

Specific impulse

Specific impulse (usually abbreviated I_{sp}) is a measure of how effectively a [rocket](#) uses propellant or a [jet engine](#) uses fuel. Specific impulse can be calculated in a variety of different ways with different units. By definition, it is the **total impulse** (or change in **momentum**) delivered per unit of **propellant consumed**^[1] and is **dimensionally equivalent** to the generated **thrust** divided by the propellant **mass flow rate** or weight flow rate.^[2] If **mass** ([kilogram](#), [pound-mass](#), or [slug](#)) is used as the unit of propellant, then specific impulse has units of **velocity**. If weight ([newton](#) or [pound-force](#)) is used instead, then specific impulse has units of time (seconds). Multiplying flow rate by the standard gravity (g_0) converts specific impulse from the weight basis to the mass basis.^[2]

A propulsion system with a higher specific impulse uses the mass of the propellant more efficiently. In the case of a rocket or other vehicle governed by the [Tsiolkovsky rocket equation](#), this means less propellant needed for a given **delta-v**.^[3] In rockets, this means the vehicle the engine is attached to can more efficiently gain altitude and velocity. This effectiveness is less important in jet aircraft that are lifted by aerodynamic forces, use outside air for combustion, and carry payloads that are much heavier than the propellant.

Specific impulse can include the contribution to impulse provided by external air that has been used for combustion and is exhausted with the spent propellant. Jet engines use outside air, and therefore have a much higher specific impulse than rocket engines. The specific impulse in terms of propellant mass spent has units of distance per time, which is a notional velocity called the *effective exhaust velocity*. This is higher than the *actual* exhaust velocity because the mass of the combustion air is not being accounted for. Actual and effective exhaust velocity are the same in rocket engines operating in a vacuum.

Specific impulse is inversely proportional to **specific fuel consumption** (SFC) by the relationship $I_{sp} = 1/(g_0 \cdot \text{SFC})$ for SFC in kg/(N·s) and $I_{sp} = 3600/\text{SFC}$ for SFC in lb/(lbf·hr).

General considerations[edit]



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The amount of propellant can be measured either in units of mass or weight. If mass is used, specific impulse is an **impulse** per unit mass, which **dimensional analysis** shows to have units of speed, specifically the **effective exhaust velocity**. As the SI system is mass-based, this type of analysis is usually done in meters per second. If a force-based unit system is used, impulse is divided by propellant weight (weight is a measure of force), resulting in units of time (seconds). These two formulations differ from each other by the standard [gravitational acceleration](#) (g_0) at the surface of the earth.

The rate of change of momentum of a rocket (including its propellant) per unit time is equal to the thrust. The higher the specific impulse, the less propellant is needed to produce a given thrust for a given time and the more efficient the propellant is. This should not be confused with the physics concept of **energy efficiency**, which can decrease as specific impulse increases, since propulsion systems that give high specific impulse require high energy to do so.^[4]

Thrust and specific impulse should not be confused. Thrust is the force supplied by the engine and depends on the amount of reaction mass flowing through the engine. Specific impulse measures the impulse produced per unit of propellant and is proportional to the exhaust velocity. Thrust and specific impulse are related by the design and propellants of the engine in question, but this relationship is tenuous. For example, [LH₂/LOx](#) bipropellant produces higher I_{sp} but lower thrust than [RP-1/LOx](#) due to the exhaust gases having a lower density and higher velocity (H₂O vs CO₂ and H₂O). In many cases, propulsion systems with very high specific impulse—some [ion thrusters](#) reach 10,000 seconds—produce low thrust.^[5]

When calculating specific impulse, only propellant carried with the vehicle before use is counted. For a chemical rocket, the propellant mass therefore would include both fuel and [oxidizer](#). In rocketry, a heavier engine with a higher specific impulse may not be as effective in gaining altitude, distance, or velocity as a lighter engine with a lower specific impulse, especially if the latter engine possesses a higher **thrust-to-weight ratio**. This is a significant reason for most rocket designs having multiple stages. The first stage is optimised for high thrust to boost the later stages with higher specific impulse into higher altitudes where they can perform more efficiently.

For air-breathing engines, only the mass of the fuel is counted, not the mass of air passing through the engine. Air resistance and the engine's inability to keep a high specific impulse at a fast burn rate are why all the propellant is not used as fast as possible.

If it were not for air resistance and the reduction of propellant during flight, specific impulse would be a direct measure of the engine's effectiveness in converting propellant weight or mass into forward momentum.

Units[edit]

Various equivalent rocket motor performance measurements, in SI and English engineering units				
	Specific impulse		Effective exhaust velocity	Specific fuel consumption
	By weight	By mass		
SI	= x s	= $9.80665 \cdot x$ N·s/kg	= $9.80665 \cdot x$ m/s	= $101,972/x$ g/(kN·s)
English engineering units	= x s	= x lbf·s/lb	= $32.17405 \cdot x$ ft/s	= $3,600/x$ lb/(lbf·hr)

The most common unit for specific impulse is the second, as values are identical regardless of whether the calculations are done in **SI**, **imperial**, or **customary** units. Nearly all manufacturers quote their engine performance in seconds, and the unit is also useful for specifying aircraft engine performance.^[6]

The use of **metres per second** to specify effective exhaust velocity is also reasonably common. The unit is intuitive when describing rocket engines, although the effective exhaust speed of the engines may be significantly different from the actual exhaust speed, especially in **gas-generator cycle** engines. For **airbreathing jet engines**, the effective exhaust velocity is not physically meaningful, although it can be used for comparison purposes.^[7]

Meters per second are numerically equivalent to Newton-seconds per kg (N·s/kg), and SI measurements of specific impulse can be written in terms of either units interchangeably.^[citation needed]

Specific fuel consumption is inversely proportional to specific impulse and has units of g/(kN·s) or lb/(lbf·hr). Specific fuel consumption is used extensively for describing the performance of air-breathing jet engines.^[8]

Specific impulse in seconds[edit]



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The time unit of seconds to measure the performance of a propellant/engine combination can be thought of as "How many seconds this propellant can accelerate its own initial mass at 1 g". The more seconds it can accelerate its own mass, the more delta-V it delivers to the whole system.

In other words, given a particular engine and a **pound mass** of a particular propellant, specific impulse measures for how long a time that engine can exert a continuous **pound of force** (thrust) until fully burning through that pound of propellant. A given mass of a more energy-dense propellant can burn for a longer duration than some less energy-dense propellant made to exert the same force while burning in an engine.^[note 1] Different engine designs burning the same propellant may not be equally efficient at directing their propellant's energy into effective thrust. In the same manner, some car engines are better built than others to maximize the miles-per-gallon of the gasoline they burn.

For all vehicles, specific impulse (impulse per unit weight-on-Earth of propellant) in seconds can be defined by the following equation:^[9]

where:

is the thrust obtained from the engine ([newtons](#) or [pounds force](#)),

is the [standard gravity](#), which is nominally the gravity at Earth's surface (m/s^2 or ft/s^2),

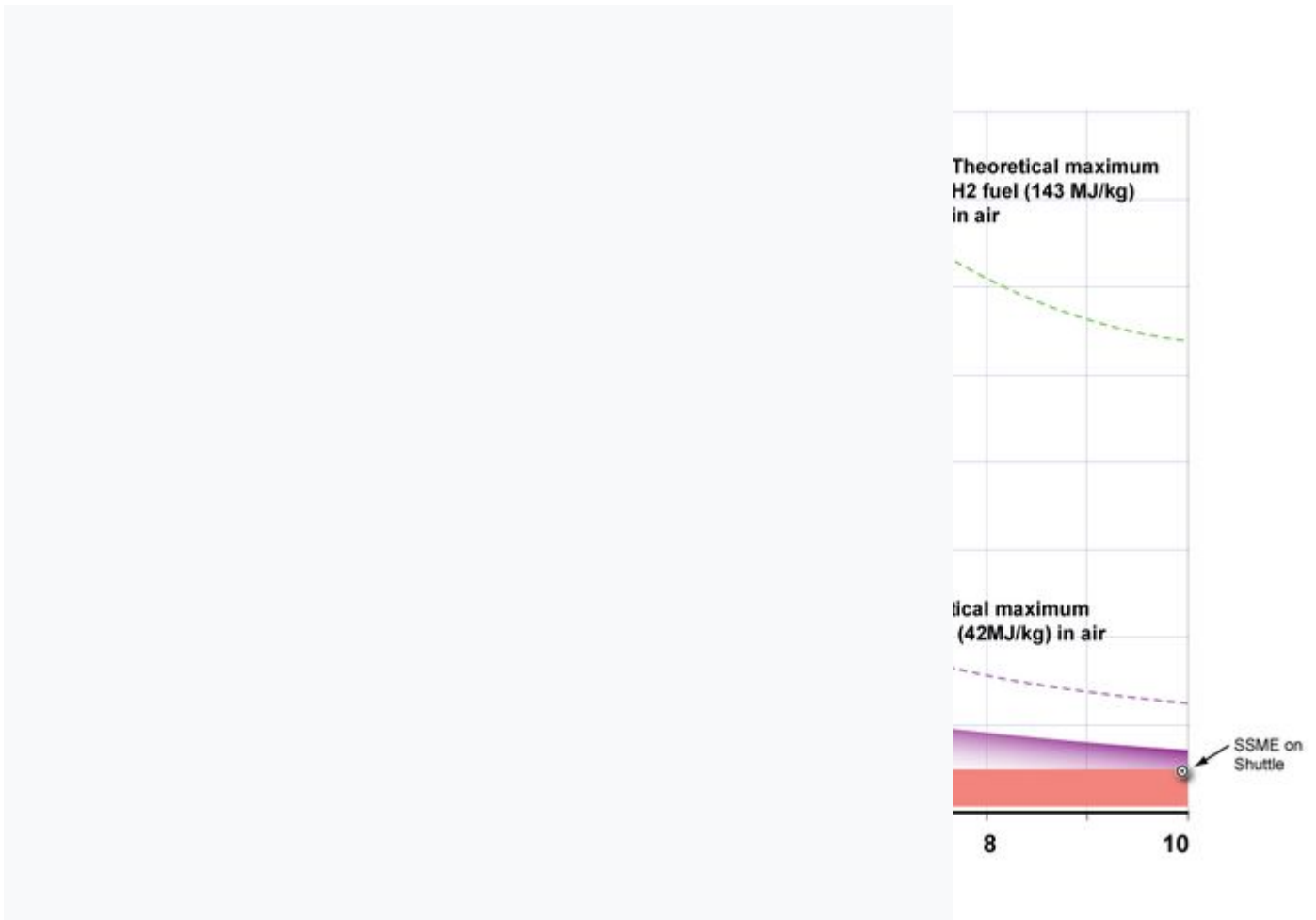
is the specific impulse measured (seconds),

is the [mass flow rate](#) of the expended propellant (kg/s or [slugs/s](#))

The [English unit pound mass](#) is more commonly used than the slug, and when using pounds per second for mass flow rate, the conversion constant g_0 becomes unnecessary, because the slug is dimensionally equivalent to pounds divided by g_0 :

I_{sp} in seconds is the amount of time a rocket engine can generate thrust, given a quantity of propellant whose weight is equal to the engine's thrust.

The advantage of this formulation is that it may be used for rockets, where all the reaction mass is carried on board, as well as airplanes, where most of the reaction mass is taken from the atmosphere. In addition, it gives a result that is independent of units used (provided the unit of time used is the second).



The specific impulse of various jet engines {SSME=Space Shuttle Main Engine}

Rocketry[\[edit\]](#)

In rocketry, the only reaction mass is the propellant, so an equivalent way of calculating the specific impulse in seconds is used. Specific impulse is defined as the thrust integrated over time per unit **weight**-on-Earth of the propellant.^[2]

where

is the specific impulse measured in seconds,

is the average exhaust speed along the axis of the engine (in ft/s or m/s),

is the **standard gravity** (in ft/s² or m/s²).

In rockets, due to atmospheric effects, the specific impulse varies with altitude, reaching a maximum in a vacuum. This is because the exhaust velocity isn't simply a function of the chamber pressure, but is **a function of the difference between the interior and exterior of the**

[combustion chamber](#). Values are usually given for operation at sea level ("sl") or in a vacuum ("vac").

Specific impulse as effective exhaust velocity^[edit]



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Because of the geocentric factor of g_0 in the equation for specific impulse, many prefer an alternative definition. The specific impulse of a rocket can be defined in terms of thrust per unit mass flow of propellant. This is an equally valid (and in some ways somewhat simpler) way of defining the effectiveness of a rocket propellant. For a rocket, the specific impulse defined in this way is simply the effective exhaust velocity relative to the rocket, v_e . "In actual rocket nozzles, the exhaust velocity is not really uniform over the entire exit cross section and such velocity profiles are difficult to measure accurately. A uniform axial velocity, v_e , is assumed for all calculations which employ one-dimensional problem descriptions. This effective exhaust velocity represents an average or mass equivalent velocity at which propellant is being ejected from the rocket vehicle."^[10] The two definitions of specific impulse are proportional to one another, and related to each other by:

where

is the specific impulse in seconds,

is the specific impulse measured in [m/s](#), which is the same as the effective exhaust velocity measured in [m/s](#) (or [ft/s](#) if g is in [ft/s²](#)),

is the [standard gravity](#), [9.80665 m/s²](#) (in [Imperial units](#) [32.174 ft/s²](#)).

This equation is also valid for air-breathing jet engines, but is rarely used in practice.

(Note that different symbols are sometimes used; for example, c is also sometimes seen for

exhaust velocity. While the symbol might logically be used for specific impulse in units of [N·s/kg](#); to avoid confusion, it is desirable to reserve this for specific impulse measured in seconds.)

It is related to the [thrust](#), or forward force on the rocket by the equation:^[11]

where \dot{m} is the propellant mass flow rate, which is the rate of decrease of the vehicle's mass.

A rocket must carry all its propellant with it, so the mass of the unburned propellant must be accelerated along with the rocket itself. Minimizing the mass of propellant required to achieve a given change in velocity is crucial to building effective rockets. The [Tsiolkovsky rocket equation](#) shows that for a rocket with a given empty mass and a given amount of propellant, the total change in [velocity](#) it can accomplish is proportional to the effective exhaust velocity.

A spacecraft without propulsion follows an orbit determined by its trajectory and any gravitational field. Deviations from the corresponding velocity pattern (these are called Δv) are achieved by sending exhaust mass in the direction opposite to that of the desired velocity change.

Actual exhaust speed versus effective exhaust speed^[edit]

When an engine is run within the atmosphere, the exhaust velocity is reduced by atmospheric pressure, in turn reducing specific impulse. This is a reduction in the effective exhaust velocity, versus the actual exhaust velocity achieved in vacuum conditions. In the case of [gas-generator cycle](#) rocket engines, more than one exhaust gas stream is present as [turbopump](#) exhaust gas exits through a separate nozzle. Calculating the effective exhaust velocity requires averaging the two mass flows as well as accounting for any atmospheric pressure.^[*citation needed*]

For air-breathing jet engines, particularly [turbofans](#), the actual exhaust velocity and the effective exhaust velocity are different by orders of magnitude. This is because a good deal of additional momentum is obtained by using air as reaction mass. This allows a better match between the airspeed and the exhaust speed, which saves energy/propellant and enormously increases the effective exhaust velocity while reducing the actual exhaust velocity.^[*citation needed*]