

## SCRAMJET

A **scramjet (supersonic combustion ramjet)** is a variant of a [ramjet airbreathing jet engine](#) in which [combustion](#) takes place in [supersonic airflow](#). As in ramjets, a scramjet relies on high vehicle speed to compress the incoming air forcefully before combustion (hence *ramjet*), but whereas a ramjet decelerates the air to [subsonic](#) velocities before combustion, the airflow in a scramjet is supersonic throughout the entire engine. That allows the scramjet to operate efficiently at extremely high speeds

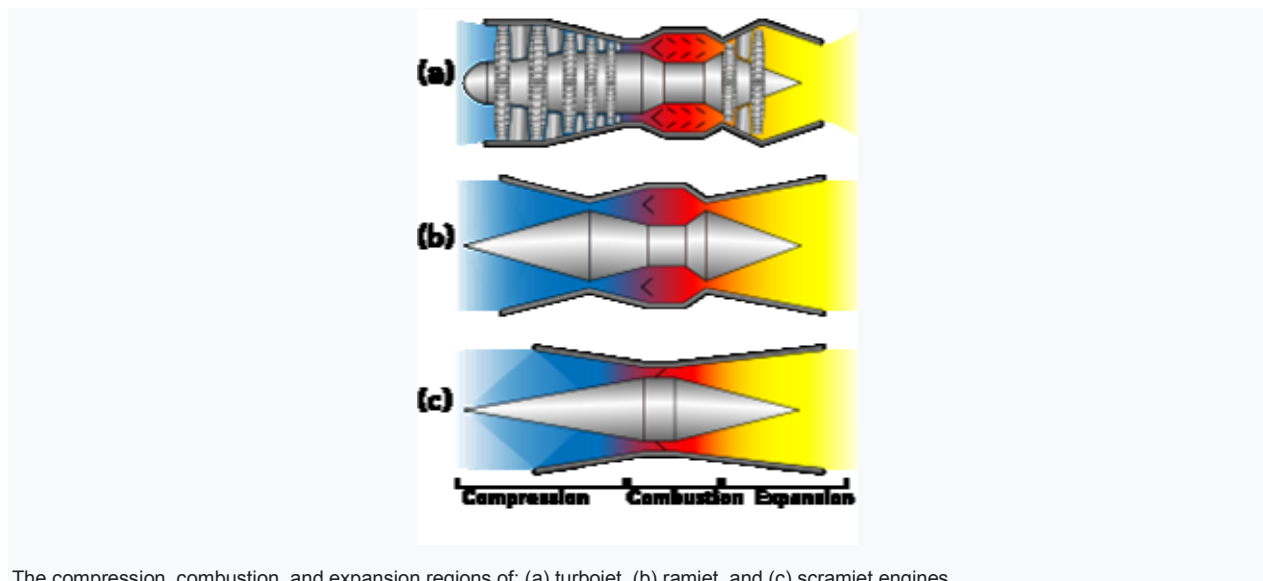
## Design principles<sup>[[edit](#)]</sup>

Scramjet engines are a type of jet engine, and rely on the combustion of fuel and an oxidizer to produce thrust. Similar to conventional jet engines, scramjet-powered aircraft carry the fuel on board, and obtain the oxidizer by the ingestion of atmospheric oxygen (as compared to [rockets](#), which carry both fuel and an [oxidizing agent](#)). This requirement limits scramjets to suborbital atmospheric propulsion, where the oxygen content of the air is sufficient to maintain combustion.

The scramjet is composed of three basic components: a converging inlet, where incoming air is compressed; a combustor, where gaseous fuel is burned with atmospheric [oxygen](#) to produce heat; and a diverging nozzle, where the heated air is accelerated to produce [thrust](#). Unlike a typical jet engine, such as a [turbojet](#) or [turbofan](#) engine, a scramjet does not use rotating, fan-like components to compress the air; rather, the achievable speed of the aircraft moving through the atmosphere causes the air to compress within the inlet. As such, no [moving parts](#) are needed in a scramjet. In comparison, typical turbojet engines require multiple stages of rotating [compressor rotors](#), and multiple rotating [turbine](#) stages, all of which add weight, complexity, and a greater number of failure points to the engine.

Due to the nature of their design, scramjet operation is limited to near-[hypersonic](#) velocities. As they lack mechanical compressors, scramjets require the high [kinetic energy](#) of a hypersonic flow to compress the incoming air to operational conditions. Thus, a scramjet-powered vehicle must be accelerated to the required velocity (usually about Mach 4) by some other means of propulsion, such as turbojet, [railgun](#), or rocket engines.<sup>[29]</sup> In the flight of the experimental scramjet-powered [Boeing X-51A](#), the test craft was lifted to flight altitude by a [Boeing B-52 Stratofortress](#) before being released and accelerated by a detachable rocket to near Mach 4.5.<sup>[29]</sup> In May 2013, another flight achieved an increased speed of Mach 5.1.<sup>[30]</sup>

While scramjets are conceptually simple, actual implementation is limited by extreme technical challenges. Hypersonic flight within the atmosphere generates immense drag, and temperatures found on the aircraft and within the engine can be much greater than that of the surrounding air. Maintaining combustion in the supersonic flow presents additional challenges, as the fuel must be injected, mixed, ignited, and burned within milliseconds. While scramjet technology has been under development since the 1950s, only very recently have scramjets successfully achieved powered flight.<sup>[31]</sup>



The compression, combustion, and expansion regions of: (a) turbojet, (b) ramjet, and (c) scramjet engines.

## Basic principles [\[edit\]](#)

Scramjets are designed to operate in the hypersonic flight regime, beyond the reach of turbojet engines, and, along with ramjets, fill the gap between the high efficiency of turbojets and the high speed of rocket engines. [Turbomachinery](#)-based engines, while highly efficient at subsonic speeds, become increasingly inefficient at transonic speeds, as the compressor rotors found in turbojet engines require subsonic speeds to operate. While the flow from [transonic](#) to low supersonic speeds can be decelerated to these conditions, doing so at supersonic speeds results in a tremendous increase in temperature and a loss in the total [pressure](#) of the flow. Around Mach 3–4, turbomachinery is no longer useful, and ram-style compression becomes the preferred method. <sup>[32]</sup>

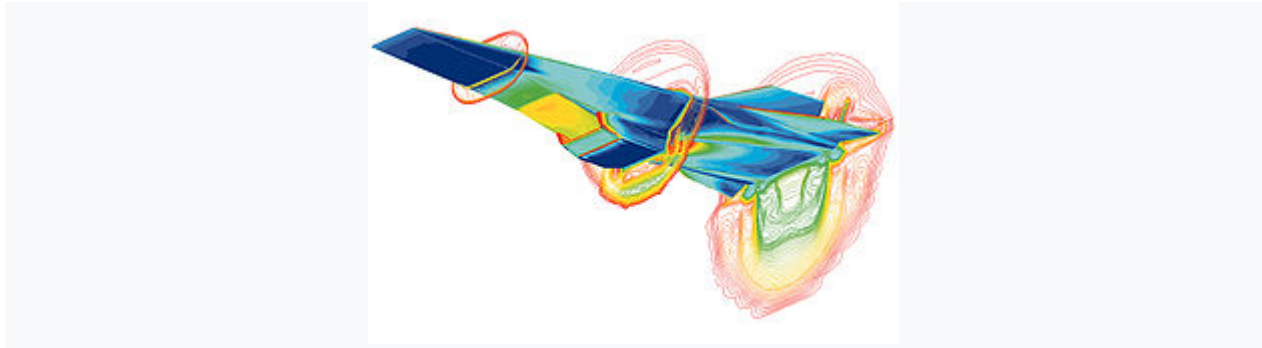
[Ramjets](#) utilize high-speed characteristics of air to literally 'ram' air through an inlet diffuser into the combustor. At transonic and supersonic flight speeds, the air upstream of the inlet is not able to move out of the way quickly enough, and is compressed within the diffuser before being diffused into the combustor. Combustion in a ramjet takes place at subsonic velocities, similar to turbojets, but the combustion products are then accelerated through a [convergent-divergent nozzle](#) to supersonic speeds. As they have no mechanical means of compression, ramjets cannot start from a standstill, and generally do not achieve sufficient compression until supersonic flight. The lack of intricate turbomachinery allows ramjets to deal with the temperature rise associated with decelerating a supersonic flow to subsonic speeds, but this only goes so far: at near-hypersonic velocities, the temperature rise and inefficiencies discourage decelerating the flow to the magnitude found in ramjet engines. <sup>[32]</sup>

Scramjet engines operate on the same principles as ramjets, but do not decelerate the flow to subsonic velocities. Rather, a scramjet combustor is supersonic: the inlet decelerates the flow to a lower Mach number for combustion, after which it is accelerated to an even higher Mach number through the nozzle. By limiting the amount of deceleration, temperatures within the engine are kept at a tolerable level, from both a material and combustive standpoint. Even so, current scramjet technology requires the use of high-energy fuels and active cooling schemes to maintain sustained operation, often using [hydrogen](#) and [regenerative cooling](#) techniques. <sup>[33]</sup>

## Theory [\[edit\]](#)

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All scramjet engines have an intake which compresses the incoming air, fuel injectors, a combustion chamber, and a divergent [thrust nozzle](#). Sometimes engines also include a region which acts as a [flame holder](#), although the high [stagnation temperatures](#) mean that an area of focused waves may be used, rather than a discrete engine part as seen in turbine engines. Other engines use [pyrophoric](#) fuel additives, such as [silane](#), to avoid flameout. An isolator between the inlet and combustion chamber is often included to improve the homogeneity of the flow in the combustor and to extend the operating range of the engine.



[Computational fluid dynamics](#) (CFD) image of the [NASA X-43A](#) with scramjet attached to the underside at [Mach 7](#)

A scramjet is reminiscent of a [ramjet](#). In a typical ramjet, the supersonic inflow of the engine is decelerated at the inlet to subsonic speeds and then reaccelerated through a nozzle to supersonic speeds to produce thrust. This deceleration, which is produced by a normal [shock](#), creates a total [pressure](#) loss which limits the upper operating point of a ramjet engine.

For a scramjet, the kinetic energy of the freestream air entering the scramjet engine is largely comparable to the energy released by the reaction of the oxygen content of the air with a fuel (e.g. hydrogen). Thus the heat released from combustion at Mach 2.5 is around 10% of the total enthalpy of the working fluid. Depending on the fuel, the [kinetic energy](#) of the air and the potential combustion heat release will be equal at around Mach 8. Thus the design of a scramjet engine is as much about minimizing drag as maximizing thrust.

This high speed makes the control of the flow within the combustion chamber more difficult. Since the flow is supersonic, no downstream influence propagates within the freestream of the combustion chamber. Throttling of the entrance to the thrust nozzle is not a usable control technique. In effect, a block of gas entering the combustion chamber must mix with fuel and have sufficient time for initiation and reaction, all the while traveling supersonically through the combustion chamber, before the burned gas is expanded through the thrust nozzle. This places stringent requirements on the pressure and temperature of the flow, and requires that the fuel injection and mixing be extremely efficient. Usable [dynamic pressures](#) lie in the range 20 to 200 kilopascals (2.9 to 29.0 psi), where

where

$q$  is the dynamic pressure of the gas

$\rho$  ( $\rho$ ) is the [density](#) of the gas

$v$  is the [velocity](#) of the gas

To keep the combustion rate of the fuel constant, the pressure and temperature in the engine must also be constant. This is problematic because the airflow control systems that would facilitate this are not physically possible in a scramjet launch vehicle due to the large speed and altitude range involved, meaning that it must travel at an altitude specific to its speed. Because air density reduces at higher altitudes, a scramjet must climb at a specific rate as it accelerates to maintain a constant air pressure at the intake. This optimal climb/descent profile is called a "constant dynamic pressure path". It is thought that scramjets might be operable up to an altitude of 75 km.<sup>[34]</sup>

Fuel injection and management is also potentially complex. One possibility would be that the fuel be pressurized to 100 bar by a turbo pump, heated by the fuselage, sent through the turbine and accelerated to higher speeds than the air by a nozzle. The air and fuel stream are crossed in a comb-like structure, which generates a large interface. Turbulence due to the higher speed of the fuel leads to additional mixing. Complex fuels like kerosene need a long engine to complete combustion.

The minimum Mach number at which a scramjet can operate is limited by the fact that the compressed flow must be hot enough to burn the fuel, and have pressure high enough that the reaction be finished before the air moves out the back of the engine. Additionally, in order to be called a scramjet, the compressed flow must still be supersonic after combustion. Here two limits must be observed: First, since when a supersonic flow is compressed it slows down, the level of compression must be low enough (or the initial speed high enough) not to slow the gas below Mach 1. If the gas within a scramjet goes below Mach 1 the engine will "choke", transitioning to subsonic flow in the combustion chamber. This effect is well known amongst experimenters on scramjets since the waves caused by choking are easily observable. Additionally, the sudden increase in pressure and temperature in the engine can lead to an acceleration of the combustion, leading to the combustion chamber exploding.

Second, the heating of the gas by combustion causes the speed of sound in the gas to increase (and the Mach number to decrease) even though the gas is still travelling at the same speed. Forcing the speed of air flow in the combustion chamber under Mach 1 in this way is called "thermal choking". It is clear that a pure scramjet can operate at Mach numbers of 6–8,<sup>[35]</sup> but in the lower limit, it depends on the definition of a scramjet. There are engine designs where a ramjet transforms into a scramjet over the Mach 3–6 range, known as dual-mode scramjets.<sup>[36]</sup> In this range however, the engine is still receiving significant thrust from subsonic combustion of the ramjet type.

The high cost of flight testing and the unavailability of ground facilities have hindered scramjet development. A large amount of the experimental work on scramjets has been undertaken in cryogenic facilities, direct-connect tests, or burners, each of which simulates one aspect of the engine operation. Further, vitiated facilities (with the ability to control air impurities<sup>[37]</sup>), storage heated facilities, arc facilities and the various types of shock tunnels each have limitations which have prevented perfect simulation of scramjet operation. The [HyShot](#) flight test showed the relevance of the 1:1 simulation of conditions in the T4 and HEG shock tunnels, despite having cold models and a short test time. The [NASA](#)-CIAM tests provided similar verification for CIAM's C-16 V/K facility and the Hyper-X project is expected to provide similar verification for the Langley AHSTF,<sup>[38]</sup> CHSTF,<sup>[39]</sup> and 8 ft (2.4 m) HTT.

[Computational fluid dynamics](#) has only recently<sup>[\[when?\]](#)</sup> reached a position to make reasonable computations in solving scramjet operation problems. Boundary layer modeling, turbulent mixing, two-phase flow, flow separation, and real-gas aerothermodynamics continue to be problems on the cutting edge of CFD. Additionally, the modeling of kinetic-limited combustion with very fast-reacting species such as hydrogen makes severe demands on computing resources.<sup>[\[citation needed\]](#)</sup> Reaction schemes are [numerically stiff](#) requiring reduced reaction schemes.<sup>[\[clarification needed\]](#)</sup>

Much of scramjet experimentation remains [classified](#). Several groups, including the [US Navy](#) with the SCRAM engine between 1968 and 1974, and the [Hyper-X](#) program with the [X-43A](#), have claimed successful demonstrations of scramjet technology. Since these results have not been published openly, they remain unverified and a final design method of scramjet engines still does not exist.

The final application of a scramjet engine is likely to be in conjunction with engines which can operate outside the scramjet's operating range.<sup>[\[citation needed\]](#)</sup> Dual-mode scramjets combine [subsonic](#) combustion with [supersonic](#) combustion for operation at lower speeds, and [rocket](#)-based combined cycle (RBCC) engines supplement a traditional rocket's propulsion with a scramjet, allowing for additional [oxidizer](#) to be added to the scramjet flow. RBCCs offer a possibility to extend a scramjet's operating range to higher speeds or lower intake dynamic pressures than would otherwise be possible.

## Advantages and disadvantages of scramjets<sup>[\[edit\]](#)</sup>

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### Advantages<sup>[\[edit\]](#)</sup>

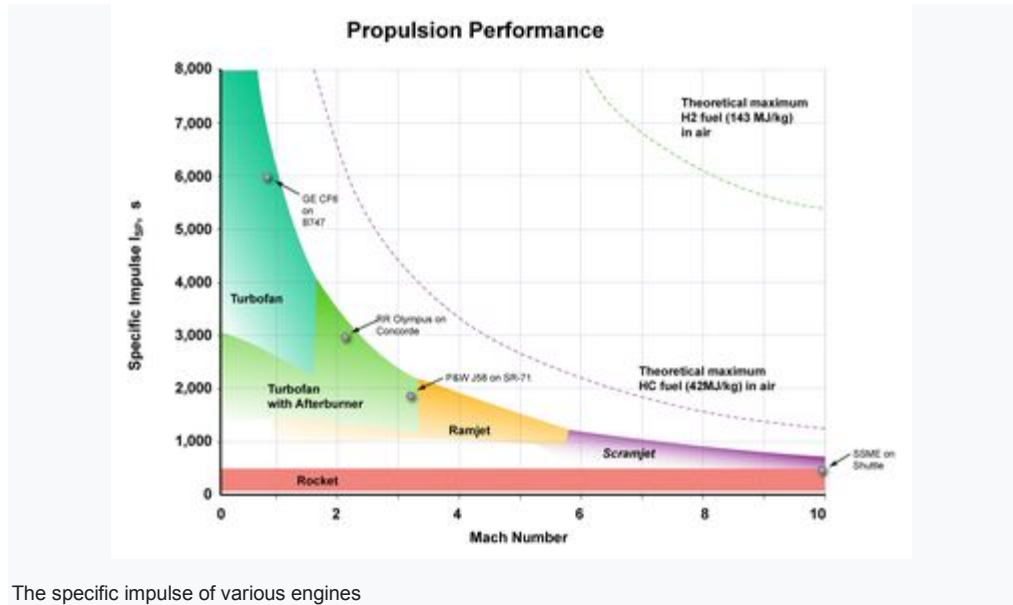
1. Does not have to carry oxygen
2. No rotating parts makes it easier to manufacture than a turbojet
3. Has a higher [specific impulse](#) (change in momentum per unit of propellant) than a rocket engine; could provide between 1000 and 4000 seconds, while a rocket typically provides around 450 seconds or less.<sup>[\[40\]](#)</sup>
4. Higher speed could mean cheaper access to outer space in the future

### Special cooling and materials<sup>[\[edit\]](#)</sup>

Unlike a rocket that quickly passes mostly vertically through the atmosphere or a turbojet or ramjet that flies at much lower speeds, a hypersonic airbreathing vehicle optimally flies a "depressed trajectory", staying within the atmosphere at hypersonic speeds. Because scramjets have only mediocre thrust-to-weight ratios,<sup>[\[41\]](#)</sup> acceleration would be limited. Therefore, time in the atmosphere at supersonic speed would be considerable, possibly 15–30 minutes. Similar to a [reentering](#) space vehicle, heat insulation would be a formidable task, with protection required for a duration longer than that of a typical [space capsule](#), although less than the [Space Shuttle](#).

New materials offer good insulation at high temperature, but they often [sacrifice](#) themselves in the process. Therefore, studies often plan on "active cooling", where coolant circulating throughout the vehicle skin prevents it from disintegrating. Often the coolant is the fuel itself, in much the same way that modern rockets use their own fuel and oxidizer as coolant for their engines. All cooling systems add weight and complexity to a launch system. The cooling of scramjets in this way may result in greater efficiency, as heat is added to the fuel prior to entry into the engine, but results in increased complexity and weight which ultimately could outweigh any performance gains.

### Vehicle performance<sup>[\[edit\]](#)</sup>



The specific impulse of various engines



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The performance of a [launch system](#) is complex and depends greatly on its weight. Normally craft are designed to maximise range ( ), orbital radius ( ) or payload mass fraction ( ) for a given engine and fuel. This results in tradeoffs between the efficiency of the engine (takeoff fuel weight) and the complexity of the engine (takeoff dry weight), which can be expressed by the following:

Where :

- is the empty mass fraction, and represents the weight of the superstructure, tankage and engine.
- is the fuel mass fraction, and represents the weight of fuel, oxidiser and any other materials which are consumed during the launch.
- is initial mass ratio, and is the inverse of the payload mass fraction. This represents how much payload the vehicle can deliver to a destination.

A scramjet increases the mass of the motor over a rocket, and decreases the mass of

the fuel . It can be difficult to decide whether this will result in an increased (which would be an increased payload delivered to a destination for a constant vehicle takeoff weight). The logic behind efforts driving a scramjet is (for example) that the reduction in fuel decreases the total mass by 30%, while the increased engine weight adds 10% to the vehicle total mass. Unfortunately the uncertainty in the calculation of any mass or efficiency

changes in a vehicle is so great that slightly different assumptions for engine efficiency or mass can provide equally good arguments for or against scramjet powered vehicles.

Additionally, the drag of the new configuration must be considered. The drag of the total

configuration can be considered as the sum of the vehicle drag ( ) and the engine

installation drag ( ). The installation drag traditionally results from the pylons and the coupled flow due to the engine jet, and is a function of the throttle setting. Thus it is often written as:

Where:

- is the loss coefficient
- is the thrust of the engine

For an engine strongly integrated into the aerodynamic body, it may be more convenient

to think of ( ) as the difference in drag from a known base configuration.

The overall engine efficiency can be represented as a value between 0 and 1 ( ), in terms of the specific impulse of the engine:

Where: