

The world's first scramjet engine to demonstrate operability at Mach 4.5–6.5 using conventional fuel

As the 21st century unfolds, a revolutionary engine technology is aiming to fly craft at high Mach speeds and seamlessly integrate air-to-space operations. The supersonic combustion ramjet, or scramjet, uses no rotating parts, will power vehicles hundreds of miles in minutes, and will make rapid global travel and affordable access to space a reality.

These goals drew closer to achievement this spring when the first scramjet-powered aircraft flew on its own. On the afternoon of March 27, an unpiloted X-43A, a National Aeronautics and Space Administration (NASA) craft mounted on a Pegasus booster rocket, dropped from a B-52 flying at 40,000 ft off the coast of California. The rocket sent

the experimental aircraft soaring to its test altitude of 95,000 ft, where the X-43A separated from its booster, and its scramjet engine fired for a planned 10-s test, achieving an incredible Mach 7, or 5,000 mph.

Data from that flight helped validate the concept of a hypersonic craft with an air-breathing engine. More flights during the next several years will expand on the engine and aerodynamics data obtained in March, and could put some scramjet vehicles in service in less than a decade.

Scramjets will enable three categories of hypersonic craft: weapons, such as cruise missiles; aircraft, such as those designed for global strike and reconnaissance missions; and space-access vehicles that will take off and land like airliners.

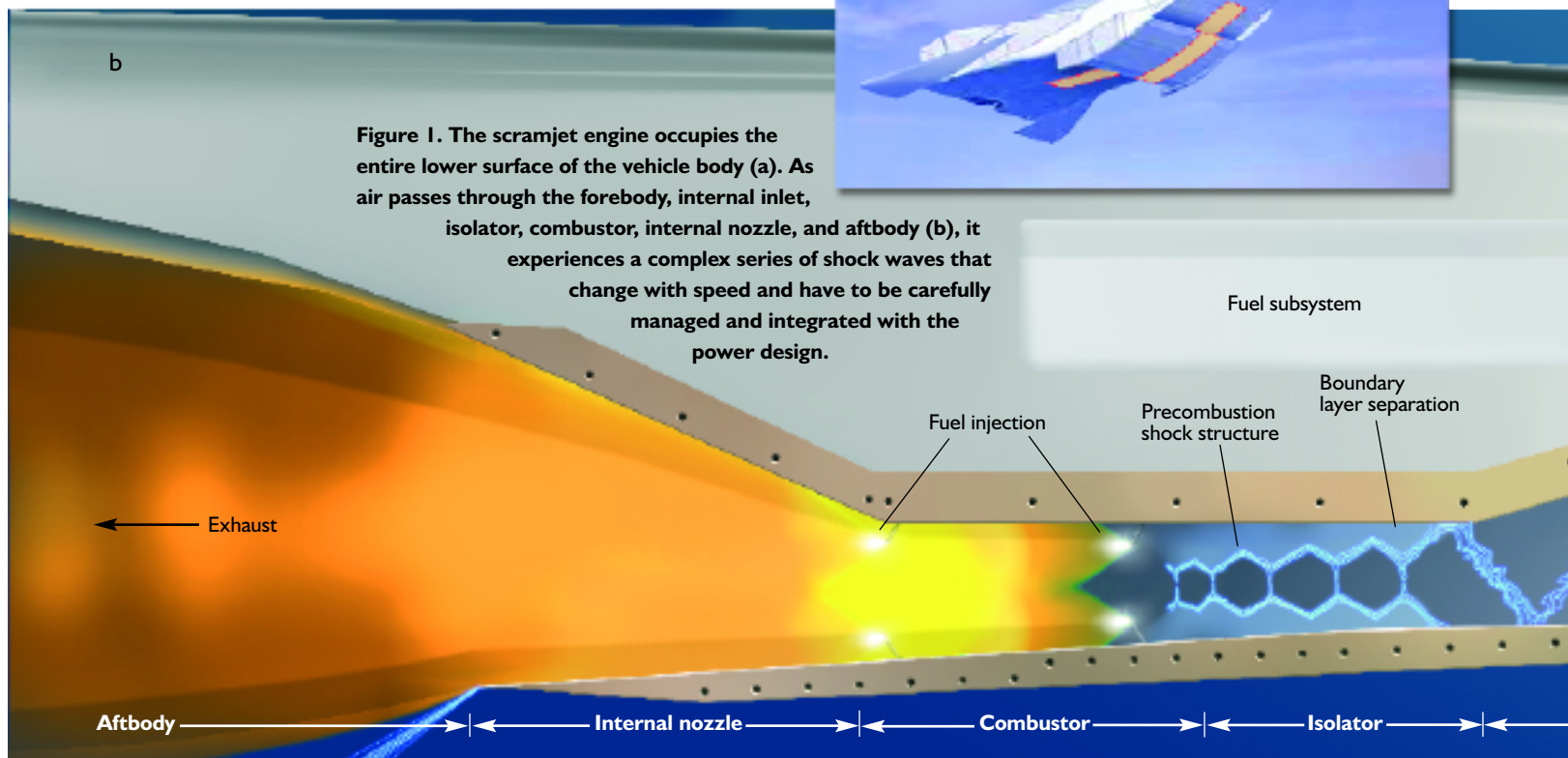
Scramjets have a long and active development history in the United States.

On the basis of theoretical studies started in the 1940s, the U.S. Air Force, Navy, and NASA began developing scramjet engines in the late 1950s. Since then, many hydrogen- and hydrocarbon-fueled engine programs have helped scramjet technology evolve to its current state. The most influential of these efforts was NASA's National Aerospace Plane (NASP) program, established in 1986 to develop a vehicle with speed greater than Mach 15 and horizontal takeoff and landing capabilities. The program ended in 1993, but the original NASP engine design, significantly modified by NASA, provided the foundation for the power plant used during the X-43A's recent flight.

The U.S. Air Force and Pratt & Whitney ground-tested the first uncooled hydrocar-



Figure 1. The scramjet engine occupies the entire lower surface of the vehicle body (a). As air passes through the forebody, internal inlet, isolator, combustor, internal nozzle, and aftbody (b), it experiences a complex series of shock waves that change with speed and have to be carefully managed and integrated with the power design.



bon-fueled scramjet engine at simulated Mach 4.5–6.5 in 2001. This collaboration also demonstrated in 2003 a scramjet made from nickel-based alloys and cooled by its JP7 jet fuel. The 2003 engine has the potential to power future missiles, aircraft, and access-to-space vehicles. Last year, the Defense Advanced Research Projects Agency, U.S. Navy, Boeing, Aerojet, and Johns Hopkins University also ground-tested a scramjet engine, which was constructed primarily from nickel alloys, powered by JP10 jet fuel, and intended exclusively for hypersonic missiles.

What is a scramjet?

In a conventional ramjet, the incoming supersonic airflow is slowed to subsonic speeds by multiple shock waves, created by back-pressuring the engine. Fuel is added to the subsonic airflow, the mixture combusts, and exhaust gases accelerate through a narrow throat, or mechanical choke, to supersonic speeds. By contrast, the airflow in a pure scramjet remains supersonic throughout the combustion process and does not require a choking mechanism, which provides optimal performance over a wider operating range of Mach numbers. Modern scramjet engines can function as both a ramjet and scramjet and seamlessly make the transition between the two (Figure 2).

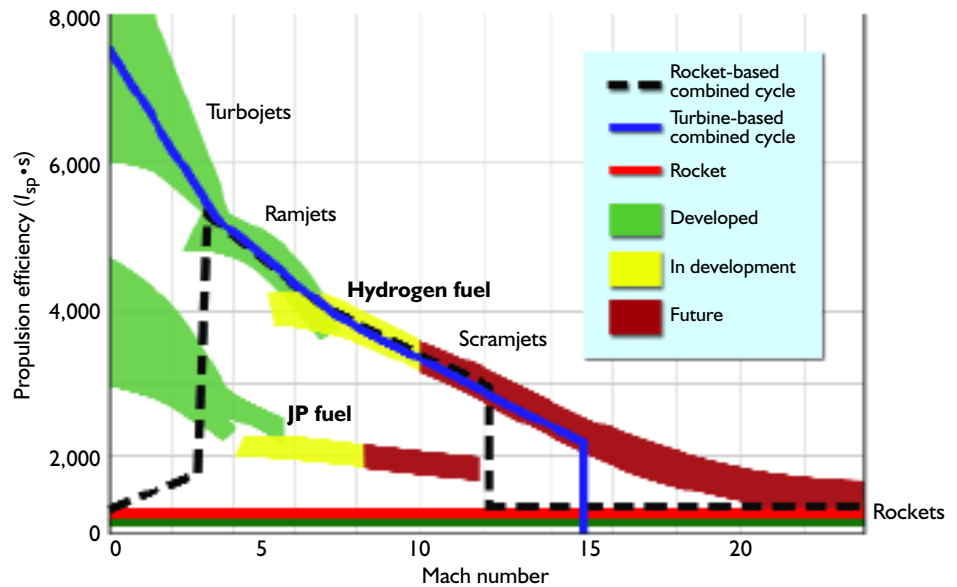
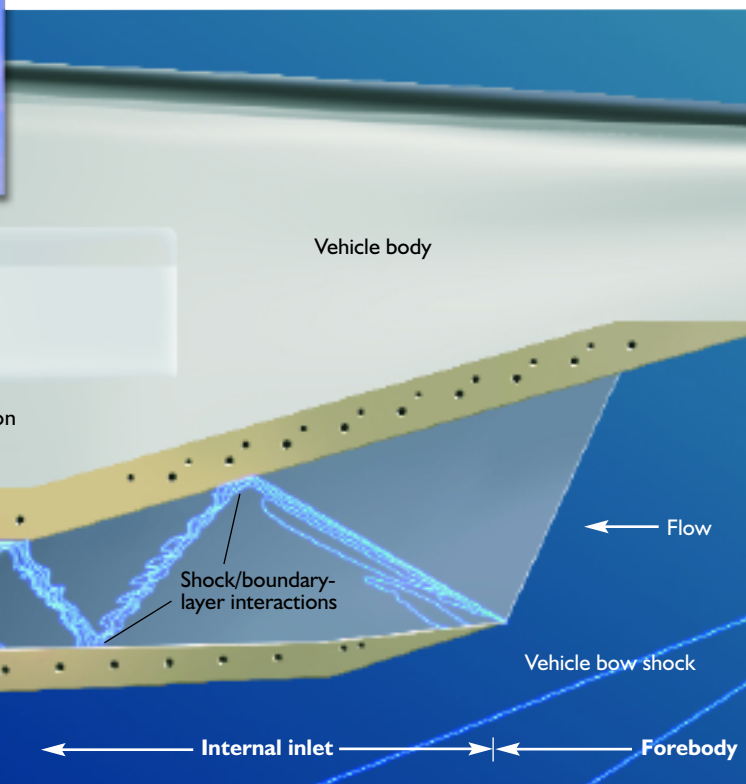


Figure 2. Propulsion efficiency decreases with speed as we progress from turbojets through ramjets and scramjets to rockets; hydrogen is more efficient than jet fuel.

Propulsion efficiency is $I_{sp} \cdot s$, where effective specific impulse (I_{sp}) is determined by the ratio of thrust to drag.

The scramjet provides the most integrated engine–vehicle design for aircraft and missiles. The engine occupies the entire lower surface of the vehicle body (Figure 1a). The propulsion system consists of five major engine and two vehicle components: the internal inlet, isolator, combustor, internal nozzle, and fuel supply subsystem, and the craft's forebody, essential for air induction, and aftbody, which is a critical part of the nozzle component.

The high-speed air-induction system consists of the vehicle forebody and internal inlet, which capture and compress air for processing by the engine's other components. Unlike jet engines, vehicles flying at high supersonic or hypersonic speeds can achieve adequate compression without a mechanical compressor. The forebody provides the initial compression, and the internal inlet provides the final compression. The air undergoes a reduction in Mach number and an increase in pressure and temperature as it passes through shock waves at the forebody and internal inlet (Figure 1b).

The isolator in a scramjet is a critical component. It allows a supersonic flow to adjust to a static back-pressure higher than the inlet static pressure. When the combustion process begins to separate the boundary layer, a precombustion shock forms in the isolator. The isolator also enables the combustor to achieve the required heat release and handle the induced rise in combustor pressure without creating a condition called inlet unstart, in which shock waves prevent airflow from entering the isolator.

The combustor accepts the airflow and provides efficient fuel–air mixing at several points along its length, which optimizes engine thrust. The expansion system, consisting of the internal nozzle and vehicle aftbody, controls the expansion of the high-pressure, high-temperature gas mixture to produce net thrust. The expansion process converts the potential energy generated by the combustor to kinetic energy. The important physical phenomena in the scramjet nozzle include flow chemistry, boundary-layer effects, nonuniform flow conditions, shear-layer interaction, and three-dimensional effects. The design of the nozzle has a major effect on the efficiency of the engine and the vehicle, because it influences the craft's pitch and lift.

Operations

An air-breathing hypersonic vehicle requires several types of engine operations to reach scramjet speeds. The vehicle may utilize one of several propulsion systems to accelerate from takeoff to Mach 3. Two

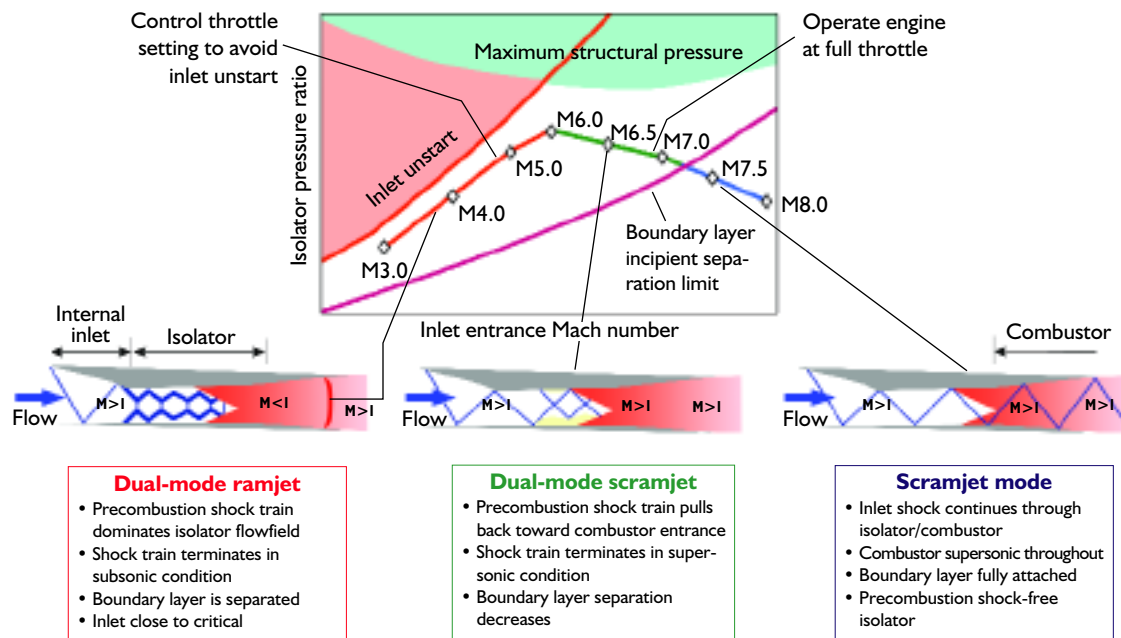


Figure 3. As the vehicle speed increases from Mach 3 to Mach 8, the isolator pressure ratio passes through a peak at Mach 6. As the shock train and boundary layer retreat, the modes change from dual-mode ramjet to dual-mode scramjet to pure scramjet mode.

examples are a bank of gas-turbine engines in the vehicle, or the use of rockets, either internal or external to the engine.

At Mach 3–4, a scramjet transitions from low-speed propulsion to a situation in which the shock system has sufficient strength to create a region(s) of subsonic flow at the entrance to the combustor. In a conventional ramjet, the inlet and diffuser decelerate the air to low subsonic speeds by increasing the diffuser area, which ensures complete combustion at subsonic speeds. A converging–diverging nozzle behind the combustor creates a physical throat and generates the desired engine thrust. The required choking in a scramjet, however, is provided within the combustor by means of a thermal throat, which needs no physical narrowing of the nozzle. This choke is created by the right combination of area distribution, fuel–air mixing, and heat release.

During the time a scramjet-powered vehicle accelerates from Mach 3 to 8, the air-breathing propulsion system undergoes a transition between Mach 5 and 7. Here, a mixture of ramjet and scramjet combustion occurs. The total rise in temperature and pressure across the combustor begins to decrease. Consequently, a weaker precombustion system is required, and the precombustion shock is pulled back from the inlet throat toward the entrance to the combustor.

As speeds increase beyond Mach 5, the use of supersonic combustion can provide

higher performance (Figure 3). Engine efficiency dictates using the ramjet until Mach 5–6. At around Mach 6, decelerating airflow to subsonic speeds for combustion results in parts of the airflow almost halting, which creates high pressures and heat-transfer rates. Somewhere between Mach 5 and 6, the combination of these factors indicates a switch to scramjet operation.

When the vehicle accelerates beyond Mach 7, the combustion process can no longer separate the airflow, and the engine operates in scramjet mode without a precombustion shock. The inlet shocks propagate through the entire engine. Beyond Mach 8, physics dictates supersonic combustion because the engine cannot survive the pressure and heat buildup caused by slowing the airflow to subsonic speeds.

Scramjet operation at Mach 5–15 presents several technical problems to achieving efficiency. These challenges include

MACH NUMBERS

Dividing an object's speed by the speed of sound yields its Mach number, a ratio named for 19th-century Austrian physicist Ernst Mach, who laid out the principles of supersonic speed. Mach 1 equals the speed of sound (transonic), and a Mach number lower than 1 is subsonic. Supersonic covers speeds greater than Mach 1 up to Mach 5, and hypersonic is any speed greater than Mach 5.

Technology

fuel–air mixing, management of engine heat loads, increased heating on leading edges, and developing structures and materials that can withstand hypersonic flight.

When the velocity of the injected fuel equals that of the airstream entering the scramjet combustor, which occurs at about Mach 12, mixing the air and fuel becomes difficult. And at higher Mach numbers, the high temperatures in the combustor cause dissociation and ionization. These

factors—coupled with already-complex flow phenomena such as supersonic mixing, isolator–combustor interactions, and flame propagation—pose obstacles to flow-path design, fuel injection, and thermal management of the combustor.

Several sources contribute to engine heating during hypersonic flight, including heating of the vehicle skin from subsystems such as pumps, hydraulics, and electronics, as well as combustion. Thermal-management schemes focus on the engine in hypersonic vehicles because of its potential for extremely high heat loads. The engine represents a particularly challenging problem because the flow path is characterized by very high thermal, mechanical, and acoustic loading, as well as a corrosive mix of hot oxygen and combustion products. If the engine is left uncooled, temperatures in the combustor would exceed 5,000 °F, which is higher than the melting point of most metals. Fortunately, a combination of structural design, material selection, and active cooling can manage the high temperatures.

Hypersonic vehicles also pose an extraordinary challenge for structures and materials. The airframe and engine require lightweight, high-temperature materials and structural configurations that can withstand the extreme environment of hypersonic flight. These include:

- very high temperatures,
- heating of the whole vehicle,

ROCKETS AND JETS

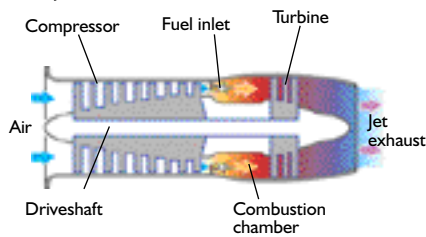
Both rockets and jet engines burn a mixture of fuel and an oxidizer to create propulsive thrust. Their fundamental difference is that rockets carry the oxidizer onboard, whereas jets obtain it from the air. Engines that use air are referred to as air-breathing engines.

In a *turbojet*, the air passes through a compressor, a burner, and a turbine, where some of the flow energy is extracted to drive the compressor. In a *turbofan* engine, there is an additional shaft, and a fan in front that bypasses the engine and sends some high-speed air directly to the exhaust. In a supersonic *ramjet*, which has no moving parts, pressure is boosted by reducing air moving through

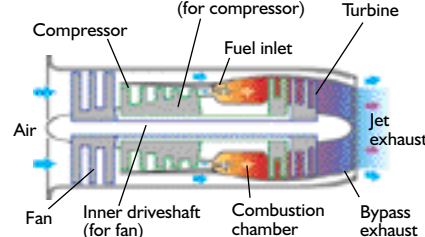
the engine to subsonic levels before combustion. *Scramjets* are ramjets that fly at hypersonic speeds and whose airflow through the combustor is supersonic. To meet the demands of supersonic flight, both engines eject small amounts of exhaust at high velocity.

A craft's cooling and the systems needed to meet its mission typically determine the choice between hydrogen and hydrocarbon as its fuel. Missiles and short-range aircraft may use hydrocarbon fuels for their storability and volumetric energy density. Long-range cruise aircraft and rockets tend toward hydrogen because of its superior energy release per pound and heat absorption capability.

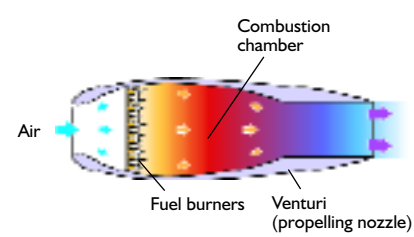
Turbojet



Turbofan



Ramjet



- steady-state and transient localized heating from shock waves,
- high aerodynamic loads,
- high fluctuating pressure loads,
- the potential for severe flutter, vibration, fluctuating, and thermally induced stresses,
- erosion from airflow over the vehicle and through the engine.

With the completion of the successful X-43A flight and the ground-testing of several full-sized demonstration engines, confidence in the viability of the hydrogen- and hydrocarbon-fueled scramjet engines has increased significantly. NASA plans to launch another X-43A this fall and fly it at Mach 10, or 6,750 mph.

The U.S. Air Force, Pratt & Whitney, and Boeing's Phantom Works will conduct flight tests of a hydrocarbon-fueled scramjet in 2007 or 2008. The tests—using an engine that is relatively easy to manufacture—will

demonstrate significant acceleration, operate the engine for several minutes at Mach 4.5–6.5, and use sensors and computers to control the engine and flight.

Demonstrating these technologies, along with additional ground- and flight-test experiments, will pave the way for affordable and reusable air-breathing hypersonic engines for missiles, long-range aircraft, and space-access vehicles around 2010, 2015, and 2025, respectively.

Further reading

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B I O G R A P H Y

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