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CHARACTERISTICS AND RELATIVE MERITS OF ADVANCED MARINE VEHICLE TYPES

1. INTRODUCTION

Increasing the speed and improving the seakeeping behaviour of a conventional displacement ship is only possible to a certain extent. At a Froude number above 0.4, wave resistance increases with a relatively high power of the ship speed. Above this boundary the necessary power will increase disproportionately with the ship speed. The seakeeping behaviour will also worsen with the speed due to high wave forces and critical impact forces. This can only be dealt with increasing the size, i.e. increasing the displacement.

Substantially higher speeds and considerably better seakeeping behaviour can be obtained, if the greatest part of the displacement volume is located above or deeply under the water surface. The magnitude of the wavemaking resistance is related with the square of the water disturbance. If the displacement volume is located either above or below the free surface, the wavemaking, hence wavemaking resistance, will be low. This is the key issue for the design of most promising AMV types.

Additionally the wave forces on the hull, therefore ship motions, will be low if the hull is outside of the range of the surface waves.

Some of the advanced marine vehicles have the displacement volume above the water surface, e.g. ACV, SES, and planing crafts. This can be achieved by a combination of hydrostatic, hydrodynamic and aerostatic forces. The others have the displacement volume below the water surface, e.g. SWATH.

Using these descriptions of AMV following types can be identified (Fig.1-1):
Semi-planing or Semi-Displacement Monohull Craft
Planing Monohull Craft
Catamarans
SWATH (Small Waterplane Area Twin Hull Ship)
ACV (Air Cushion Vehicle)
SES (Surface Effect Ship)
Hydrofoil Craft

In the following section each of these types is described briefly, then relative merits of these types are compared with each other and the conventional ships.

2. FAST DISPLACEMENT SHIPS AND HIGH SPEED MONOHULLS

Although not considered as an AMV, fast displacement ships are of interest due to low cost to build and less weight critical characteristics comparing to AMVs. Fast displacement ships are defined as the vessels operating above Fn=0.4 based on the waterline length.

Between Fn=0.4 and 0.5 (pre-primary resistance hump regime) displacement ships experience significant wave resistance. This is because the hull length is less than one wavelength. The bow is supported by the peak of the wave while the stern is only supported by the hollow. The result is an unfavourable bow-up trim. Broad transoms and flat buttocks are required to minimise the bow-up trim. In order to minimise the power requirement, $L/\nabla^{1/3}$ values must be over 8. Typical ships operating in these conditions are frigates and destroyers.

In so called post-primary resistance hump regime (0.5<Fn<0.7), the displacement ship experiences of a wave length of more than twice of the waterline length. The wave resistance is mainly made up of the bow wave. Hence it is essential to reduce the bow wave in order to minimise the power requirement, i.e. to reduce the bow-up trim. This can be achieved by very fine bowlines (This type is known as slender ship). $L/\nabla^{1/3}$ must be in excess of 10. These ships have improved seakeeping properties over their higher displacement counterparts.

The Froude number range between 0.7 and 1.0 is the regime of the so-called semi-displacement or semi-planing hulls (Fig 1-2). If the hull has suitably designed flat buttocks, a significant amount of dynamic lift (%20 - %30 of the displacement) is generated. This causes appreciable reduction in the wetted surface. $L/\nabla^{1/3}$ values are in the range of 6 to 7 at the higher speeds. Here the ship beam becomes more important for the generation of dynamic lift.

Speeds in excess of Fn=0.7, the dynamic lift generated by the hull reaches more than %50 of the hull displacement. This is called planing craft regime. The hull features a hard chine and/or well defined spray rails (Fig 1-3). Length displacement ratio ($L/\nabla^{1/3}$) is typically between 4-5 for calm speed, 6-7 for rough sea operation. V sections are used with convex or concave lines.

In the planing hull, the speed is superior to a comparable size displacement vessel, the behaviour in a seaway is not so.

3. HIGH SPEED CATAMARANS AND SWATH SHIPS

The requirement of large deck space for a given length has led to the development of the catamarans (Fig. 1-4). Each one of the two hulls, called demihull can be symmetrical, asymmetrical or fully asymmetrical (wall sided). The hulls can operate in slender ship, semi-planing or planing regimes.

An important aspect of catamarans is the demihull spacing due to resistance, structures and manoeuvring characteristics. As the distance between the hulls gets smaller the resistance interference becomes very unfavourable while structural problems gets easier. Further complexity inherent in the form appears, as these characteristics are highly dependent on the Froude number.

Seakeeping behaviour is probably the biggest handicap of the catamarans. Pitching is worse than the conventional hulls. Additionally the vertical accelerations are very high on the deck side. Wave piercing catamaran (Fig.1-5) is introduced to reduce the contouring.

SWATH Ships (so called S3, Trisec, LWP Catamaran, Semisubmerged catamaran, Fast displacement catamaran) features with relatively deeply submerged two cylindrical hulls, a box shaped deck and connecting these : a pair of surface piercing struts with a small volume and waterplane area (Fig.1-5). Small waterplane area struts give SWATH Ship a superior behaviour in waves although antipiching fins are a necessity. Low wavemaking resistance but a large wetted surface restricts the maximum speed. Main disadvantages are sensitivity to trim, pitching, broaching, and weight sensitivity and deep draft.

4. HYDROFOIL CRAFT

In order to break speed barrier and improve seakeeping abilities, hydrofoil craft uses two sets of underwater hydrofoils generating enough lift to take the main hull above the water surface. This craft operates on displacement mode (hullbourne) for slow speeds, while at high speeds it operates on foilbourne mode. The seakeeping is vastly improved as the waves affect only the struts.

Three types of operation can be observed for hydrofoil: platforming, contouring and intermediate response (Fig.1-6). In platforming operation the vessel does not show any significant motion. While at the other end of the spectrum, the vessel follows all the waves on contouring. In practice the hydrofoils designed for the intermediate operation mode.

There are two types of hydrofoil craft: fully submerged and surface piercing (Fig.1-7). Fully submerged foils operate entirely below the water surface. An automatic lift control system controls the lift generated on the foils which can be operated with flaps, foil incidence control or air stabilisation.

Three types of submerged foil arrangement system are observed: Canard, aeroplane and tandem configurations (Fig.1-8).

Foil retraction systems enable hydrofoil craft to operate in hullbourne mode in shallow water, However this system increases the cost and weight. Strut and foil design is important aspects of these craft due to low resistance, strength and cavitation problems. Fully submerged hydrofoils up to 320 tons, 65m length and 12 m width existing craft can operate about 40-50 knots.

Surface piercing type of hydrofoil has inherent stability as the ship heaves down a larger area of foil produces lift hence suppressing the motion very quickly. Most of them are in tandem configuration operating speeds are about 30-40 knots foils are less complex. Seakeeping (harsh ride) is improved by air emission systems to control the lift. Main application area is commercial (passenger ferry) transportation although few research and military craft exist. In hullbourne mode the wetted surface from the foils show disadvantages.

In general fully submerged foil hydrofoils shows better seakeeping as the wave loading does not effect the dynamic lift. The vertical motions of surface piercing will be about two-four times more than fully submerged foils.

5. AIR CUSHION VEHICLE (ACV) AND SURFACE EFFECT SHIP (SES)

Air cushion vehicle raises itself over the water surface by supplying air pressure between water surface and the craft. Two types of air-cushion vehicle can be observed: ACV, SES (Fig.1-9).

ACV (Air cushion vehicle) has air cushion that is enclosed by flexible skirts made up of many components called "fingers" touching water (Fig.1-10). These vessels may be propelled by jets, water propellers or air propellers. If air propellers are used ACV is an amphibious vehicle.

ACVs are operated at calm water speeds of up to 70 knots and up to 200 tons for commercial and military operators. Main disadvantage of ACV is the speed reduction in a seaway.

Skirt design is an important aspect of this kind of craft. The wear and shape of the skirt must be planned in detail. Weight sensitivity, aircraft design, course keeping, directional stability, watertight integration are main design parameters.

Surface effect Ships (SES) (Fig.1-12) differs from ACV in that rigid sidewalls plus bow and stern seals are used to contain the air cushion rather than one flexible skirt. Hence SES is not amphibious. Supported by air-cushion lift and hydrodynamic and hydrostatic lift generated by the sidewalls. The percentage of hydrostatic lift varies among the craft. When cushion pressure is atmospheric, SES behaves like a catamaran. The sidewalls can give room for water propellers or waterjets.

Active and passive lift systems can be used to maintain cushion pressure. In the active lift systems a "ride control" system is integrated to reduce the motions and accelerations of the vessel either by changing the speed and/or pitch of the lifting fans or by air leakage control on the sidewalls.

6. HYBRID VESSEL

A number of hybrid types that make use of a combination of the aerostatic, hydrodynamic and hydrostatic lift are investigated. Although a viable design is not produced yet, more research is currently on progress. Fig 1-11 shows possible hybrid vessel configurations. There is an interest on hydrofoil air cushion ships to obtain more efficient ride control system. Other possible configuration is to use submerged cylindrical hulls on hydrofoils to achieve a longer range. However the most successful configuration is hydrofoil catamaran used in commercial market today.

7. POTENTIAL MARKET FOR ADVANCED MARINE VEHICLES

Not all marine transportation can benefit from high speed. So the question arises for a given mission whether or not to build an n AMV instead of conventional vessel to be more efficient or more economical.

If shipping is considered as an overall subject the following business areas for marine vehicles can be identified for economical operation.

- Transportation
- Leisure
- Oil Production and Support
- Mineral Extraction
- Military
- Scientific
- Cable/pipe laying

If the market need for all these types is investigated scientific, military, leisure and transportation areas show potential to benefit from AMV concepts due to their speed and seakeeping improvements.

Scientific: There is no evidence that there may be desire for speed increase. However seakeeping improvements are highly desirable for stable working.

Leisure: many leisure boats are too small for AMV concepts (except semi-planing, planing monohulls). But cruise liners may benefit from AMV designs.

Military: An important potential market for AMV designs is the military applications, However selection criterion is vastly variable.

Transportation: The biggest segment of the shipping market, therefore transportation is the largest potential market for AMV.

Ever increasing speeds in the transportation, especially on air passenger transportation, forced improvements on sea transportation. The main improvement areas are reliability, comfort, safety, cost and most importantly speed. A review of this market reveals two possible areas of potential applications:

Shorthaul Passenger/RoRo
Longhaul Passenger/RoRo/Cargo (container)

In the military craft, improved seakeeping qualities of AMV are utilised on helicopter platform ships, patrol boats in order to utilise speed advantage of AMV.

8. SIZE SPEED AND POWER

Gabrielli and Von Karman formulated a method to compare different means of transport. The power per unit weight is chosen as measure of merit. Nowadays the measure of merit is taken as a product of weight and speed divided by installed power. It is plotted as a function of speed (Fig.1-12). The higher curves represent the more efficient means of transport. According this argument, five zones can be described.

- When the speed is not important
  . Tankers, Bulk carriers (VLLC)
- Speeds up to 25 knots
  . Tankers, bulk carriers (VLLC)
  . Other merchant ships
  . Warships
  . Horse
  . Bicycle
  . Human
- Speeds from 25 to 60 knots
  . Airships
  . Automobiles
  . Hydrofoils
  . Air-cushion vehicles
  . Planing craft
- Speeds from 60 to 150 knots
  . Airships
  . Automobiles
  . Air-cushion vehicles
  . Hydrofoils
  . Helicopter
- Above 150 knots
  . Jet plane

Fig 1-13 describes the transport efficiency in calm water for the marine vehicles of different sizes. There is an important effect of vehicle size on the efficiency especially when viscous resistance is the prime part of the resistance.

. Up to 30 knots conventional displacement ship has the highest efficiency
. 35 to 60 knots hydrofoil is the most efficient vessel
. Above 60 knots ACV and SES have the highest efficiency
. 30 to 40 knots SWATH ship has the prospect of being most efficient vessel
. Planing boats has the lowest efficiency
. Below 45 knots ACV and SES has very low efficiency.

It must be considered that SWATH and Hydrofoil ships will show better efficiencies due to low speed loss in a seaway. ACV and SES will actually be somehow less efficient in waves.

In this efficiency diagrams the propulsion efficiency is also included. Typical maximum efficiency envelopes for propulsors is given in Fig. 1-14. Up to 40 knots conventional subcavitating propellers are the most efficient propulsors. Between 40 knots and 70 knots, others means of propellers, i.e. transcavitating and semi-submerged propellers, show potential. And at the top end of the graph air propellers are the most efficient. The common propulsor waterjet shows a less efficient envelope. However easy of use and mechanically simplicity is the reason behind the success of the waterjet.

9. BEHAVIOUR IN A SEAWAY

Two aspects with regard to the behaviour in a seaway are especially important for fast vessels, i.e. magnitude of vertical accelerations and the potentiality of the vessel to maintain her speed and course in waves.

The so called ride quality is mainly determined by the magnitude of the vertical accelerations. Some AMVs have ride control systems such as antipiching foils, air-cushion control systems. This feature makes a straightforward comparison quite difficult.

It is observed that the vertical accelerations are quite dependent on the effective height of strut height in a hydrofoil and cushion height in a Hovercraft. Vertical accelerations can be compared for vessels having a ratio defined as wave height divide by effective height ($h_W/h_S=0.5$) (Fig.1-15). For the fully submerged hydrofoil vessel acceleration will be in the range of 0.03g to 0.04g. SES vessel with a ride control this will be about 0.07g. Surface piercing hydrofoils have acceleration about 0.1g. And ACV's accelerations lie within the band of 0.15g to 0.5g.

For the other types of AMVs effective height can not be defined, instead a ratio of $h_W/V^{1/3}$ can be defined where h_S will be about 0.61 $V^{1/3}$.

In SWATH vessels with ride control vertical accelerations are about 0.15g, while planing hull has about 0.35 g.

Hence AMVs can be put into a sequence of
- Fully submerged hydrofoil
- SWATH
- SES with ride control
- Surface piercing hydrofoil
- ACV without ride control
- Planing vessels

Second important factor is the speed loss in a seaway, which is directly related to slamming, added resistance, deck wetness and ship motions. In the case of SES and ACV the air loss below the hull or skirt must be taken into account as well. Fig 1-16 shows speed loss for a variety of AMVs.

This figure indicates the best AMVs keeping its speed is hydrofoil and SWATH and the worst are ACV and SES. Planing hull and displacement shows intermediate response. By putting vessels into sequence

- Hydrofoil and SWATH
- Displacement vessels
- Planing ship
- ACV, SES

10. STRUCTURES

Advanced marine vehicles without any exception are weight limited. Hence the materials, structural design, weight optimisation are important aspects of the design.

Steel is the main material for conventional vessels. SWATH concept above 1000 tons can make use of steel. However smaller SWATH and other advanced marine vehicles must make use of lighter materials. Aluminium, although expensive, is used extensively. Glass reinforced plastic and carbon reinforced plastics are used in small vessels.

Weight densities of AMVs are given in Fig.1-17 for given material. SWATH appears to be only AMV to cope with steel weight.

11. ENGINES

Gas turbine and high speed diesels appear to be the winner due to their high power to weight ratios. The bigger ships will definitely use gas turbines. Slow and medium speed diesels are too very for AMV applications. A comparison among AMV types is not sensible.

12. COST

On the basis of the available data Fig 1-18 is derived. This figure clearly indicates conventional ship is clearly the cheapest on the comparison of per ton basis. SWATH vessels show only about 20 to 100 % increase. The planing vessels are up to 3 times more expensive. However the most expensive cases are hydrofoils, ACV and SES ships. Although the hydrofoil is expensive is very expensive due to its foil systems and control mechanisms it is still cheaper than the ACV and SES. The last two are very expensive due to cost of their fans, and propulsor. Fig.1-19 gives the cost on the basis of speed. In this figure the difference between hydrofoil and ACV can be seen as operating in different speeds.

13. CONCLUSIONS

Some conclusions can be drawn from the comparison of the arguments above.

Below 30 knots the conventional displacement ships are certainly the most efficient and cheapest ships.

SWATH vessel has prospect of having very good seakeeping and being an efficient vessel between 30 and 40 knots.

Between 40 knots and 60 knots, hydrofoil appears to be the solution. However the cost and complex engineering aspects must be considered.

Above 60 knots both SES and ACV are the best though they have to reduce the speed very fast in a seaway.

The comparisons can only be meaningful, if they are made for a given mission. The comparisons based on displacement can be misleading. E.g. a helicopter patrol boat may need some deck space, and a stable platform. And this can achieved by a 100 ton SWATH or 200 ton monohull. Hence all the comparisons must be made between these two vessels. A preliminary design tool to explore the concept design of all the AMV types is necessary to make meaningful comparisons.

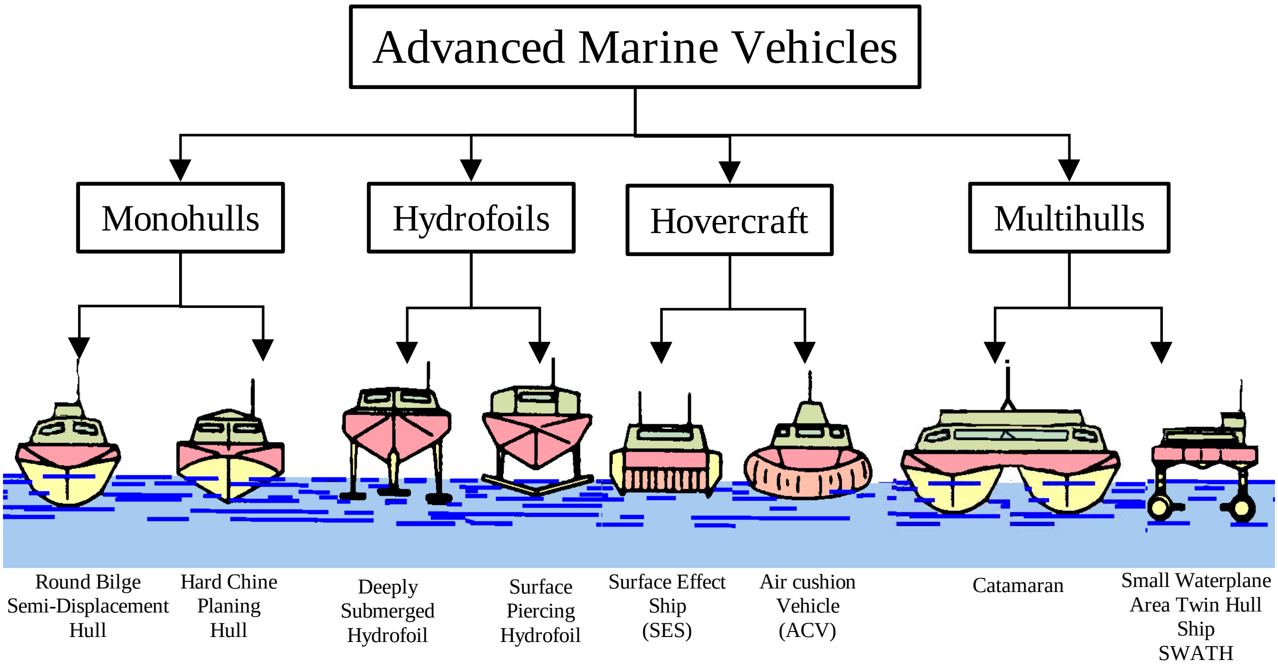


Figure 1-1: Types of Advanced Marine Vehicles

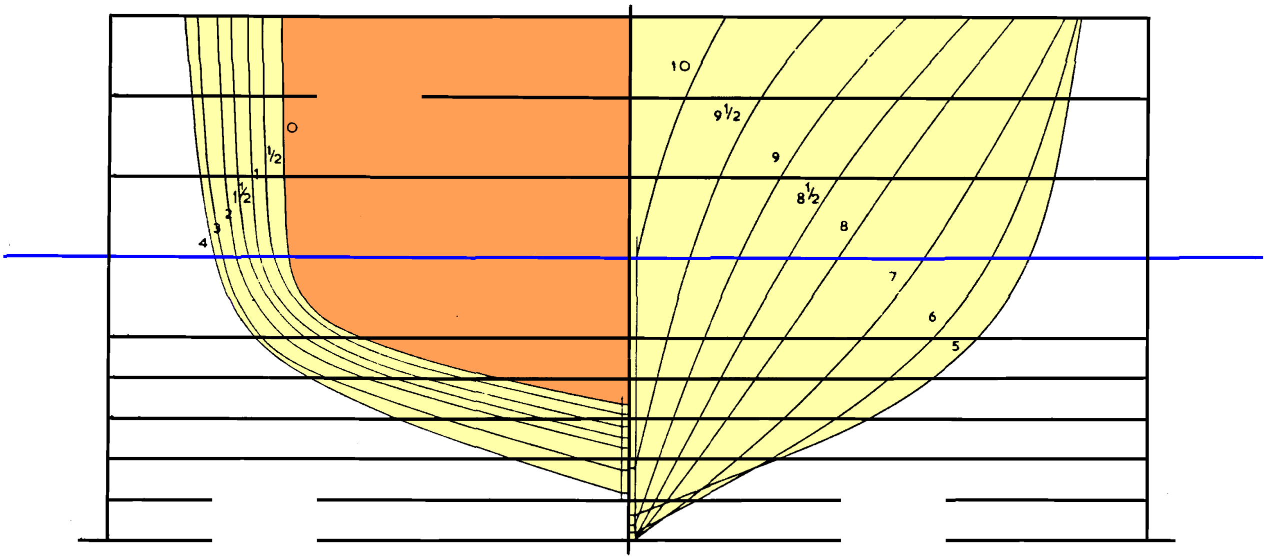


Figure 1-2: High Speed Semidisplacement Round Bilge Hull Form

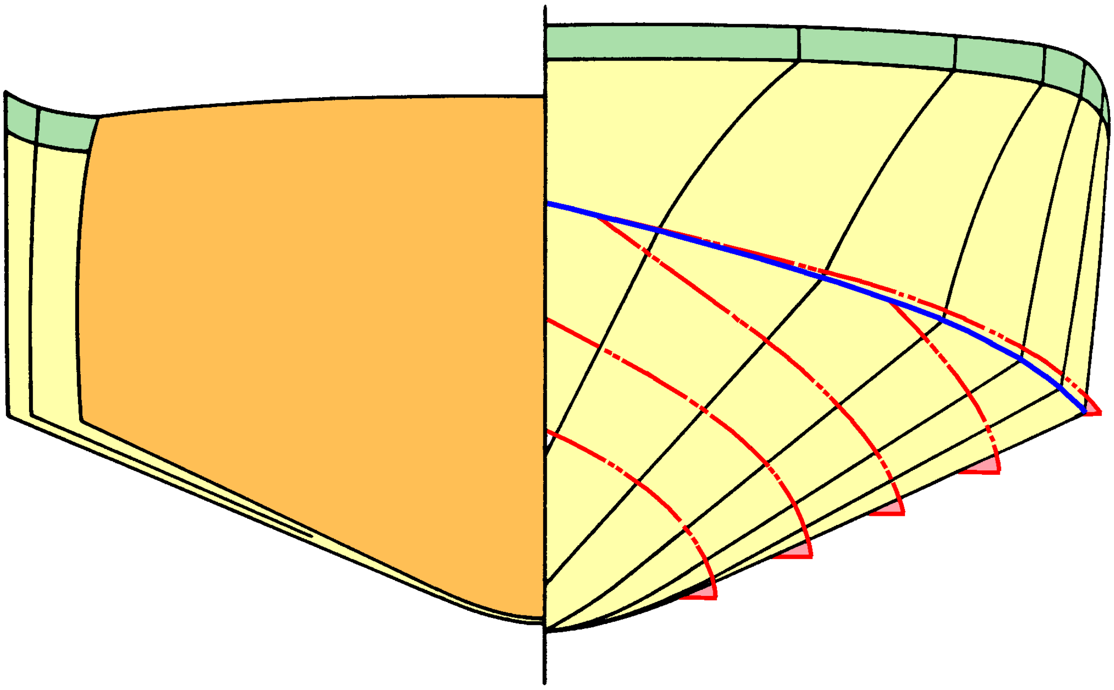


Figure 1-3: High Speed Hard Chine Form

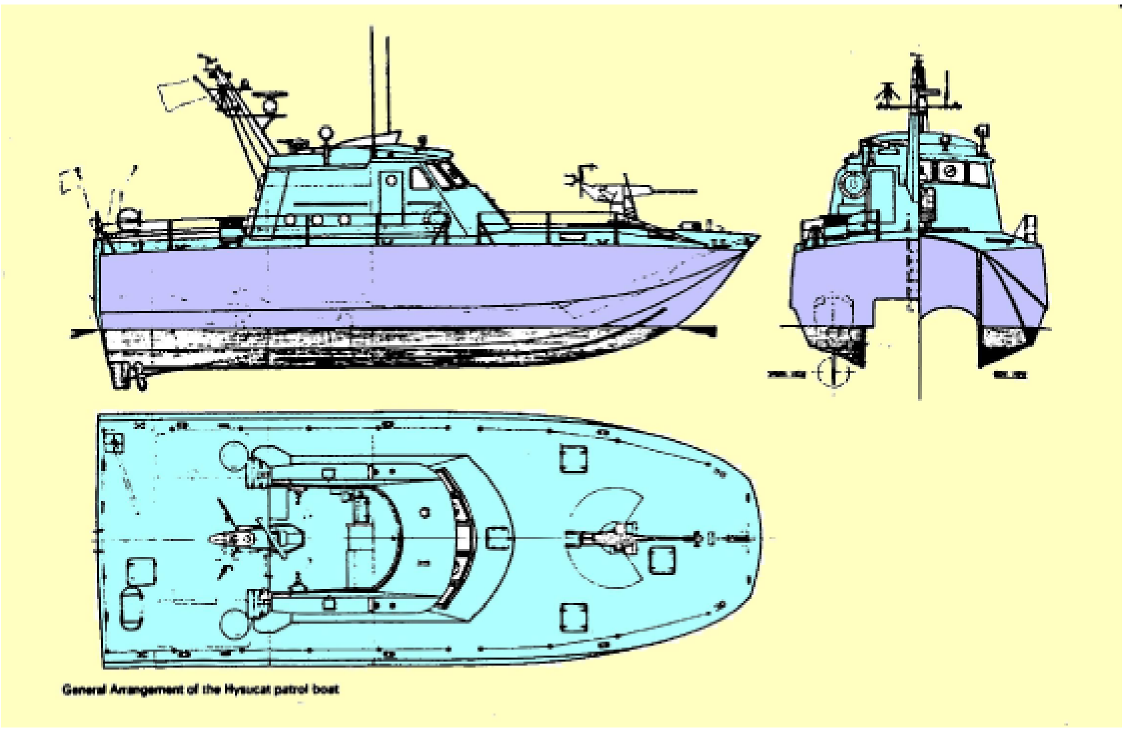


Figure 1-4: Asymmetric Catamaran

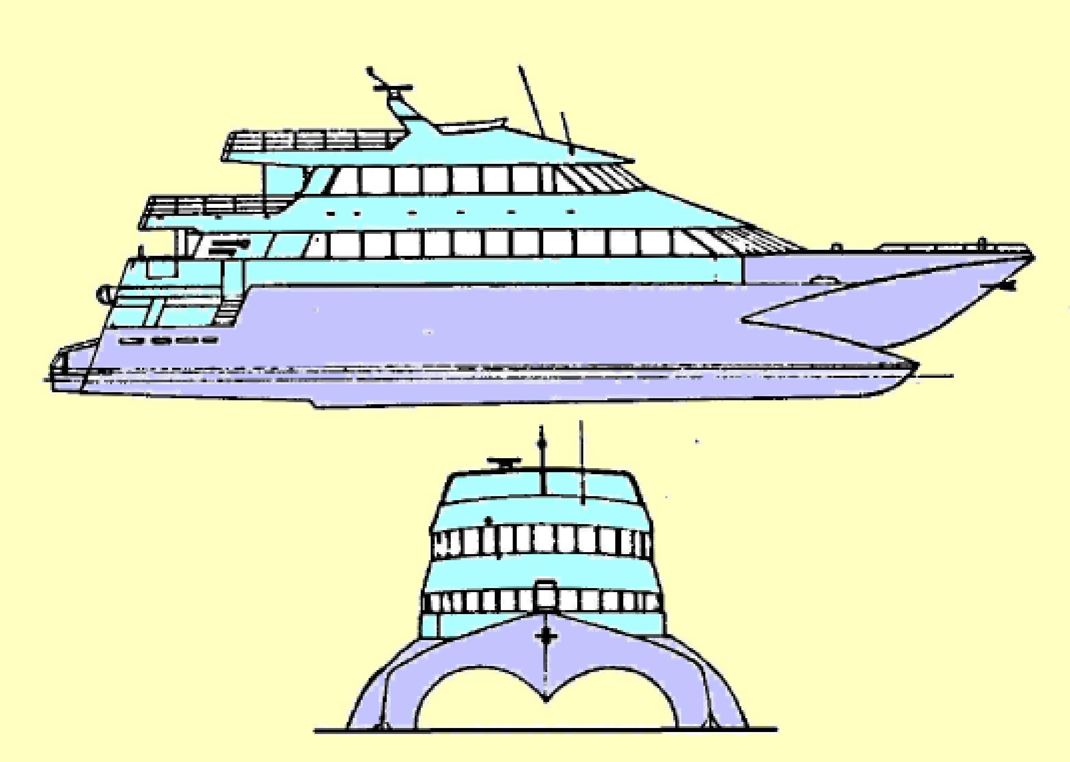


Figure 1-5: Wavepiercing Catamaran

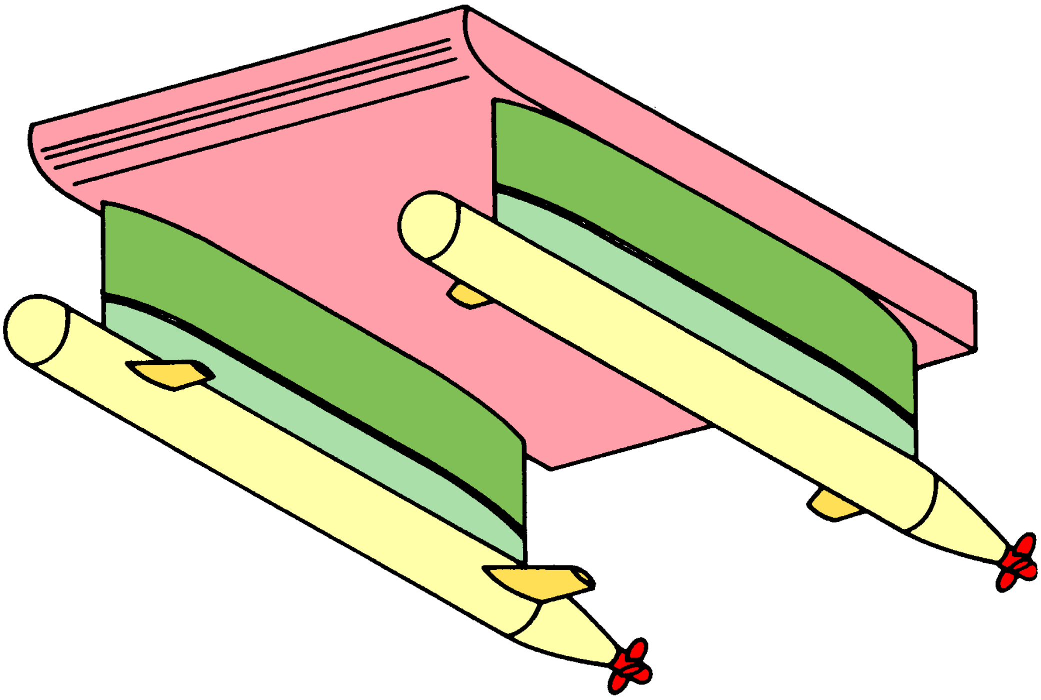
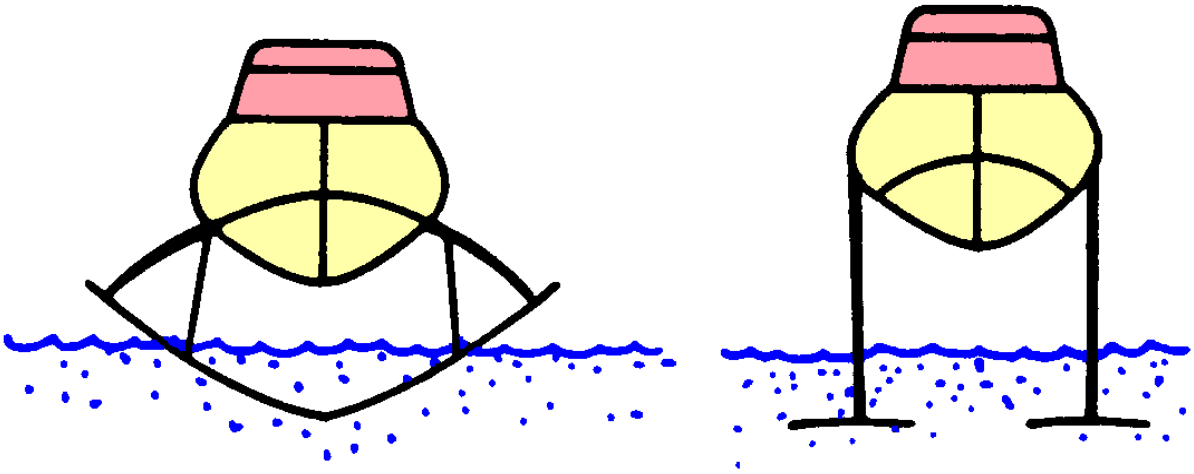


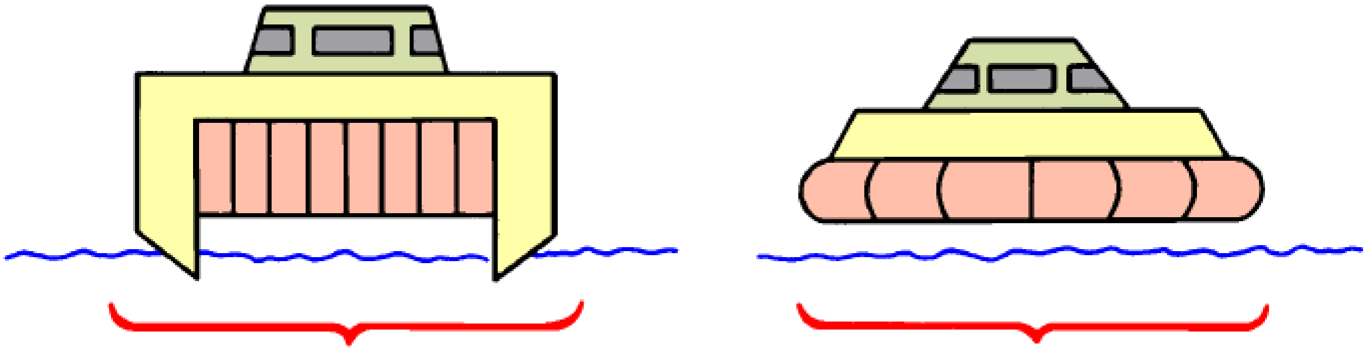
Figure 1-6: SWATH



Surface Piercing

Fully Submerged

Figure 1-7: Hydrofoils



Surface Effect Ship

HoverCr

Figure 1-8: Air Cushion Vehicles

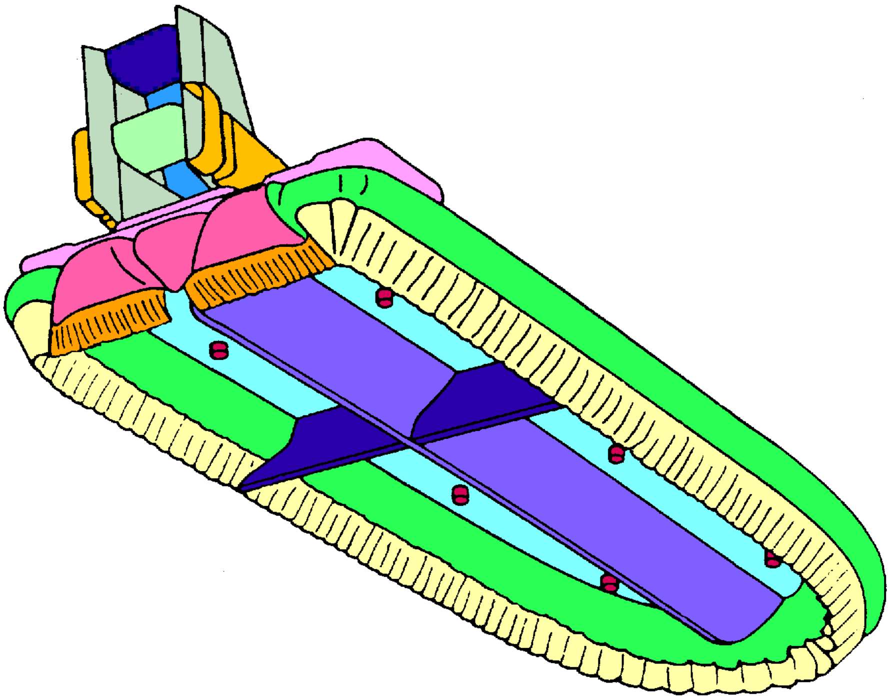


Figure 1-9: Hovercraft

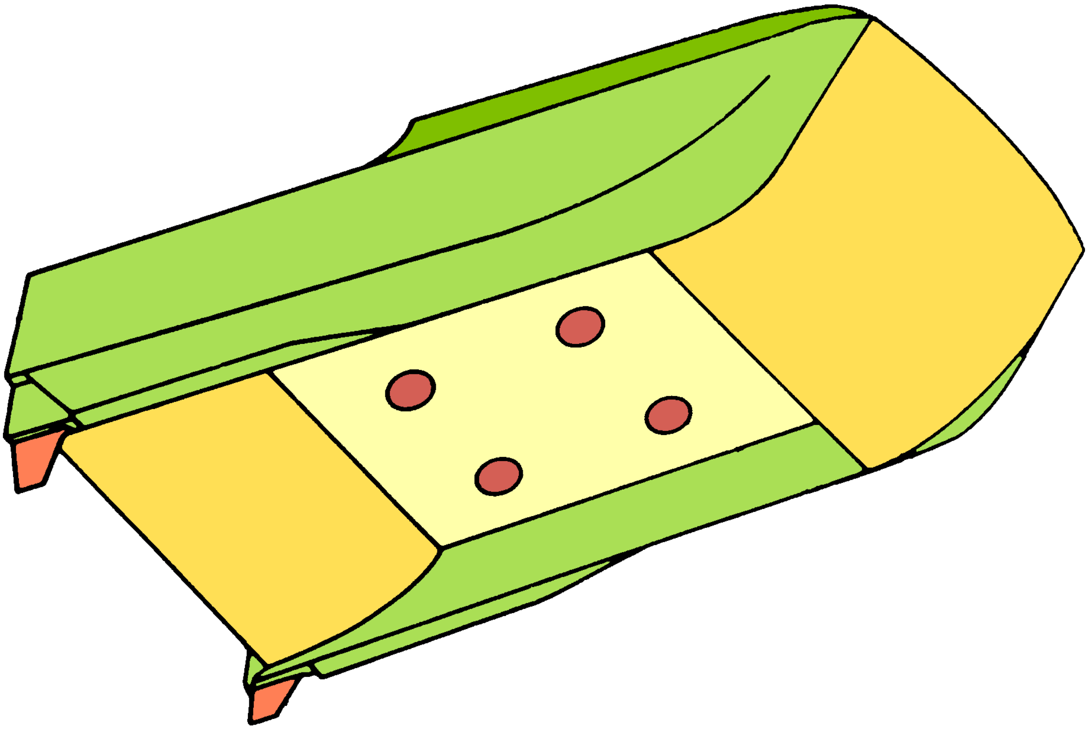


Figure 1-10: Surface Effect Ship

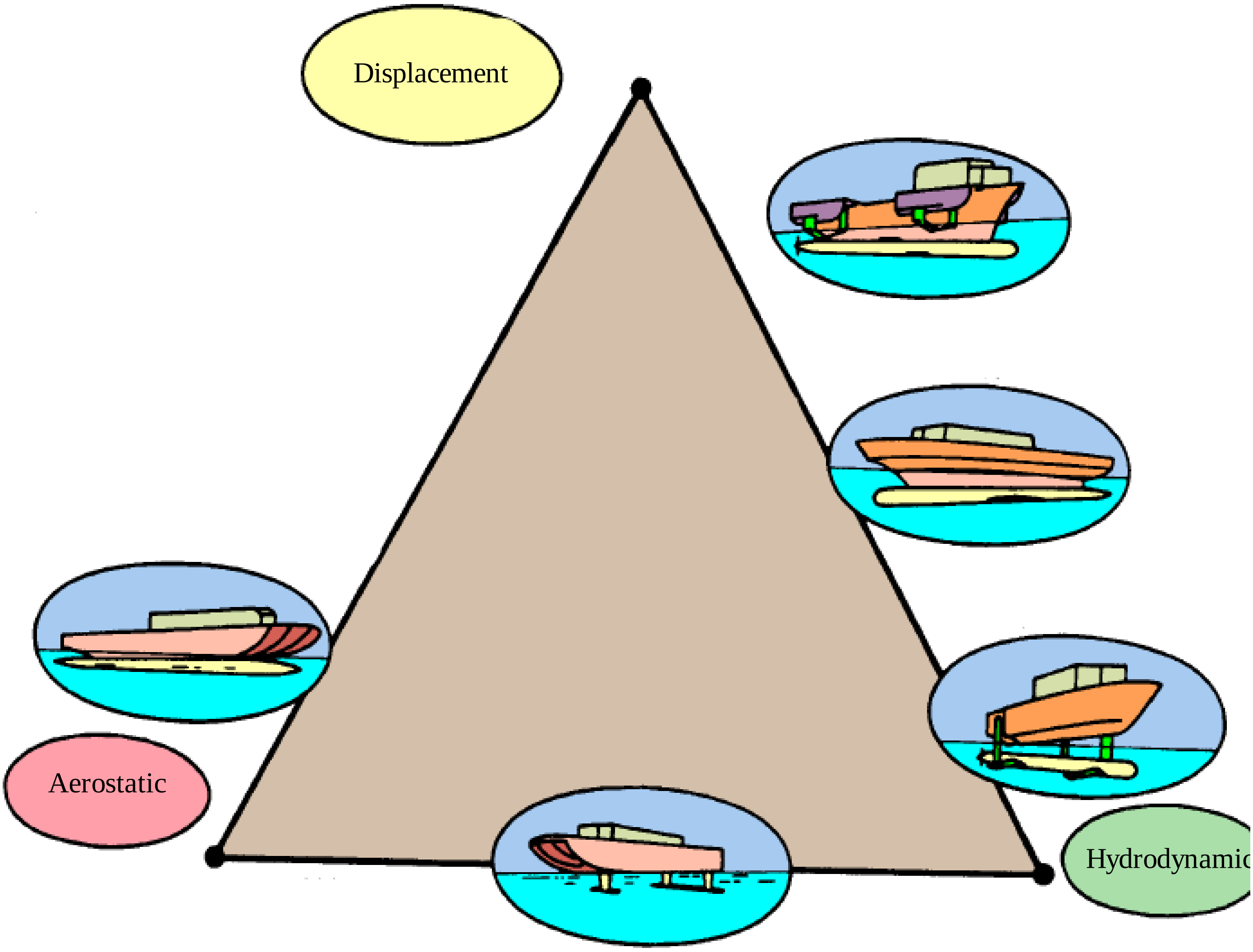


Figure 1-11: Types of Hybrid Ships

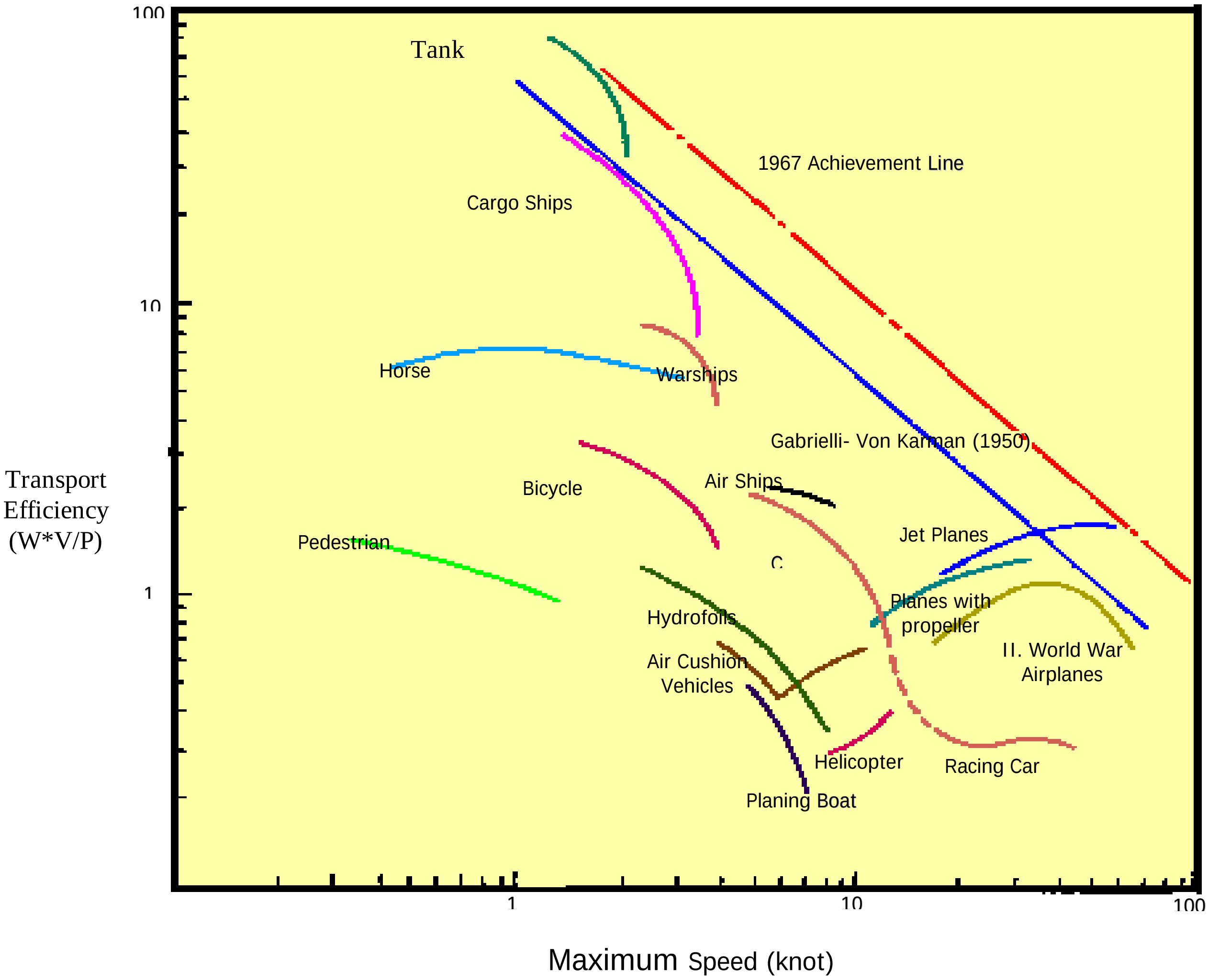


Figure 1-12: Efficiency of Various Transport Types

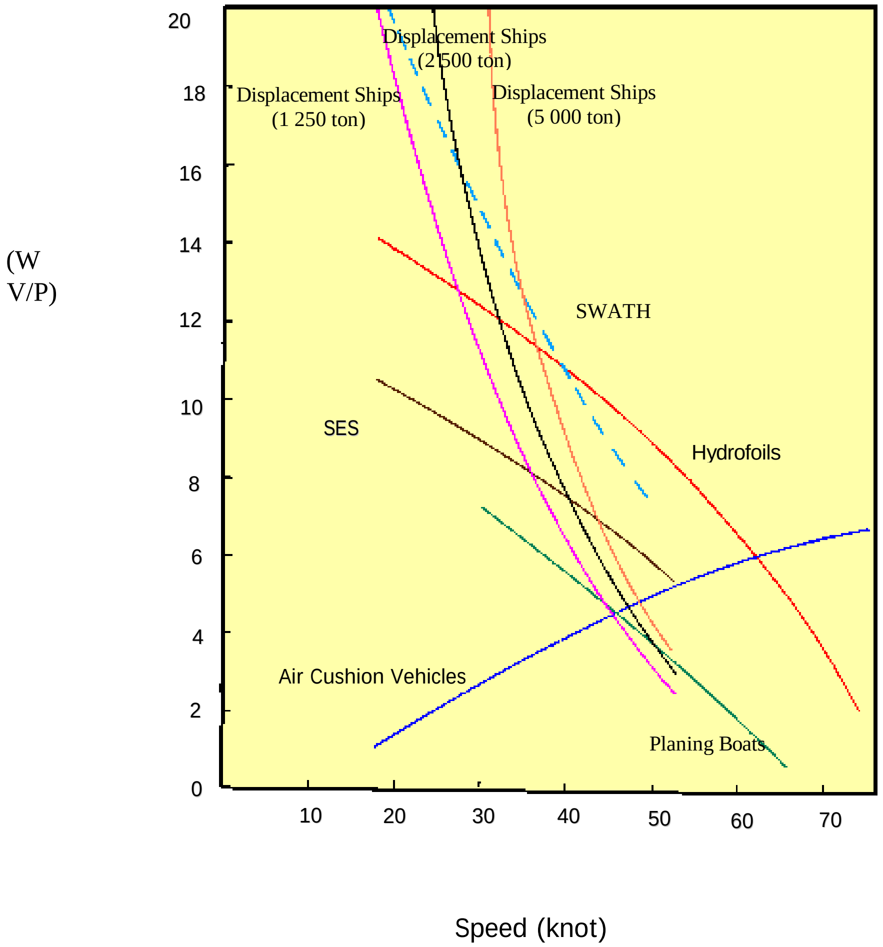


Figure 1-13: Efficiency of Advanced Marine Vehicles

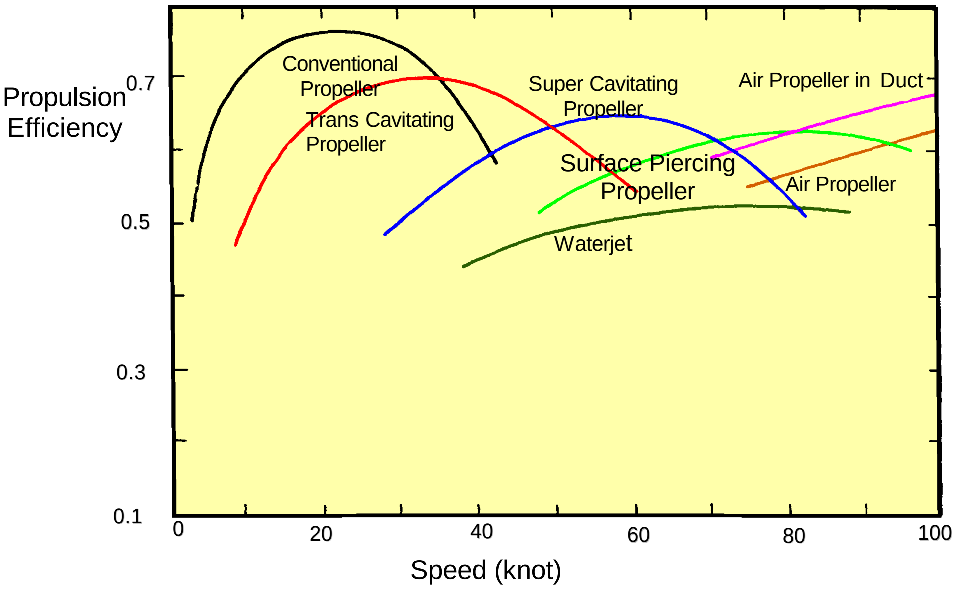


Figure 1-14: Efficiency of various possible propulsion devices

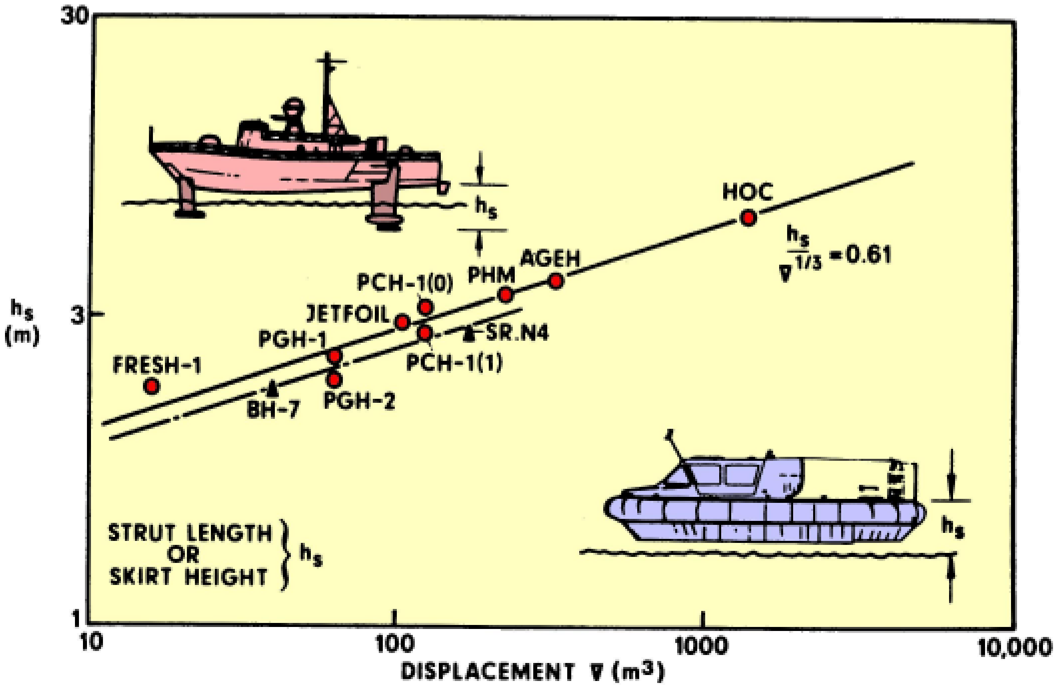


Figure 1-15: Relationship between effective height above water and craft size

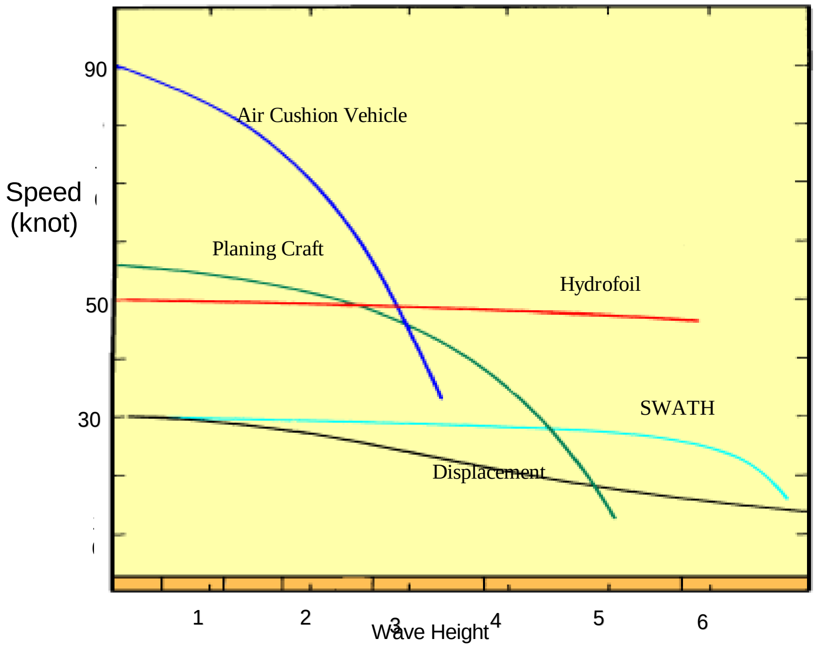


Figure 1-16: Maximum sustainable speed for Advanced Marine Vehicles

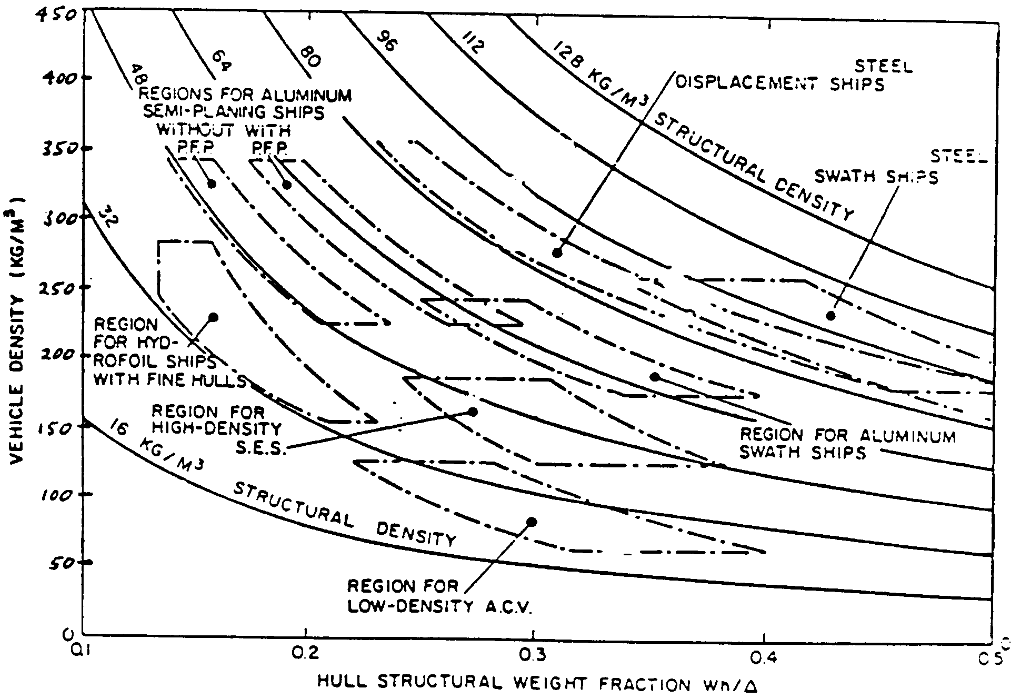


Figure 1-17: Vehicle Densities

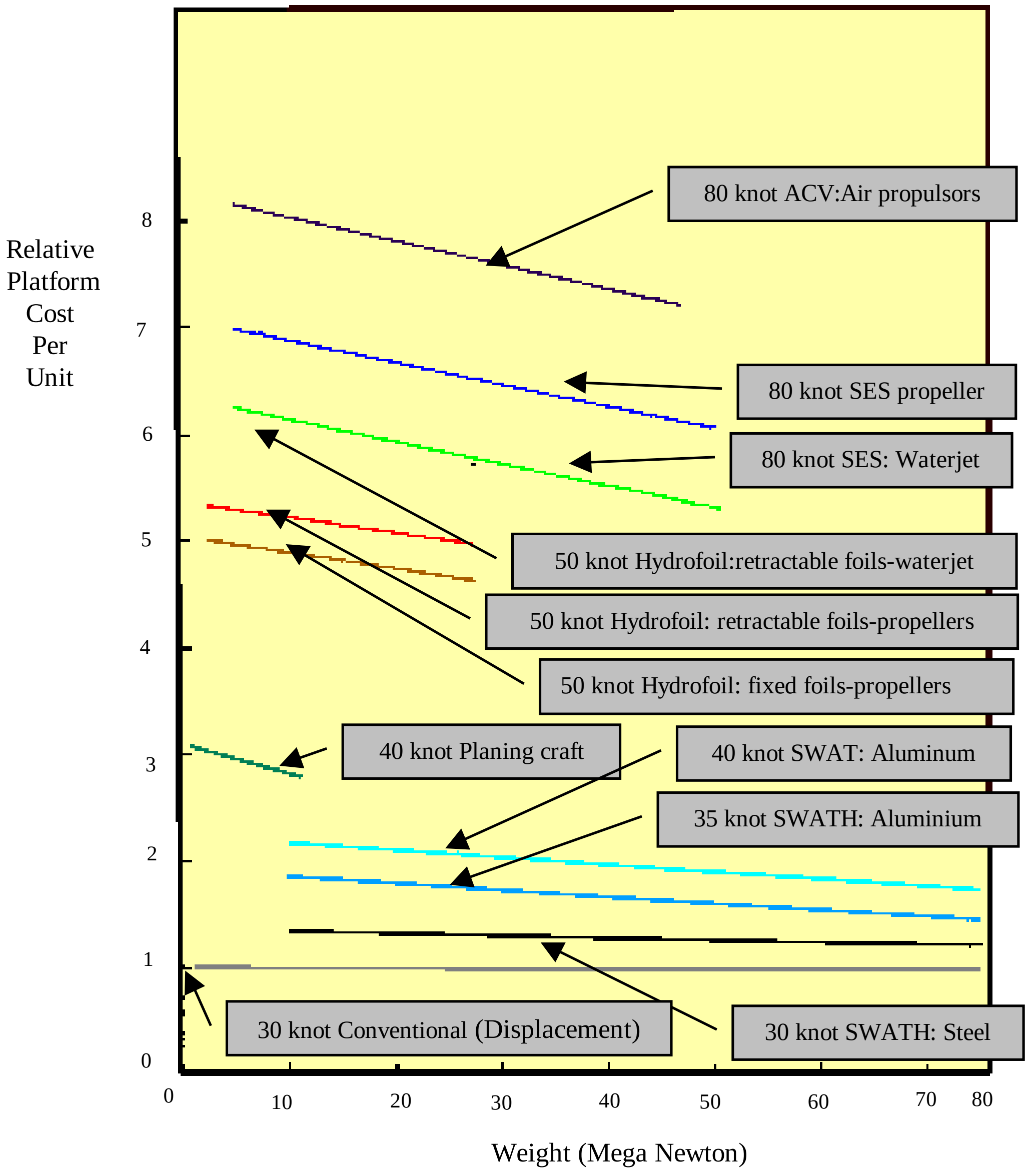


Figure 1-18Relative Building Cost of Advanced Marine Vehicles

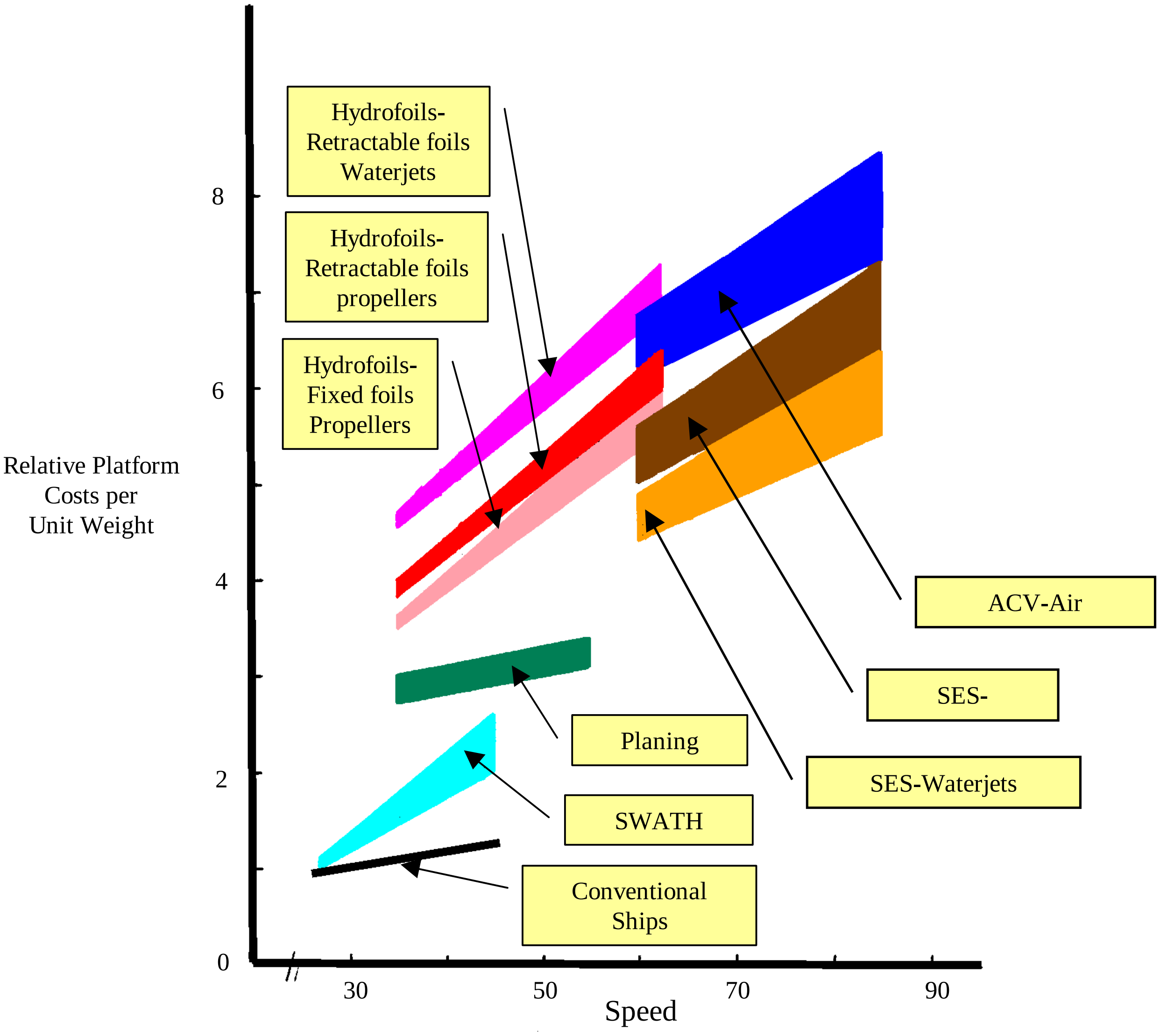


Figure 1-19Relative Building Cost of Advanced Marine Vehicles

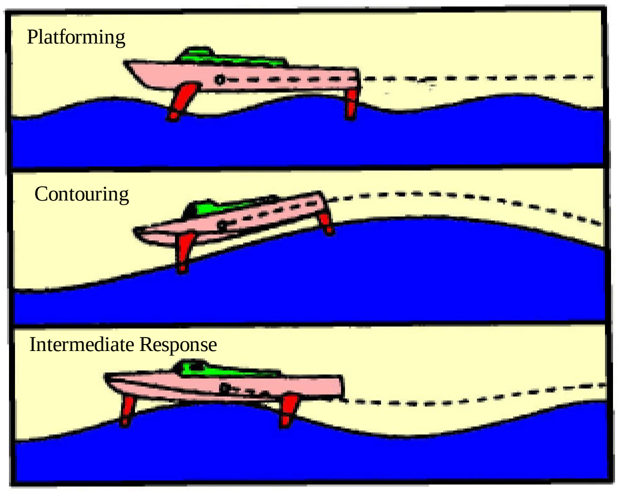


Figure 1-20. Modes of Operation

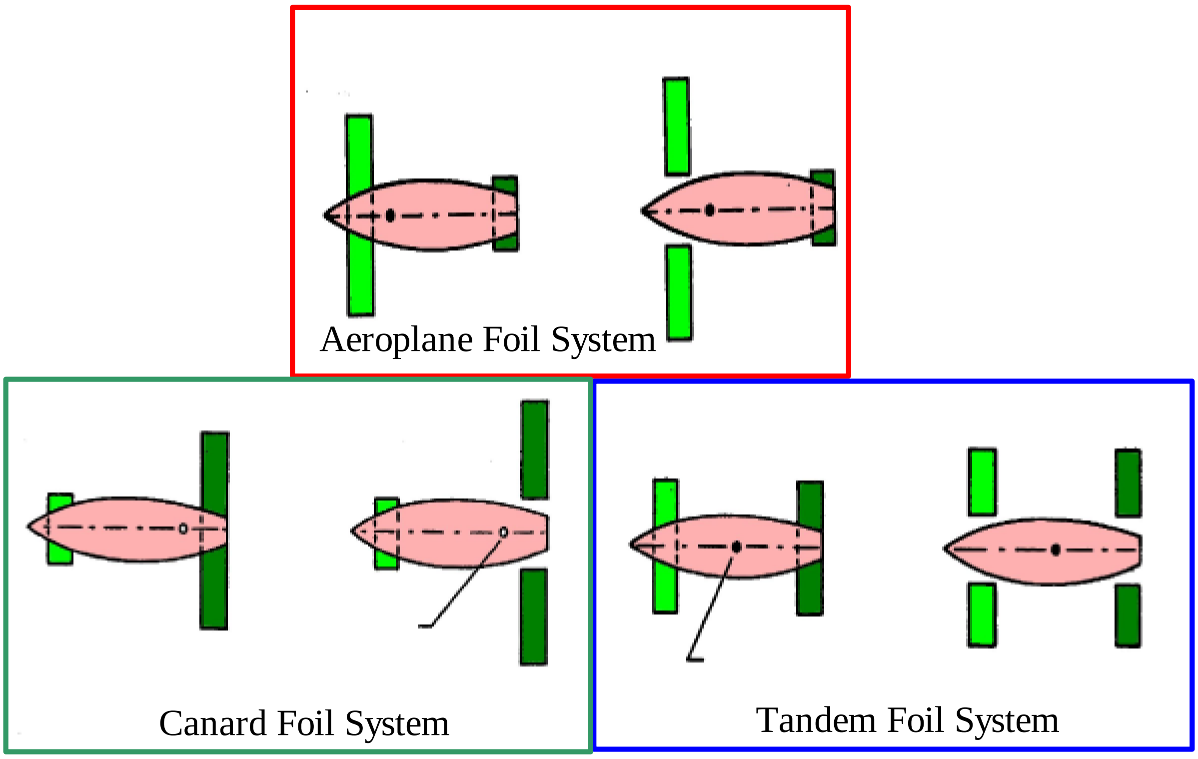


Figure 1-21: Foil configurations for hydrofoils

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