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MARINE PROPULSION

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MARINE PROPULSION

Travel at sea is the easiest compared with land transport and flying: a log floats and is carried with the current; no hills to climb, no thick vegetation to be pushed aside... But, to go where we want, we need propulsion, and fluid propulsion is by far more difficult than land propulsion (in spite of the ease of fish locomotion by [fins](#), as compared with terrestrial locomotion by [legs](#)).

The reason of this difficulty is that, for us to advance, we need to push something backwards ([Propulsion fundamentals](#)), and it is far more efficient to push a massive object (the Earth) back by [solid-friction](#) forces at our feet (or by wheels), than to push a small amount of fluid back (the mass of water you can take in with your hands, or with oars, or even the mass of air surrounding the sail).

[Watercraft](#) may be grouped by size, type of propulsion, type of cargo, type of activity... Shipping may be for fishing, commerce, recreation, or the military purpose. Sea transport has been the largest carrier of freight all throughout history because it is the cheapest way (passenger transport was taken over by aviation because the saved time was more valued). The term watercraft covers a range of different vehicles including [ships](#), [boats](#), [hovercraft](#), [submersibles](#), and [submarines](#). A boat is a vessel small enough to be carried aboard another larger vessel (a ship), but submarines are called boats and not ships. Marine ships are said naval if military, or merchant if civil.

Propulsion is vessels is needed not only to go ahead against natural forces (water and air [drag](#), and going up a river), but to decelerate and stop, and even to keep position at the surface or under water. Without propulsion, a surface ship cannot steer (all rudders work only dynamically), the boat being dangerously

rolled by waves; and underwater, without propulsion it is almost impossible to keep a fixed depth of immersion simply by buoyancy. Of course, crawling propulsion can be used to move along the sea floor, but this is a rarity because of the muddy bottom.

Most watercraft nowadays (since the 1920s) are [powered by diesel engines](#) mechanically driving [screw propellers](#), because of its fuel economy.

PROPULSION SYSTEMS

A [propulsion system](#) consists of three parts: an energy source (carried aboard as animal or fuel energy, or collected from outside as wind or solar power), an engine that transforms it to a mechanical form, and the [propulsor](#) or thruster (that pushes the surrounding water backwards).

A pictorial overview of some marine propulsion systems is presented in Fig. 1.

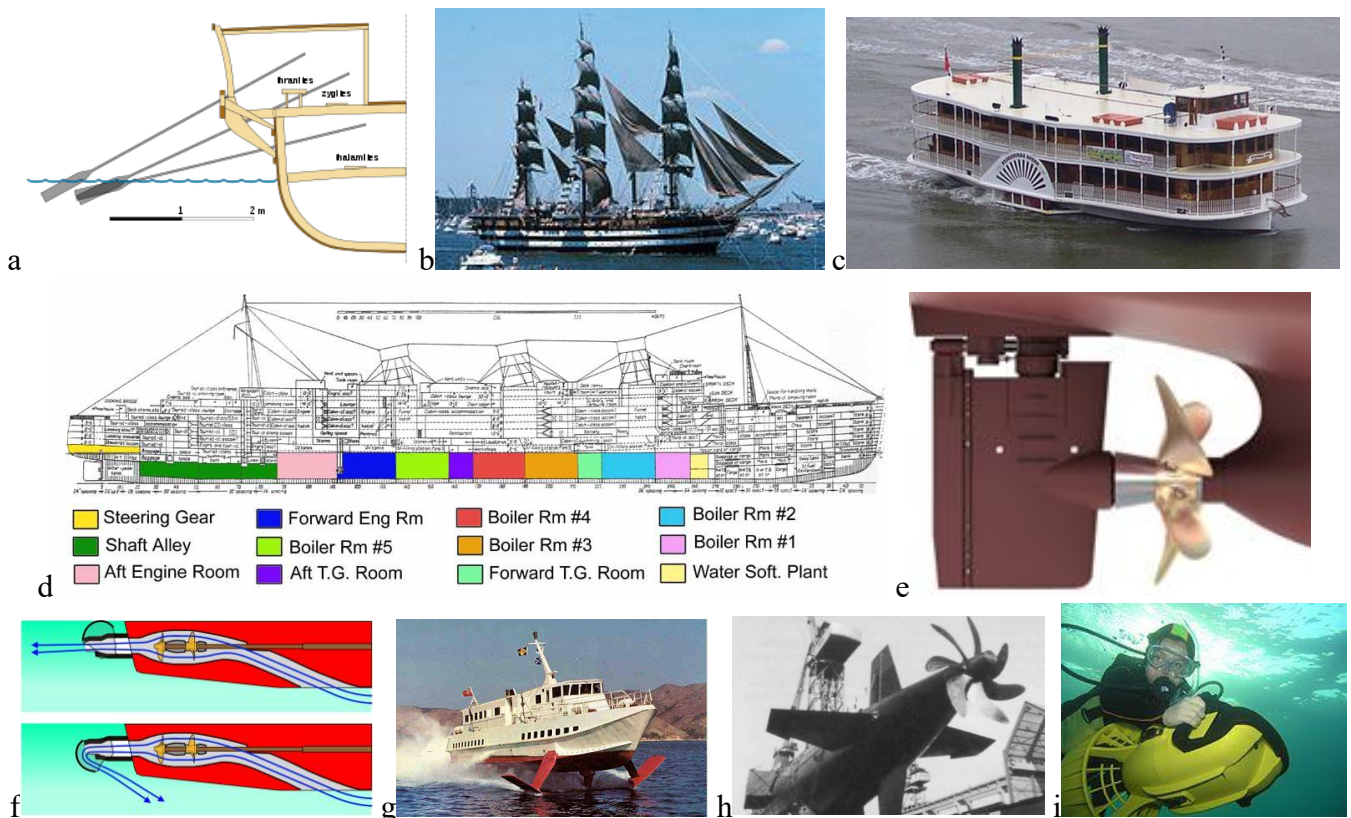


Fig. 1. Some watercraft propulsion systems: a) Oar layout in a Greek [trireme](#). b) Amerigo Vespucci, [full-rigged ship](#). c) [Paddle-wheel](#) boat (diesel powered). d) Engine room (coloured) in [Queen Mary](#). e) Modern integrated [propeller and rudder](#) system. f) [Water-jet](#) propulsion, showing reverse thrust. g) [Hydrofoils](#) are usually waterjet-propelled. h) Seven-bladed screw [submarine propeller](#). i) Battery-powered [diver propulsion](#) device.

Types of energy source

A brief grouping may be:

- Animal power, usually human rowing (Fig. 1a), but horse-driven boats have been used (both [towing](#) with ropes from the shore in canals, and turning a on a [treadmill](#) linked to a propeller, aboard).

- Environmental power-gathering: wind power ([sails](#)), solar power ([photovoltaic](#)). Electrical propulsion in marine engineering refers to electric-motor-driven propellers, with electricity produced by heat engines, and not to direct electric sources, like batteries or solar panels, used in some small boats, and most small underwater vessels.
- Chemical fuels carried aboard, usually a petroleum-derivative liquid-fuel, taking advantage of the surrounding oxidiser in the air. [Marine diesel](#) is by far the most used fuel.
- [Nuclear fuel](#), only used in [nuclear submarines](#), using highly enriched fuel (>20 % U-235) in fission-reactors, usually of pressurised-water type ([PWR](#)), always through steam turbines (they are similar to external combustion engines).

The first vessels might surely have been propelled by hand work, but it was obvious that wind has an important entrainment effect, and the larger the frontal area the larger the push, what originated the sail. There is evidence of [sailing](#) boats and wooden oars in the Middle East dating from 5000 [BCE](#), and, in ancient Egypt by 3000 BCE, the Nile was the main transport route, taking advantage of the water current to go downstream, and of the prevailing Northern winds to go upstream.

Sailing (other than downwind) requires great expertise in varying wind and sea conditions, sometimes with extraordinary insight (e.g. how to come back to port): both pioneers in the [Age of Discovery](#), [Columbus](#) in the Atlantic and [Urdaneta](#) in the Pacific, made use of the [Easterly](#) winds in low latitudes (Trade winds), and of the [Westerly](#) winds in mid latitudes, together with the general ocean circulation circuits (clockwise in the North hemisphere), to link distant-continent populations and establish permanent trade routes.

Most watercrafts (as for any other type of land, air, or space vehicle) are presently powered by a liquid fuel stored aboard, and a heat engine that converts the chemical energy of the combustion of that fuel with an oxidiser, to the mechanical energy needed to actually perform the propulsion work. Hence, to this last respect, propulsion is always a mechanical effect; however, mechanical propulsion usually refers to engine-propelled vehicles, in this case vessels, leaving aside manual (rowing) and wind (sailing).

Types of engines

A brief grouping, more or less in chronological order, including rowing and sailing, may be:

- Mechanical transmission from energy source to thruster, e.g. from animal power to [oars](#) or wheels.
- [Sailing](#), i.e. wind power propulsion acting on extended surfaces (sails).
- [Steam engine](#), an external combustion engine, working in a [Rankine cycle](#), with water as working fluid, used in practically all ships in the 19th century, initially with reciprocating pistons and later with turbines (the first in 1897 with the [Turbinia](#) steamer), and on a few vessels since then (in some very large ships, and in nuclear submarines). The name of steam ships are often prefixed with SS.
- [Diesel engine](#), an internal combustion engine (ICE), working in a Diesel cycle, using marine diesel or heavy fuel oil, and used in most ships since 1930s. also known as motor ships. Diesel engines were limited in power for many decades, but nowadays there are no limit in practice, with

[MAN/B&W](#) and [Wärtsilä-Sulzer](#) as the major engine manufacturers. The name of [motor ships](#) are often prefixed with MS.

- [Gas turbine](#), an internal combustion engine (ICE), working in a Brayton cycle, derived from aviation turbines, able to burn marine diesel, kerosene, or jet fuel, are used in some fast ships (e.g. hydrofoils), warships (for quick action), and large cruisers. The first passenger ferry to use a gas turbine was the GTS Finnjet, built in 1977; four years later, diesel engines were added to decrease fuel expense, becoming the first ship with a combined diesel-electric and gas ([CODAG](#)) propulsion.
- Dual fuel engines, like the [LNG engine](#), an internal combustion engine working in a Diesel cycle, using liquefied natural gas (LNG) as main fuel, sometimes working in dual-fuel mode with partial marine-diesel injection.
- Gasoline engines (ICE), used in small [outboard motors](#).
- Electric motors, which may be powered by:
 - Electrical batteries, like in model ships and submarines.
 - Diesel engines. This combination of a sizeable power source (ICE) driving an electrical generator, with a flexible electrical connection to the electrical motors driving the propellers, is very convenient in spite of its extra cost. Most large ships, particularly [cruisers](#), use electric motors in [pods](#) called azimuth thrusters underneath to allow for 360° rotation, making the ships far more manoeuvrable.
 - [Photovoltaic](#) panels (only able to propel small ships).
 - [Fuel cells](#), first used as air-independent propulsion (AIP) in German [Type 212](#) submarines since 1998, based on proton exchange membrane fuel cells (PEMFC) of around 250 kW in total. Other PEM-FC are used in auxiliary power units on board ships, and more powerful molten carbonate (MCFC) and solid oxide (SOFC) high-temperature fuel cells are being considered for general and especial ship propulsion (e.g. [hydrogen fuelled ships](#)), in combination with some heat-recovery bottom cycle, enlarging the hybrid engine type of solutions (the first hybrid propulsion was sailing and steam, followed by the diesel-electric submarine, and CODAG combinations).

The first machine use for mechanical propulsion (on land and on water) was the [steam engine](#) which, after some trials as early as 1770, took over in 1815 with the first crossing of the English Channel by the steamship [Élise](#). The first thruster used was the [paddle wheel](#), where a number of paddles are set around the periphery of a partially submerged wheel. The first screw-driven ship was [Stevens' Little Juliana](#), in 1811, which was the first [ferry](#), crossing the Hudson river. In 1880, the American passenger steamer [Columbia](#) became the first ship to utilize incandescent [light bulbs](#), powered by a [dynamo](#); this was the first application of incandescent lighting, before [Edison's](#) first public [power station](#) in 1882, and soon after Edison mastered the technology in his lab in 1878.

The main engine sits in the [engine room](#), one of the largest and more complex ship compartments, and the noisier (Fig. 2b). It is usually located at the aft bottom of the ship, to minimise the shaft length to the propellers (at the stern), though the increased use of diesel-electric propulsion systems has released this constrain. In large ships there are several engine rooms and engine-ancillary rooms (e.g. see Fig. 1d).

Marine propulsion



Fig. 2. a) World's largest diesel engine, [RTA96-C](#). b) A ship's [engine room](#).

As an example of changing times in marine propulsion, consider the two cruisers [QM](#) and [QM2](#). [RMS Queen Mary](#) was a steamer cruise of 2139 pax, built in 1936 and retired in 1967; its propulsion system delivered 120 MW (for propulsion and hotel) from 24 [Yarrow](#) boilers that fed 4 [Parson](#) turbines, each linked with a shaft to a screw propeller, with a service speed of 15 m/s. [RMS Queen Mary 2](#), built in 2003, is a part-time cruiser and transatlantic ocean liner (the only one in service, between Southampton and New York), of 2620 pax. To its 117 MW of total installed power contribute four diesel engines ([Wärtsilä 16V 46C-CR](#)) of 16.8 MW each at 500 rpm operating on the 4-stroke cycle, and two gas turbines ([GE LM2500+](#)) of 25 MW each, with the power turbine spinning at 3600 rpm, and specific fuel consumption $c_{sp}=159$ g/kWh and 38% thermal efficiency. It uses electrical generators and electrical motors for propulsion (the first passenger ship with [integrated electric propulsion](#)), with four screw-propellers pods of 6 m in diameter spinning at 144 rpm (the forward pair fixed and the aft two rotatable 360° in azimuth, removing the need for a rudder), each of 21.5 MW (Rolls-Royce/Alstom Mermaid), with five blades separately bolted (the ship carries eight spare blades). The gas turbines are not housed at or near the engine room, deep in her hull, but instead are in a soundproofed enclosure directly beneath the funnel, to shorten their large air intakes. Service speed is 15 m/s.

A diesel ship's propulsion plant is similar to a ground diesel plant (as used in cogeneration and emergency power-supply), with a wide shaft-power range: from 10 kW to 100 MW. They burn marine diesel oil (MDO), or heavy fuel oil (HFO) when sulfur emissions can be tolerated (its price is nearly half of the former). The largest the ship, the lower the engine regime; e.g. the largest reciprocating engine can deliver 7 MW per cylinder, which has a bore of $D=1$ m, stroke of $L=4$ m, runs at 60 rpm (1 Hz), in the [two-stroke](#) cycle, with uni-flow-scavenging, and an efficiency of $\eta=54\%$ (BSFC=155 g/kWh). Slow engines spin at <200 rpm, medium-speed engines at 200..1000 rpm, and fast marine engines at >1000 rpm (in [four-stroke](#) cycle, with about 100 kW per cylinder).

When the ship's cargo is a fuel (oil tankers, liquefied natural-gas carriers, LNG, or liquefied petroleum-gases carriers, GLP), it could be used to propel the ship, but it is rarely done because of price (heavy fuel oil is much cheaper than any other fuel). However, [LNG carriers](#) used to be propelled by water turbines to be able to burn, besides the heavy fuel, the 0.1% by mass of the load per day, due to boil-off of the cryogenic LNG, being uneconomical to re-liquefy the boil-off. Typical LNG engine power is about 25..30

MW, for sailing at 10 m/s, burning about 50/50 by mass of heavy-fuel and natural-gas on the loaded trip, and about 80/20 on the ballast trip (some LNG must be left even when on ballast, to preserve cryogenic temperatures). Modern LNG carriers use a dual-fuel diesel engine (burning marine diesel or natural gas in a four-stroke engine), and electrically-driven propellers; engine efficiency (about 40 % for diesel against 30 % for the steam turbine) makes it more economical.



Fig. 3. a) LNG motorised by a 32 MW [steam turbines](#). b) Sketch of a 40 MW LNG dual-fuel electric propulsion system ([ABB](#)).

Types of thrusters

A brief grouping may be (in chronological order of development):

- [Paddles](#), including oars and waterwheels (and swimming).
- [Sail](#), or better sail-[keel](#) interaction, because without hydrodynamic lift, aerodynamic lift in sails could never produce ship advance against wind. Sailing upwind requires a coordination of air forces on the sail with water forces on the keel and rudder, and [tacking](#) (i.e. following a zigzag course).
- [Screw propellers](#), by far the most used, either in bronze, stainless steel, or fibre-reinforced polymers for small duties. Different types are:
 - Fixed pitch propeller.
 - Variable pitch propeller.
 - Ducted propeller.
 - Azimuth propeller.
- [Water jets](#), used in some fast ships, either powered by gas turbines or by diesel engines.

The traditional link between the ship's main engine and the propeller has been a mechanical shaft, supported and kept aligned by the spring bearings, the stern tube bearings, and the strut bearing (Fig. 4). Thrust is transmitted to the ship at the axial thrust bearings.

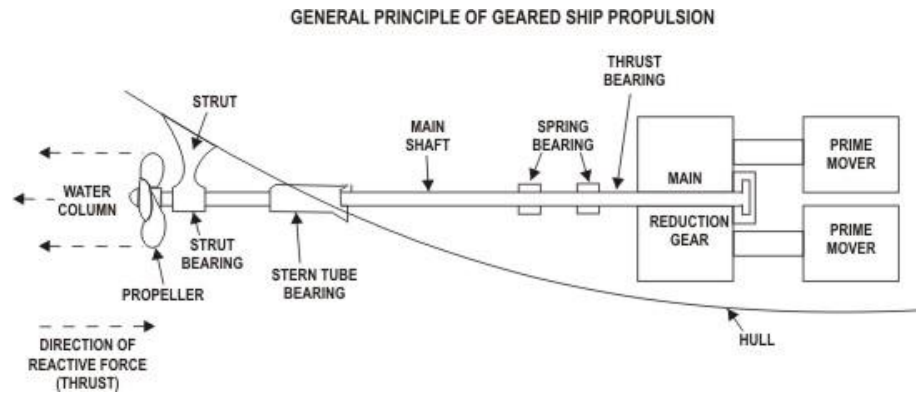


Fig. 4. [Sketch](#) of mechanical transmission in ship propulsion.

Most naval propellers are of the screw type, with 3-, 4-, or 5-blades in the largest vessels (4 is most common), and advancing speeds of 10..20 m/s (i.e. 20..40 kn (the [knot](#) is still in widespread use), with the record is at 50 m/s. Enclosing the propeller in a small duct (nozzle) increases the efficiency.

Notice that ship propellers sit at the rear, whereas in aircraft they are at the front; the reason lies in the different advancing low speeds. The rudder is behind the propellers to be effective at low advance speeds and allow harbour manoeuvres (although large ships may have separate perpendicular thrusters). Notice that the rudder is the primary steering means in ships, whereas fixed-wing aircraft have the rudder primarily to counter adverse yaw, and turning is basically achieved by ailerons on the far trailing-edge of each wing.

Water jet propulsion (with ducted axial fans, or with centrifugal pumps, powered by diesel engines or gas turbines) is used in some fast and quick-maneuvrable ships, attaining >20 m/s. Notice the great difference with aircraft speeds (100..250 m/s); however, the propulsion power needed is similar, because of the fluid-density difference in both mediums. Water propellers are less efficient than air propellers; e.g. ship propellers may have $\eta_p=0.5..0.7$ (against $\eta_p=0.8$ for air propellers), with the smaller value for large tankers (which have advance ratios $J=0.2..0.4$; see [Propellers](#), aside).

Manoeuvring is greatly increased by using [azimuth thruster](#), i.e. a propellers placed in a pod that can be rotated to any horizontal angle (azimuth), making a rudder unnecessary. Most azimuth thrusters (often named [azipods](#)) are [electric](#).

[Astern](#) propulsion is when a ship's propelling mechanism is developing thrust in a retrograde direction, either to decelerate and stop, or to go backwards. The usual way is by reversing pitch in a variable-pitch propeller, but other solutions exist (e.g. Fig. 1f). In [aircraft propulsion](#) it is named [reverse thrust](#), and in land propulsion it is named reverse gear.

The amphibious ship and helicopter carrier Juan Carlos I, the largest naval unit ever built in Spain (26 000 t displacement, 231 m length), is powered by two diesel generators and one gas turbine generator, driving two screw pods of 11 MW each. The [F-100](#) frigates (5800 t, 147 m) have two diesel generators of 4.5 MW each for normal navigation at 9 m/s, plus two gas turbines (GE LM-2500) of 17 MW each for advancing at 15 m/s, feeding two screw propellers.

Marine propulsion

[Hydrofoils](#) are watercraft equipped with underwater wings (hydrofoil surfaces below the hull, similar to [aerofoils](#)) that may support the vessel weight at high speed (recall that a wing lift is almost proportional to the speed squared). The hull is raised up and out of the water, with great reduction in drag, and fuel consumption. Unfortunately, impact of the fast and sharp hydrofoil surfaces, with large marine animals or floating objects, may cause severe damage (to both). A [hydroplane](#) is a fast motorboat, where the hull shape is such that at high speed, the weight of the boat is supported by planing forces, rather than simple buoyancy. There are also small [electric boats](#); in 2012 the [PlanetSolar](#) boat became the first ever solar electric vehicle to circumnavigate the globe. [Electrical propulsion](#) usually refers to the combination of an internal combustion engine (ICE: diesel or gas turbine) and electric motors directly driving the thruster (screw propeller or water jet), either through a mechanical transmission (with clutch and gears), or by an electrical generator coupled to the ICE and electrical transmission.

There are some crafts that take advantage of aerodynamic and/or hydrodynamic [ground effects](#) to support the weight of the vehicle (they must rely on buoyancy, however, when stopped).

There are also small watercrafts for personal use (e.g. [water scooters](#)), some for travel at the surface, and some for underwater use (see a [diver scooter](#) in Fig. 1i).

ENVIRONMENTAL EFFECTS

As of 2015, about 90% of international world trade relies on shipping, transporting $10 \cdot 10^{12}$ kg/yr of goods, accounting for 3.3 % of global CO₂ emissions, 15 % of global NO_x emissions, and 13 % of global SO_x emissions. Shipping companies are required to comply with the International Maritime Organization ([IMO](#)) and the International Convention for the Prevention of Pollution from Ships ([MARPOL](#)) emissions rules. IMO has declared some emission control areas (ECA) with strict regulations (particularly on sulfur oxides), and, from 2016, ships must possess [Tier III](#) propulsion machinery.

The environmental [input](#) may be due to the load transported (e.g. oil spills), to the propulsion system (e.g. exhaust, bilge water, fuel tank cleaning), or to other human activities on board (e.g. sewage).

When burning HFO, sulfur oxides are eliminated in scrubbers, which are vertical pressure vessel (located in the funnel) where alkaline water is sprayed onto the outgoing exhaust gas through perforated plates. Fresh-water scrubbers (with added NaOH) are more efficient and costly than sea-water scrubbers (sea-water alkalinity is in the calcium salts). Scrubbers get rid of particulate emissions too. NO_x emissions can be decreased by exhaust gas recirculation.

Other marine [pollution](#), though unrelated to propulsion, may be sewage and [litter](#). Raw sewage cannot be dumped within 20 km of the coast, and approved plants must be used closer. [Ballast](#) water discharges by ships can have a negative impact on the marine environment. No plastic may be dumped at sea.

MATCHING ENGINES AND WATERCRAFTS. SHIP RESISTANCE

Two kinds of matching may be considered:

Marine propulsion

- Propulsive matching, i.e. what kind and size of engines are needed to provide the propulsion power (or thrust) to compensate the vessel drag at cruise, and the extra power for acceleration and deceleration. Further engine power must be accounted for non-propulsive duties, what may be up to a half in large cruisers.
- Location matching and ancillary interfacing, i.e., engine rooms, fuel tanks, funnels, etc.

To minimise propulsion costs, ships must be designed to move with a minimum of drag. [Ship resistance](#) (drag) is defined as the force required to tow the ship in calm water at a constant velocity. Except in sailing ships, where lateral forces may be important, on all other ships it is just the longitudinal force that must be considered (ship resistance to advance), the lateral component being negligible.

In general the drag force is the projection along the advancing speed direction, of both the tangential force (shear) and normal force (pressure) exerted by a fluid on a solid surface, but considered globally, drag can be split in different terms:

- Viscous drag (or parasite drag), due not only to the unavoidable shear at the body surface (called 'skin friction', which is predominant in streamlined bodies like ships), but also to the pressure-force unbalance on BL-detached flows (predominant in blunt bodies and detached flows). The shear can be reduced by avoiding or retarding the laminar-to-turbulent transition in the attached boundary layer (BL). The pressure-force unbalance can be avoided or minimised by making the body streamlined, and by retarding BL-detachment, if any.
- Potential drag (non-viscous), essentially due to wave-making (wave drag), but also to wave breaking, and eddy shedding.

Ships actually move at the same time through two fluids, water and air, with widely different density, each contributing a resistance to advance which, to a first approximation, is proportional to density, so that air-resistance is often neglected against water resistance. Hence, we are only considering here skin friction in the submerged part of the hull, and wave resistance, neglecting the effects of appendages (propellers, rudders, and bilge keels), pressure drag, and air-drag (on the superstructure and the part emerged from the hull).

Ship resistance to advance depends a lot on speed, size, wetted area, and other geometrical parameters, with a typical share of about 60 % viscous drag (30 % skin drag, 25 % stem-wake drag, and 5 % air drag), and 40 % wave-making drag; however, wave drag may rise to 60 % on fast ships and sailboats, and be under 20 % in very-large ships.

The most important non-dimensional parameters in drag resistance are: [Reynolds number](#) ($Re_L = v_0 L / \nu$), [Froude number](#) ($Fr = v_0 / \sqrt{Lg}$), and the [drag coefficient](#) (c_D). For similar geometries, $c_D = f(Re, Fr)$ alone, and Froude proposed that $c_{D,skin} = f(Re)$ and $c_{D,wave} = f(Fr)$.

Skin resistance

Skin resistance, D_{skin} , often the largest share in drag for all watercrafts, surface and submerged,, is modelled as:

Marine propulsion

$$D_{\text{skin}} = c_{D,\text{skin}} A_{\text{wet}} \frac{1}{2} \rho v_0^2 \quad (1)$$

where $c_{D,\text{skin}}$ is the skin-drag coefficient, A_{wet} is the wetted hull area (including the rudder but not the propeller), ρ the water density, and v_0 the advancing speed. A useful correlation for the skin-drag coefficient (1957-ITTC, International Towing Tank Committee) is:

$$c_{D,\text{skin}} = \frac{0.075}{(\log_{10} Re_L - 2)^2} \quad \text{for } Re_L > 10^7 \quad (2)$$

where $Re_L = v_0 L / \nu$ is the Reynolds number based on the waterline length L (ν is the kinematic viscosity of water). Fouling and corrosion will increase skin friction and decrease ship speed for given propulsion.

Wave resistance

Wave-making resistance takes place on surface watercraft (and to some extent on submarines navigating close to the surface), and is most important in fast ships and sailboats, i.e. for $Fr \sim 1$ (say $Fr > 0.3$). A ship moving over the surface of undisturbed water sets up waves emanating mainly from the bow and stern of the ship. The wave pattern consists of divergent (or diagonal) and transverse (or longitudinal) waves (Fig. 5), and energy is spent in its formation (which must be supplied by the propulsion system). These waves were first studied by Kelvin (in 1887, as a single pressure point traveling in a straight line over the water surface), who found that regardless of the speed of the ship, they were always contained in the 19.5° semi-angle (Fig. 5).

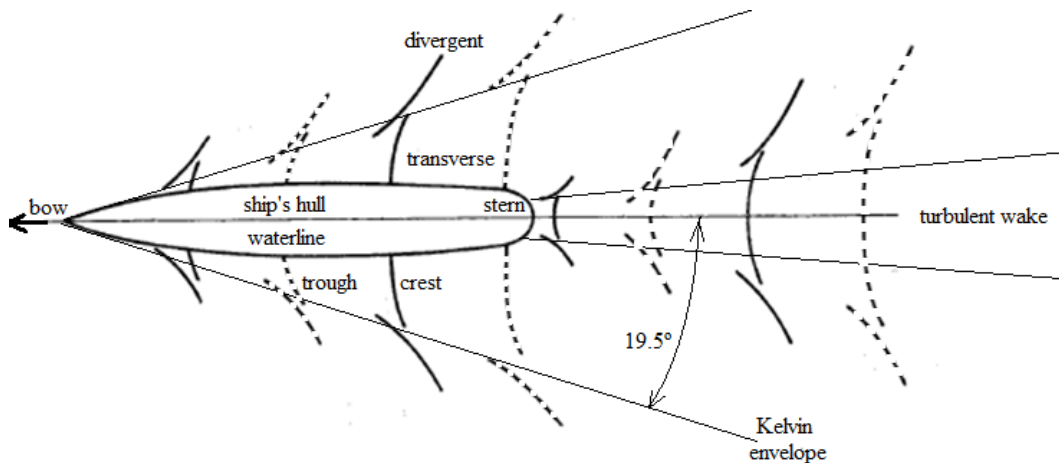


Fig. 5. Ship wave pattern of transversal and divergent waves on the water surface.

Total ship drag is the sum of skin friction (viscous resistance, which monotonically increases with speed), and wave resistance, which shows up-and-downs in its dependence with ship speed, due to interference effects of the bow pattern with the stern pattern (the wavelength of both transverse and divergent waves grows with speed squared).

Increasing speed is almost always appealing in all kind of vehicles: you arrive sooner and may do more things there, your freight arrives sooner and you may increase your turnaround, and, for war and

emergency, you can reach to the target and escape from the site sooner. But the power required to propel a ship through the water is the product of total hull resistance and ship speed, and there are a v_0^2 term in the skin-resistance term, and further speed effects on the skin-drag coefficient, what finally yields a power requirement proportional to v_0^3 , v_0^4 , or v_0^5 . No wonder why typical service speed in medium and large ships is about 15 m/s.

For high-speed boats, the best is to have the minimum wetted area but a submerged propeller; different trade-offs are achieved in [SWATH](#)-ships (small waterline area twin hull ships), thin elongated bows (like [catamaran](#)), hydrofoil ships, hovercraft, and hydroplanes. In fact, supercavitation under water (see Supercavitation, below) can be considered a means of reducing the wetted area of the moving object.

Large ships may reduce drag by using a [bulbous bow](#) (a protruding bulb below the bow waterline). In a conventionally shaped bow, a bow wave forms immediately before the bow. When a bulb is placed below the water ahead of this wave, water is forced to flow up over the bulb. If the trough formed by water flowing off the bulb coincides with the bow wave, the two partially cancel out and reduce the vessel's wake.

UNDERWATER PROPULSION

Underwater propulsion poses a special problem due to lack of air for oxidising the fuel in a normal thermochemical engine. Leaving aside small unmanned ([AUV](#)) and manned [submersibles](#), and the large nuclear-powered submarines (>350 units worldwide, whose endurance is only limited by personnel exhaust), the standard propulsion system in submarines is diesel-electric.

The lack of air for the engines is also applicable to the crew; a traditional submarine may hold enough fresh air in its habitable volume to satisfy crew needs during an immersion (several hours), until air is renovated at the surface, but portable sources of oxygen and CO₂ sinks ([rebreathers](#)) are available for emergencies. Cartridges with KO₂ or LiO₂ are used (K₂O₂ has also been utilized, but it burns with water, $2K_2O_2 + 2H_2O = 4KOH + O_2$). The main reaction in rebreathers is the conversion of CO₂ into O₂, e.g. $4KO_2 + 2CO_2 = 2K_2CO_3 + 3O_2$, i.e. the yellow KO₂ changes to white K₂CO₃ producing $3 \cdot 32 / (4 \cdot 71) = 0.34$ kgO₂/kgKO₂, while absorbing $2 \cdot 44 / (4 \cdot 71) = 0.31$ kgCO₂/kgKO₂ (but notice that human also produces less CO₂-molecules than O₂-molecules-needed, because oxidation of food also needs oxygen to produce water and urea).

Submarines

A typical conventional submarine is about 70 m long, 7 m in diameter, 2500 t, have a crew of some 30 people, and a 3..4 MW diesel-electric plant (composed of 2 or 3 engines, for redundancy and load matching); non-propulsion power requirements may reach 100 kW. The propulsion system, Fig. 6a, which may occupy up to 50 % of the pressurised hull volume, typically operates in the following way:

- Normal operation is in fully-submerged navigation (patrol mode), down to 200 m depth limit, with electric lead-acid batteries supplying propulsion and housekeeping power. The typical speed is about 2 m/s for a maximum endurance of about 8..10 hours (0.3 MW), or a maximum speed of 15 m/s for about half an hour (3 MW).

- Snorkel operation (or snorting), at periscope depth (about 10 m below surface), is primarily used to recharge the batteries with the diesel engines, since the boat speed is limited to about 3 m/s by structural strength of the snorkel mast. The snorkel is a device which allows a submarine to operate submerged, taking in air from above the surface (engine exhaustion takes place always under water, to minimise the thermal signature; in military surface ships the exhaust is through a funnel, but with the flue gases diluted with air to minimise thermal signature). A key feature is the head-valve on top of the air-intake mast that must prevent water from entering.
- Surface navigation, diesel powered, with electric generators delivering a total of 3..4 MW to one or two low-rpm DC-motors directly driving the propeller (one, or two counter-rotating), providing a speed of up to 5..6 m/s, with endurance limited to one or two months by fuel-tank capacity.

Propulsion power is proportional to v^3 , but endurance is proportional to $\exp(-bv)$, with $b \approx 0.35$ s/m. Hidden submerged endurance is limited by batteries energy capacity to less than 12 h; even with an air-independent engine (see AIP, below) it is limited by LOX mass to less than 15 days (for a large 50 t LOX load); on nuclear-powered submarines it is the crew endurance that sets a limit to over 3 months. Waste disposal may endanger stealth, particularly those emitted by the propulsion system: exhaust gases, thermal plume, ballast, noise... Submarine propellers are relatively large and have many blades (Fig. 1h) with a complex curvature, intended to minimize noise while in patrol navigation, and cavitation at high spinning rate.

Nuclear submarines are much more powerful and truly 'submarine operational' (i.e. able to travel underwater, down to 500 m depth, at high speed for unlimited periods), though they have a big handicap: in peace-time they are banned to operate in most-interesting litoral regions. Their nuclear reactors provide 100..200 MW of heat that convert to 30..70 MW of power in a steam-turbine engine. There are almost 400 nuclear submarines worldwide (up to 10 being replaced each year), the largest being the Russian [Typhon](#) class (175 m long, 48 000 t submerged displacement, 75 MW power), and the smaller being the French [Rubis](#) class (74 m long, 2 600 t submerged displacement, 7 MW power).

Submarines have two hulls: the outer hull provides a streamlined shape to minimise resistance, whereas the inner hull allows normal habitable pressure (around 100 kPa) by protecting the interiors from extreme pressures at greater ocean depths; the hulls are generally made from an alloy which is a combination of nickel, molybdenum, and chromium. Between these two hulls are located the ballast tanks (Fig. 6b), which serve to change buoyancy between surface and submerged conditions; changes in navigation depth and attitude are dynamically performed with the propulsion and the control planes; there are other interconnected internal tanks, independent of ballast tanks, to fine-control attitude and buoyancy. In case of a submarine is unable to surface, there is a life-support system with a few days of autonomy, and rescue vehicles (Fig. 6c) that, once transported to a close location, can travel independently to the downed submarine, latch onto the submarine over a hatch, create an airtight seal so that the hatch can be opened, and load up the crew. A diving bell may be lowered from a support ship down to the submarine, where a similar operation occurs. To raise the submarine, typically after the crew has been extracted, pontoons may be placed around the submarine and inflated to float it to the surface.

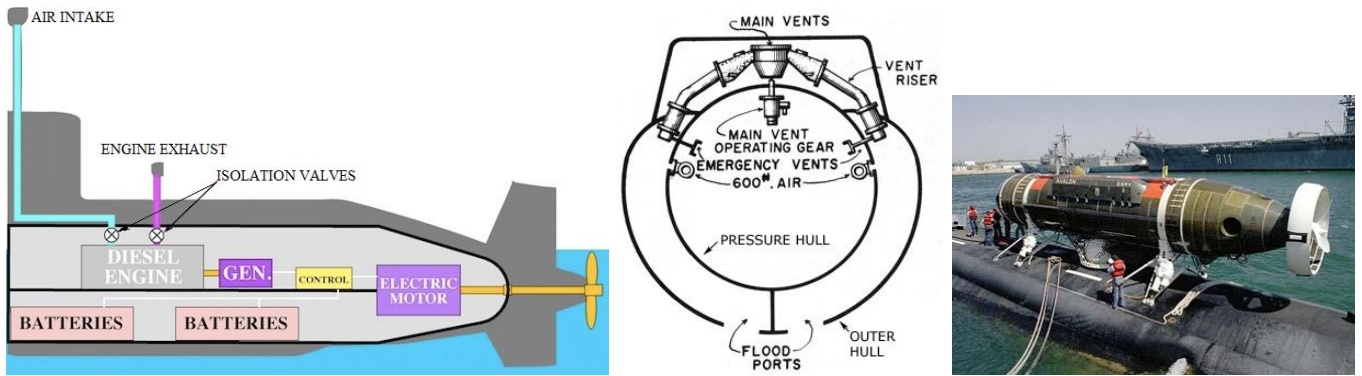


Fig. 6. a) [Sketch](#) of the standard diesel-electric submarine propulsion. b) Cross-section [diagram](#) showing the two hulls (pressurised and hydrodynamic) and the [ballast](#) system. c) Submarine [rescue vehicle](#).

Air-independent propulsion

Air-independent propulsion ([AIP](#)) systems are being developed for conventional (diesel-electric) submarines, to extend submerged endurance longer than batteries allow. Present AIP systems are relatively small in power rating (<300 kW), but allow the extension of discrete submerged endurance from less than a day to two weeks (navigating at <2 m/s). Most AIP systems use liquid oxygen (LOX) as oxidiser, but the fuel and type of engine may differ from the nominal diesel oil (e.g. using bioethanol) and from the nominal diesel engine (see Fig. 7). In any case, AIP is only an add-on to the main propulsion system (always diesel).

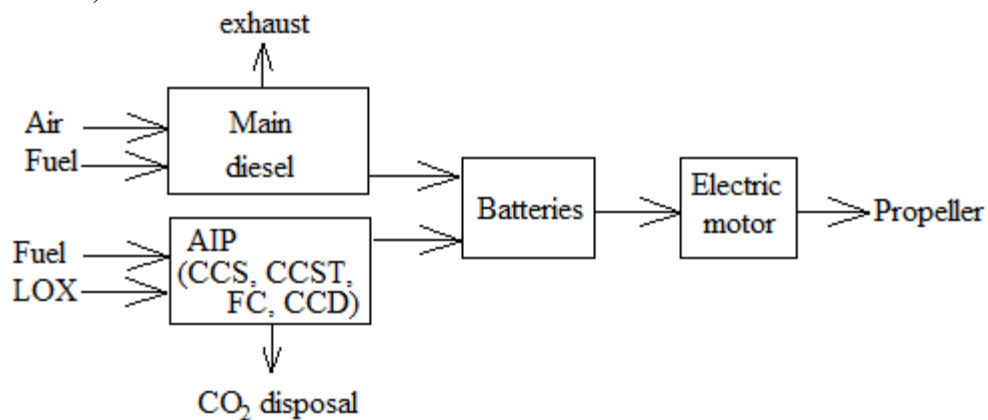


Fig. 7. Submarine propulsion configuration with air-independent propulsion (AIP). The AIP system may be a closed-cycle Stirling (CCS) using helium as working gas, a closed-cycle steam turbine (CSST), a fuel cell (FC), a closed-cycle diesel (CCD) using diesel as in main engines (but with LOX and exhaust gas recirculation), etc.

More advanced AIP systems are investigated to get rid of the oxygen need (some of them are already being used to propel torpedo), e.g.:

- Hydro-reactive metallic fuels, e.g. a flow of molten sodium burning in water, $\text{Na(l)} + \text{H}_2\text{O(l)} = \text{NaOH(l)} + \frac{1}{2}\text{H}_2\text{(g)}$. The hydroxide can be regenerated by thermal dehydration, $2\text{NaOH(l)} = \text{Na}_2\text{O(s)} + \text{H}_2\text{O(l)}$, followed by reduction of the oxide.
- Alkaline metals with other oxidisers, e.g. a gas jet of SF_6 submerged in a molten lithium bath, $8\text{Li(l)} + \text{SF}_6\text{(g)} = 6\text{LiF(s)} + \text{Li}_2\text{S(s)}$. The released heat is used to generate steam for a Rankine cycle (CSST). A closed reservoir holds the molten metal and the products (no gas release, no effect of immersion depth).

- Using monopropellants like in conventional rockets, e.g. [Otto fuel II](#) (unrelated to Otto cycle) consists of the nitrated ester explosive propellant propylene glycol dinitrate ([PGDN](#)), to which a desensitizer (dibutyl sebacate) and a stabilizer (2-nitrodiphenylamine) have been added; their mass ratio is 76 %, 22.5 %, and 1.5 %.

Torpedos

[Weapons](#) are devices used by peaceful societies to defend themselves, and by primitive societies (and criminal organisations) to attack, causing damage to persons and property. Any tool that amplifies human power can be used as a weapon, particularly if it could act at a distance, i.e. thrown onto the enemy. The first weapon-launcher was the human arm (the origin of 'arms'); later, elastic means were used (e.g. bows and catapults); the thrust produced by confined deflagration of black powder, initially developed by the Chinese for amusement, quickly revolutionized warfare in the late Middle Ages; [air guns](#) were developed in the 17th century, with the advantage over firearms of being insensitive to moisture, being smokeless, flameless, and quieter; but further development in gunpowder materials, in loading and release mechanisms, and [ammunition](#), made [firearms](#) the undisputable winner. We only deal here with self-propelled guided bombs, missiles and torpedos, as a last example of propulsion systems. Guidance may be: wired-guided by the operator, or homing (self-guided towards a target signature: noise, wake, heat...); the longest range wire-guided missiles in current use are limited to about 4 km.

- A [missile](#) (Lat. *mittere*, to send) is a self-propelled air-flying weapon (may be launched from a vehicle on ground, air, over or under sea, or from a fixed land base). Propulsion is usually based on rocket engines, but air-breathing engines are taking over in the sustained-flight phase of medium and long-range missiles. Missiles may be launched horizontally from aircraft (or from torpedo tubes), or with an inclination, the vertical launching system ([VLS](#)) being most used by the navy (there are about 70 sizeable navies worldwide); missiles can be either hot launch (where the missile-rocket ignites in the cell), or cold launch, where the missile is expelled by gas produced by an independent gas generator, and then the missile-rocket ignites. The fact that the engine can be designed for only one use (and usually short) should not compromise safety and reliability.
- A [torpedo](#) (name derived from the electric-ray fish) is a self-propelled underwater weapon that may be launched from a submarine, a ship, an aircraft, or from the coast. In conventional design, a torpedo may travel at 10..30 m/s for 1..20 km, and therefore they need a propulsion system that can run for 1..15 minutes. Typical size is about 3..8 m long and 0.3..0.6 m in diameter and a total of 500..4000 kg (100..500 kg explosive).

Before WWII, torpedo propulsion was mainly by a pneumatic motors driven by compressed air (up to 20 MPa), with air bubbles being released. The first torpedo, the Whitehead of 1866, had a 2.6 MPa compressed-air tank, that fed a piston-engine driving a single screw-propeller at about 100 rpm, able to reach 180 m at 3 m/s; large adiabatic air expansions yielded icing problems, which were first avoided by heating the expanded air with sea water, and later by burning some fuel with the air or better with pure oxygen; most torpedoes used in World War I and World War II were of this type. After WWII, powerful electrical batteries and an electrical motor were used (the best being silver oxide Ag₂O primary batteries, which need no maintenance). However, long range torpedos need a conventional heat engines (usually a

rocket / gas-turbine combination with special fuels). [Underwater combustion](#) is a complicated process, with interest not only in propulsion but in welding and cutting metals underwater, lighting, etc.

Sizeable vanes are required to compensate the torque of single screw propellers, and two contra-rotating screws are common. [Mark-50 torpedos](#) (USA, since 1991) use a small tank of sulfur hexafluoride gas which is sprayed over a block of solid lithium, $\text{SF}_6(\text{g}) + 6\text{Li}(\text{s}) = \text{S}(\text{s}) + 6\text{LiF}(\text{s})$, an exothermic reaction with volume shrinking (no need of exhaust pipe), used to generate steam in a closed Rankine cycle supplying power to a pump-jet.

Modern submarines use either swim-out systems or a water-ram push to discharge the torpedo from the tube, both of which have the advantage of being significantly quieter than previous systems based on a pulse of compressed air or a hydraulic ram, what helps avoid detection of the firing from passive sonar. The [torpedo tube](#) in a submarine operates on the principle of an airlock.

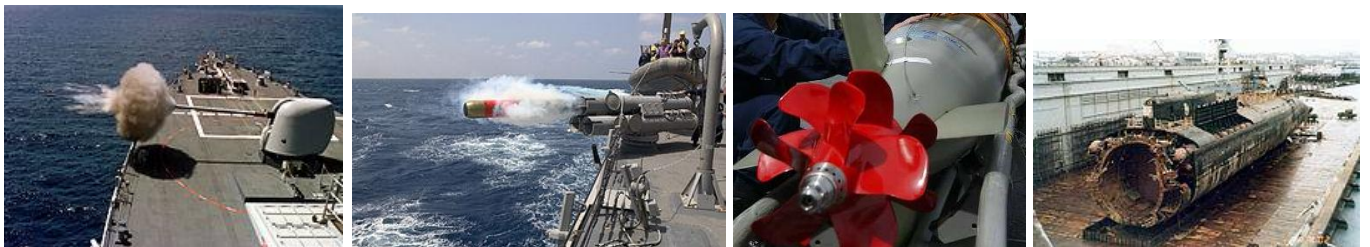


Fig. 8. a) A 127 mm calibre gun being [fired](#). b) A [torpedo](#) launched from a ship. c) Detail of [Mark-46](#) torpedo propeller. d) Wreckage of [Kursk K-141](#) submarine sunk by own torpedo accident.

Propulsion with supercavitation. Supersonic underwater motion

The shot of a firearm works by suddenly generating a lot of gasses that pushes the bullet and accelerate it to supersonic speed while leaving the gun barrel ([internal ballistics](#)). But the shot of a gun under water may burst the barrel because the gases are not capable of accelerating at a time the bullet and the water column ahead. Even if the bullet leaves the barrel, it cannot travel but a few metres because water-drag is 1000 times higher than air-drag (density ratio) for the same speed, and exit speed is low.

The largest [exit-speed](#) of ammunition (in air) may [reach](#) 2500 m/s ($M=v/c=7$); for comparison, the supersonic aircraft Concorde flew at 500 m/s at 17 km altitude, $M=2$). But even at these high speeds the penetration of a bullet in water is minimal; in fact, the ammunition may shatter on hitting the water surface at so fast speeds. Military rifles can reach only down to 2 m or 3 m depth underwater, unless they use super-cavitating bullets. In addition, it is difficult to score if the shooting is not vertical, because the target does not appear where it is, due to light refraction at the water surface. This fact was already known to naval architects in the 15th century, and they made wooden warships with a "carpenters' walk" free of fixtures just above the water line, since they knew that cannon balls made no damage underwater (and a hole further upwards was not important for the vessel to sink (only right on the water line was the big danger)).

Can anything travel at supersonic speed in water? Yes, even with the fact that sonic speed in water is 1500 m/s and in air only 340 m/s (sea-level conditions); by taking advantage of [supercavitation](#).

Supercavitation usually refers to intended cavitation with a bubble fully encompassing a solid body; unintended cavitation has always been a problem in hydraulic machinery.

Cavitation (first analysed by Froude in the 19th century while studying naval screw propellers), is the formation of bubbles within a liquid (i.e. cavities), usually by local pressure falling below the liquid-gas-equilibrium (LGE) at that temperature (e.g. at 15 °C, when pressure in pure water is lower than its vapour pressure, $p_{v,15}=1.7$ kPa, steam bubbles appear), although similar phenomena take place when local temperature increases above the LGE-value at that pressure (i.e. boiling), or when the gas concentration increases beyond LGE-values at that pressure and temperature (i.e. supersaturation). Cavitation is a significant cause of wear in hydraulic machinery because the cyclic collapsing of the cavities (cavitation) that implode near to a metal surface cause concentrated stresses and erosion.

According to the vicinity of a slid surface, cavitation bubbles may appear:

- Permanently attached to a moving solid (e.g. to the leading edge, or near a blunt body). A subdivision may be:
 - Incipient cavities (many small cavities on the body surface). Characteristic noise of collapsing bubbles.
 - Partial cavities (one cavity reattaching on the object). The cavity pulses and is unstable.
 - Supercavities (the whole object is inside the cavity).
- Transient free-bubble creation and collapse (e.g. near the neck in a venturi, induced by ultrasounds, water hammer, high-shear layers in jets or wakes...).

Supercavitation is the use of cavitation effects to create a large gas-bubble within a liquid, to support the motion of an object fully within the bubble. Let assume a body moving within a supercavitation bubble at high speed (either by being permanently propelled, or by inertia from a previous push). Notice that pressure drops across the leading edge of the supercavitating bubble, what can be compensated in different ways:

- A solid surface, named the supercavitator (e.g. a small disc or cone), may be placed at the stagnation point to force the liquid sideway, and the curvature of streamlines bending downstream keeps the negative pressure jump at a free liquid-to-gas interface, forming a large elongated bubble within which a large body can be moving with little drag.
- A high-speed gas jet may be ejected forward, to avoid any solid contact with the liquid. The gas jet may be mechanically ejected, or in-situ generated by some type of local energy deposition. This is a very unstable configuration.
- Hybrid (ventilated) bubble is the most used: a supercavitator and gas injection behind.

In any case, Archimedes buoyancy-force no longer acts, and the weight of the object must be compensated by aerodynamic lift; hence, stability becomes a serious problem. Manoeuvring may be achieved by various means such as drag fins that project through the bubble into the surrounding liquid, by tilting the nose of the object, by injecting gas asymmetrically near the nose in order to distort the geometry of the cavity, by vectoring rocket thrust through gimbaling for a single nozzle, or by differential thrust for multiple nozzles. To create a supercavitating bubble, the object must be moving at >50 m/s.

A [supercavitating propeller](#) is a variant of the typical naval screw-propeller in which the blades are wedge-shaped and spin at a high rate to force cavitation on the whole forward face, i.e. the bubble starts at the leading edge, and collapses well behind the blade, what avoids the spalling damage.

Supercavitation fluid-dynamics is a very complex field because the object moves within a bubble of unknown free boundaries. The basic parameter of cavitation flow is the cavitation number, σ :

$$\sigma \equiv \frac{p_L - p_{LGE}}{\frac{1}{2} \rho_L v_0^2} \quad (3)$$

where p_L is the undisturbed liquid pressure at that height (hydrostatic pressure, $p_L = p_{L0} + \rho_L g z$), p_{LGE} is the liquid-gas-equilibrium pressure at that temperature (e.g. the vapour pressure for a pure liquid), ρ_L the undisturbed liquid density, and v_0 the advancing speed for permanently attached cavities. For instance, in a water flow around a circular cylinder of $D=0.01$ m, one finds cavitation inception at $\sigma < 1.5$, whereas in an elliptic cylinder of $D_y=0.01$ m and $D_x=0.08$ m (at zero angle of attack), cavities do not appear until $\sigma < 0.2$. The supercavitation flow regime corresponds to $\sigma \ll 0.1$. Instead of having large values for v_0 , low cavitation numbers for supercavitation can be obtained by injecting gas (i.e. increasing p_{LGE}), what is known as artificial cavitation or ventilated cavitation.

Passing through the speed of sound does not result in a substantial variation in the cavity shape as compared to subsonic flow. In spite of the small asymmetry of the shape about the mid-section the cavity shape in supersonic flow is close to an ellipsoid of revolution as it was before.

Small projectiles (say < 0.5 kg) may be designed to sustain supersonic speed under water (> 1500 m/s) for long distances (> 100 m), when shot at about 2500 m/s. The shot is initiated by a muzzle gas bubble, through which the bullet advances (the higher the solid density the better, e.g. tungsten bullets), maintaining an elongated ellipsoidal cavity (some 100..500 bullet-diameters long and about 2..4 bullet-diameters wide at the middle). The projectile travels along a nearly straight line, decelerating ballistically; this v -decrease, makes σ in (3) to increase and the cavity size to decrease, with its back reaching the body and advancing to the front (leaving the projectile surface in contact with the liquid); the larger viscous drag on the wetted skin quickly stops the projectile. Although a successful launch results in a nearly straight projectile trajectory, the projectile itself tends to oscillate within the cavity in pitch and yaw and is typically stabilized by a process referred to as tail-slap, wherein the after body grazes the cavity boundary.

Some torpedoes, like the Russian VA-111 Shkval and the German Barracuda, use supercavitation to increase their speed to over 100 m/s; the maximum speed of torpedoes which do not use supercavitation, such as the American Mark 48 and British Spearfish, is well under 50 m/s. The Kursk nuclear-submarine [disaster](#) in 2000 was rumoured to have been due to a faulty Shkval torpedo, though later evidence pointed to a H_2O_2 leak from a faulty 65-76 torpedo. Widely available data of this nuclear-powered submarine may illustrate the propulsive solutions used in torpedoes and missiles.

- [Kursk vessel](#). A 154×18.2×9 m³ double-hull nuclear-powered submarine, with 13400..16400 t displacement, powered by two OK-650b pressurised-water nuclear reactors, with two steam turbines delivering 73 MW in total to two 7-bladed propellers, moving up to 16 m/s submerged or 9 m/s surfaced. The outer hull was made of high-nickel, high-chrome stainless steel 8.5 mm thick, with a 51 mm thick pressure-hull able to work down to 1000 m in depth. It was armed with P-700 Granit cruise missiles, and eight torpedo tubes in the bow: four 0.53 m and four 0.65 m in diameter (able to launch either type-65-76 torpedoes, or RPK-7 anti-ship missiles).
- [Kursk armament](#)
 - [Type 65-76](#) torpedos (0.65 m diameter, 11 m length, 4750 kg), with propulsion based on the reaction of concentrated hydrogen peroxide with kerosene, with the generated gases driving a turbine and contra-rotating propellers. Warhead 557 kg. Operates at 20 m depth. Wake homing sensor points upwards to detect the ships wake, the torpedo sweeps from side to side to find the edges of the wake.
 - USET-80 class torpedos (0.53 m diameter, 7.8 m length, 2000 kg), with electric propulsion based on silver-magnesium battery (using seawater as electrolyte), and an electric motor; speed is 20 m/s and range 8 km.
 - [Shkval](#) class supercavitating torpedo (0.53 m diameter, 8.2 m length, 2700 kg), with propulsion based on H₂O₂/kerosene rocket (the propellant tanks contain about 1500 kg of hydrogen peroxide and 500 kg of kerosene). They are launched at 25 m/s like normal torpedos, but shortly afterwards, its liquid-fuel rocket ignites and propels it to speeds of >100 m/s by creating a ventilated cavity with part of the exhaust gases; the range is >10 km. The torpedo controls its direction using four fins that skim the inner surface of the supercavitation envelope. To change direction, the fin or fins on the inside of the desired turn are extended, and the opposing fins are retracted. To make faster turns, the push plate on the nose can be used to control the shape of the bubble the missile is traveling in.
 - Type [P-700-Granit](#) cruise missiles (0.85 m diameter, 10 m length, 7000 kg total, 750 kg warhead), with propulsion based on a solid-fuel rocket booster, and a turbojet sustainer engine, with a 550 km range at Mach 2.5 over 20 km altitude ($M=1.6$ if flying at low altitudes).
 - [RPK-7](#) 'Stallion' anti-ship missiles (0.65 m diameter, 6.5 m length, 2150 kg), with solid-rocket propulsion, and a range of 120 km at Mach 1.5.
- [Kursk accident](#)
 - It seems that, while trying to load a 65-76 torpedo during a naval exercise, some liquid H₂O₂ inside the torpedo seeped through a faulty weld in the casing, coming in contact with materials that accelerate its exothermal decomposition into steam and oxygen, $\text{H}_2\text{O}_2(\text{l})=\text{H}_2\text{O}(\text{g})+\frac{1}{2}\text{O}_2(\text{g})+98.2 \text{ kJ/mol}$.
 - The pressure of the generated gases (and perhaps the boiling of H₂O₂ in the tank) ruptured both the oxidiser and the fuel tanks, originating a violent combustion of H₂O₂ and kerosene, with explosion of the confined compartment (but with hull integrity), and temperatures above 3000 K. The two nuclear reactors automatically shut down after this blast, registered by overseas seismographs as 1.5 on the Richter scale (equivalent to 100..200 kg TNT).
 - It seems that the high temperatures triggered detonation of some warheads, since 135 s after the first blast, a larger undersea explosion was detected (4 on the Richter scale, equivalent to

2..3 t TNT). This second blast tore a 2 m² hole in the hull, and the vessel sank to a 108 m sea floor. The bulkheads around the nuclear reactors, made of 130 mm thick resiliently steel, withstood both explosions, and 23 of the 118 crewmen survived the shocks at the other end of the vessel.

- The trapped survivors died of asphyxiation after more than 6 hours waiting rescue due to a fortuitous flash-fire. The survivors had some lighting, air at normal pressure and temperature, and available rebreathing canisters; the latter where potassium peroxide cartridges which, one triggered, generate oxygen and absorb CO₂ by the chemical reaction $4\text{KO}_2+2\text{CO}_2\rightarrow 2\text{K}_2\text{CO}_3+3\text{O}_2$; but water was slowly seeping into the compartment, increasing pressure and lowering temperature. Although it was known that KO₂ is highly reactive with water, some cartridge came in contact with the oily sea water and triggered the violent reaction $4\text{KO}_2+2\text{H}_2\text{O}\rightarrow 4\text{KOH}+3\text{O}_2$, producing a flash with sudden projection of very-hot particles that set fire on organic matter and consumed the remaining oxygen. The Russian Navy desperately tried many [rescue](#) operations (the first one 10 h after the accident), none successful until Norwegian divers opened the rescue hatch in the stern of the submarine 16 days later (the day after they arrived).

Kursk missiles and torpedoes could all be equipped with nuclear warheads.

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