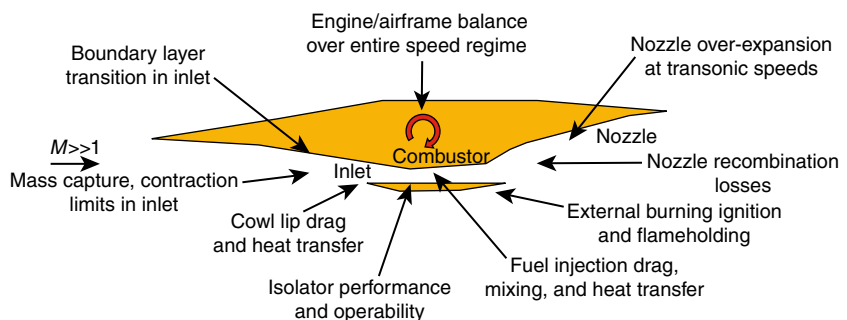


Figure 3. Engine issues for hypersonic airbreathing propulsion systems.

- The first demonstration of stable supersonic combustion for propulsion applications
- The first long-duration hydrogen-fueled scramjet combustor tests at speeds greater than Mach 10
- The first successful ground tests at hypersonic speeds of a full-scale, liquid-hydrocarbon-fueled scramjet engine integrated into a missile-like configuration

From this basis of significant propulsion advancements the following technical challenges are identified to provide the science and technology vision for hypersonic airbreathing propulsion technology development.

Understanding the Aerothermal Environment

As the flight speed of hypersonic vehicles increases, the kinetic energy of the airstream and the total energy captured by the engine increase with the flight velocity squared; thus, a vehicle flying at Mach 10 must deal with 100 times the flow energy of one flying at Mach 1. For example, a hypersonic airplane flying at Mach 10 encounters an airstream power of approximately 3 GW. Manipulating this flow energy with minimal losses is key to the successful design of a hypersonic engine. Even at extreme speeds the flow at the wall of a flight vehicle traveling in the atmosphere slows to zero relative velocity due to friction. This generates tremendous heat in the near-wall “boundary layer” region of the flow. This heat transfer is magnified inside the engine as a result of combustion. The resulting aerothermodynamic heat transfer to the walls of a hypersonic vehicle must either be radiated away from the vehicle, which leads to a loss of propulsive efficiency, or captured within an active cooling system. For speeds up to approximately Mach 6, high-temperature materials can be used to operate near the recovery temperature of the flow. Above Mach 6, actively cooled structures are required using the fuel as the coolant, which increases engine cost and complexity. Furthermore, efficient engine operation requires that the engine be designed such that the cooling requirement is balanced with the cooling capability inherent in the fuel.

With the stressing aerothermal environment at hypersonic speeds, development of improved techniques for predicting heat loads and extending thermal balance margins is required. Existing computational and empirical techniques can predict heat loads with sufficient accuracy for the conceptual design stage, but additional research is needed on the effects of nonequilibrium turbulence, surface roughness and ablation, gaps, corners, and shock impingement. By more accurately predicting heat loads, the engine thermal balance can be designed with refined margins, and techniques can be explored to expand the operating envelope of the engines. Techniques for improving the thermal margin of the engine include transpiration or film cooling and boundary layer flow control aimed at reducing the local heat transfer,

minimizing both the wetted surface area of the engine through changes to the basic engine design and the length needed for the isolator and combustor, and increasing the cooling capacity of the fuel through the use of alternate fuel blends and additives.

Achieving High Combustor Performance with Logistically Suitable Fuels

Design of the fuel injection, ignition, and flame stabilization aspects of an airbreathing engine is a key to achieving high performance. At hypersonic speeds, the resident time of the air within the engine is usually on the order of 1–3 ms, during which the fuel and air must be mixed and burned. Conventional approaches to fuel/air mixing use instream fuel injectors, which can be designed to adequately distribute the fuel; however, the injectors must operate in a stressing aerothermal environment and introduce drag losses to the engine. Advanced fuel injection techniques under investigation include the use of aerodynamically shaped wall injectors, injection of multiphase mixtures, active flow control devices to drive fluidic instabilities, and plasma discharge systems for creating large-scale vortical motion in the combustor.

Current research is focused on the use of conventional liquid hydrocarbon fuels (e.g., JP-7 and -10) for applications such as missiles and responsive aircraft, and liquid hydrogen for applications where high engine performance is paramount (e.g., space launch). The opportunity exists to improve the performance of hypersonic vehicles through the development of advanced fuels. Highly strained hydrocarbons, such as quadricyclane and bi-cyclopropylidene, and metal slurries can be used to significantly increase the energy density of fuels.

Conversion of the chemical energy of the propellant into useful thermal energy within the combustor is challenging. This is especially true of hydrocarbon fuel systems where the ignition delay time can be 1–2 orders of magnitude greater than the average flow residence. In the 1960–1970 time period, engines were developed that circumvented the ignition delay issue through the use of highly reactive fuels such as ethyldecaborane and triethyl aluminum.³ While these fuels provided excellent levels of performance, their pyrophoric and toxic nature prevented their use in operational systems.

The DCR engine was invented in the 1970s to enable the use of logistically suitable heavy hydrocarbon fuels at hypersonic flight conditions by integrating a subsonic pilot combustor in the forward end of a supersonic combustor. With the DCR, all of the fuel is added to a portion of the captured airstream, and the fuel-rich mixture is partially burned, raising the temperature and making the remaining fuel highly reactive. When the fuel-rich effluent is mixed with additional air in the supersonic combustor, robust burning occurs.

Other approaches sometimes used to achieve supersonic combustion with hydrocarbon fuel include the addition of flameholding cavities and rearward-facing steps to increase the flow residence time within some small region of the combustor; however, success in large-scale hydrocarbon-fueled engines has been limited. In all cases thus far, use of these schemes must be coupled with preconditioning of the fuel through energy addition in a heat exchanger system.

There has recently been some promising research to develop advanced approaches for ignition and flameholding. These new schemes use heterogeneous thermal energy deposition generated with pulsed DC or subcritical microwave discharges or employ highly nonequilibrium energy deposition produced with nanosecond pulsed discharges or high-power surface discharges, which couple optically to the fuel/air mixture. These ignition and flameholding systems offer the potential to achieve high levels of performance and operability in scramjets while avoiding the toxicity and handling issues associated with highly reactive fuels. Key challenges associated with this technology include devising efficient schemes for properly coupling the energy to the airstream and developing efficient and lightweight energy generation capabilities in flight vehicle scale.

Predicting Robust Engine Operation

While the baseline performance levels of hypersonic airbreathing engines are sufficient to enable new classes of flight vehicles, uncertainties exist concerning the prediction of engine dynamics and operability limits. These issues are addressed experimentally, and empirical techniques are used to generate design guidelines that incorporate sufficient margin to prevent catastrophic operating conditions from developing. Development of techniques for the accurate prediction of engine dynamics and operability limits will allow operation closer to optimum levels without the performance penalties associated with large operating margins. In addition to development of diagnostic techniques with sufficient spatial and temporal resolution, improved models for turbulent combustion and acoustic/combustion coupling must be developed. One of the promising research areas currently receiving attention is the use of active flow control devices for suppressing combustion instabilities.

Going from Ground Test to Flight

Another challenging aspect of developing hypersonic airbreathing engines concerns the development of appropriate scaling laws. For missile applications at speeds up to approximately Mach 6, ground-based facilities exist that allow testing to be run on full-scale engine hardware. For example, a full-scale representation of the DCR engine in the HyFly configuration is

shown in Fig. 4 installed in the NASA Langley Research Center 8-ft High Temperature Tunnel. Although these facilities operate using a vitiated airstream that contains contaminants, a sufficient simulation is achieved for development of most engine operating characteristics. The significant challenge for these engines lies in the demonstration of the engine thermostructural response and durability due to the limited run times of available ground test facilities. For engines sized for hypersonic aircraft or space access missions, no ground facilities exist at the required engine scale, so the issue of engine scaling becomes much more important. Development of appropriate engine scaling rules will be based on a detailed understanding of the physical processes involved in each stage of engine operation.

Developing Durable Engines

Existing approaches to hypersonic engines can be significantly improved with high-temperature materials and integrated structures. To illustrate how stressing the thermal environment can be in hypersonic airbreathing engines, Fig. 5 presents temperatures for various engine components as a function of flight Mach number. Hypersonic vehicle materials and structures must operate in this stressing aerothermal environment while being exposed to both oxidizing and reducing environments, and must at the same time be capable of surviving flight vibration, handling, and launch loads.⁴ Current approaches for building hypersonic engines use either ceramic matrix composites with oxidative coatings or fuel-cooled metallic walls. Significant room for advancements lies in improved cycle life, weight reduction, sealing concepts, and diagnostics for these material systems. In addition, creating often complex geometries associated with advanced hypersonic engines makes affordability an ever-present challenge.



Figure 4. DCR in the HyFly configuration installed in the NASA Langley Research Center 8-ft High Temperature Tunnel.

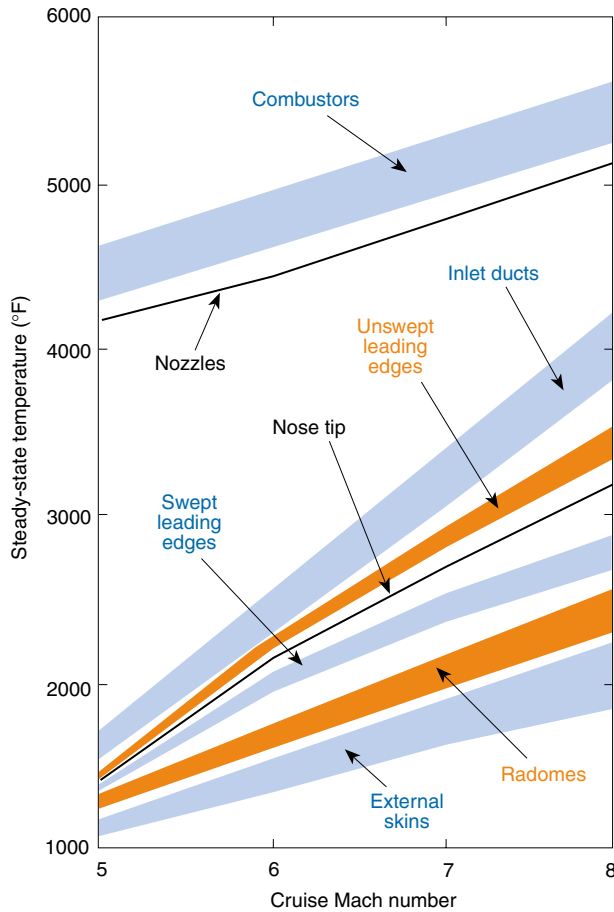


Figure 5. Steady-state temperature versus cruise Mach number for critical components at an 80,000-ft altitude.

THE PAYOFF

Successful development of high-speed weapon systems based on the application of advanced airbreathing engine technology can have dramatic payoff in warfighting capability. It is this potential that is being pursued under the DoD National Aerospace Initiative.⁵ In the near term, research being executed by the services and coordinated through the Director of Defense Research and Engineering is focused on the development of enabling technologies for high-speed missiles. The DARPA/ONR HyFly program is maturing the APL-invented DCR engine concept for flight demonstration in a vehicle that is consistent with a Mach 6 cruise missile for use against time-sensitive, hardened, and heavily defended targets.

To understand the real potential of such a weapon one must put

weapon capability in the context of an end-to-end system. The time line for defeat of time-sensitive targets (TSTs) can be described in terms of “find, fix, target, track, engage, and assess” (F2T2EA). To reliably and effectively counter TSTs all elements of the F2T2EA kill chain must get compressed and each element must work seamlessly with the others.

Historically, the limiting factor in responsive strike has been the ability to execute the front end of the F2T2EA process within a timescale consistent with the limited window of vulnerability of a TST. However, numerous initiatives are being worked to develop advanced technologies and processes to provide actionable information (i.e., target identification and location with sufficient accuracy to direct a weapon to the target) within tens of minutes. With that capability, the weapon flyout time becomes a major issue in our ability to address TSTs from a significant stand-off range. For comparison, a standard subsonic cruise missile traveling at Mach 0.7 flies between 70 and 80 nmi in 10 min, whereas a cruise missile traveling with an average velocity of around Mach 5.0 can fly 500 nmi in 10 min. In terms of area coverage from a single launch platform, for this same 10-min example, a launch platform carrying a subsonic cruise missile can hold at risk an area of approximately 15,400 nmi² compared to over 785,000 nmi² for a launch platform carrying a hypersonic cruise missile (Fig. 6).

Such a capability, when coupled with the dramatically reduced time lines being achieved with advanced C2ISR (command and control, intelligence, surveillance, and reconnaissance) technologies can provide revolutionary warfighting capability to achieve “effects on demand” to defeat TSTs (Fig. 7). In addition to improved capability to defeat TSTs, high-speed weapons provide dramatically improved kinetic energy at impact for attack of hardened targets (high-speed impact velocities

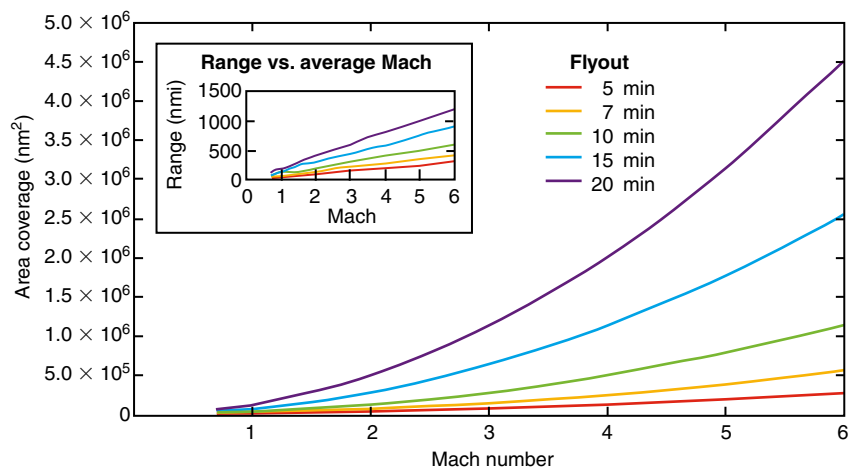


Figure 6. Area coverage and range as a function of Mach number for various mission flyout times.

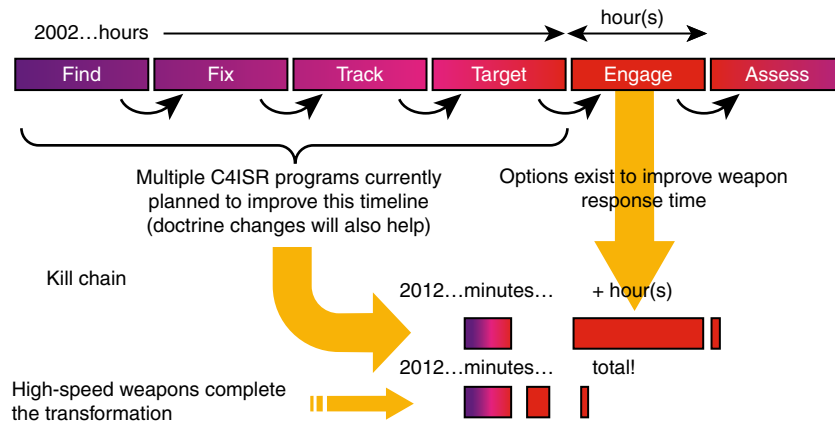


Figure 7. High-speed weapons coupled with advances in C2ISR have the potential to enable transformational warfighting capability to defeat time-sensitive targets.

can increase penetration depth by a factor of 5 or more for penetrator missions) and a significant improvement in weapons survivability as a result of the high-altitude, high-speed flight profile. The result is a weapon capability that can handle a significant subset of the strike warfighting needs and provide transformational capabilities to defeat current and future time-sensitive, hardened, and/or heavily defended targets.

SUMMARY

Hypersonic airbreathing engines are being investigated and developed for application to new mission

areas such as time-critical strike, access to space, and hypersonic global reach. APL has had a leadership position in this technology from its inception and continues to be on the forefront of developing the science and technology associated with these engines. Through combined experimental, analytical, and computational investigations, significant improvement in the performance and operability of hypersonic engines can be realized. This technology, when closely coupled with emerging systems, offers the potential to provide truly transformational capabilities.

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