16

Power unit selection

16.1 Introduction

An ACV or SES requires power for propulsion, air cushion and for electrical and other systems on board. Depending on the craft size, all the needs may be supplied by one motor, or one or more units may be installed for each individual function.

The first step towards power unit selection is to identify the power requirements for each of these functions. A methodology for this is given in section 16.2. Selection of the optimum power unit for a particular SES or ACV also needs consideration of a number of parameters, as discussed below.

Consistent with the approach throughout this book, we approach power unit selection from a 'user' point of view, with a summary of aspects relating to use for fast marine craft. Detailed background on marine diesel and gas turbine engines can be found in textbooks such as ref. 117.

Power units for ACV and SES should be selected and rated with care. A touch of conservatism is advised! Optimism has in the past resulted in craft with limited power margins, and operation at or above MCR (Maximum Continuous power Rating) leading to much reduced MTBO (Mean Time Between Overhaul). Negative consequences include higher noise, vibration and fuel consumption. Care should also be exercised in interpreting engine manufacturers power ratings to ensure that the appropriate duty cycle is being used for reference. In order to obtain a reasonable time between overhauls, it is important for the ACV or SES designer to clearly identify the average cycle time between starts, and the times at service speed, idle, etc., based on the craft intended service.

Total system weight

The ACV/SES designer's primary target is minimum total installed weight for the power unit system. This includes the engine itself, the transmission system of gearbox and shafting, auxiliary systems, enclosures and skid mountings, and the fuel payload required for the craft mission. By achieving this, the useful payload can be maximized. Including the fuel takes account of the craft range necessary for its service requirement and the engine fuel efficiency. Initial weight estimates have been outlined in Chapter 11.

Fast marine craft have been designed and built with steam turbines, nuclear power plant, electric motors, gas turbines and reciprocating engines fuelled by gasoline and diesel fuel. Steam and nuclear power plant can be designed for very high power ratings, but are not suitable for small craft. The same applies to electric drive, which is normally powered by a steam generator system. While project proposals have been made for large ACV and SES with nuclear power plant for example, so far, the engines which have been successfully applied are gas turbines and diesel engines, and gasoline engines on light ACVs

In most countries regulations for passenger-carrying vehicles prevent the use of fuel with a flashpoint of lower than 35°C, consistent with paragraph 7.5.8 of the IMO High Speed Code [118]. Diesel fuels normally have flashpoints between 65 and 120°C, kerosene and gasoline 33–50°C. For fuels with flashpoint below 43°C fuel tanks have to be physically separated from machinery spaces and inboard of shell plate and bulkheads which might be damaged in a collision.

Gasoline engines (referred to as petrol engines in Europe) are suitable for small recreational and utility craft, but due to the volatile nature of gasoline, are not generally suitable for commercial vehicles. This leaves gas turbines and diesel engines as the primary candidates for SES and ACVs. Marine gas turbines are lower in weight than diesel engines, but in general have higher specific fuel consumption. For endurances longer than about 12 hours the total installed weight for a high speed diesel system is least, as shown in Fig. 16.1.

Where the total installed power required is very high, for example for large SES, the only practical option is a gas turbine system. While multiple high-speed diesels could be linked to the same output shaft, this would add to the weight with additional

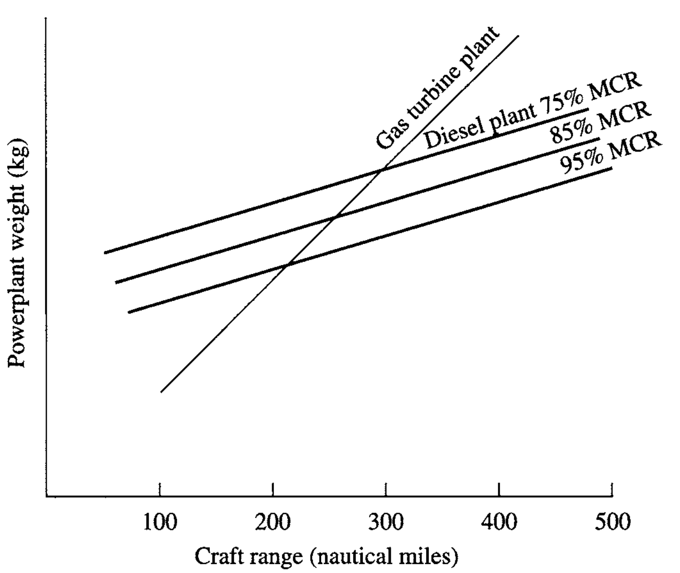


Fig. 16.1 Total installed weight vs craft range for different power settings.

gearboxes and shafting. Craft range for large SES is therefore limited by the fuel load which can be carried without reducing the payload for goods or passengers below the designer's target.

Engine power ranges

Engines are available in a limited range of power ratings and so the designer often has to adjust craft sizing or mission parameters to optimise around the chosen motor(s). Figures 16.2 and 16.3 show examples of diesel and gas turbine engines which have been used for ACV and SES to date.

Engine suppliers are constantly improving their products, mainly in response to demands from the industrial and marine markets which procure many thousands of units each year. ACVs and SES are too small a market to justify more than minor adjustments to the base product.

Multiple engines

Except for craft smaller than 1000 kg payload it is generally convenient to install multiple engines. This has an additional safety advantage of redundancy in the case of failure, so long as the craft design takes this into account by ensuring an acceptable emergency performance with one engine only.

It is normal on medium-size craft to install dedicated diesel motor/generator sets for auxiliary power. Dependent on the range of services required, these motors may be duplicated. Starting power is by battery, which is also used to supply the emergency power system on board an SES or ACV. Generator sets on an ACV need to be air cooled, or liquid cooled by a closed circuit system. The latter type is much quieter, but has a weight penalty. SES can use open circuit cooled units, saving the weight of the

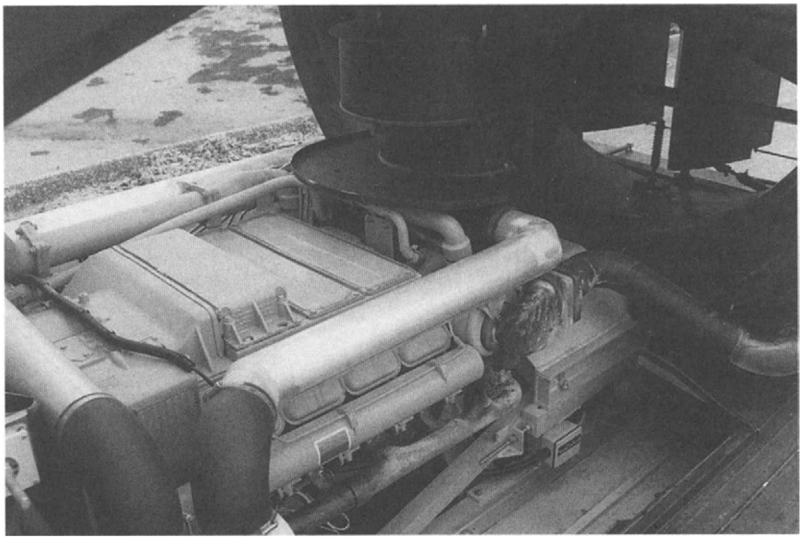
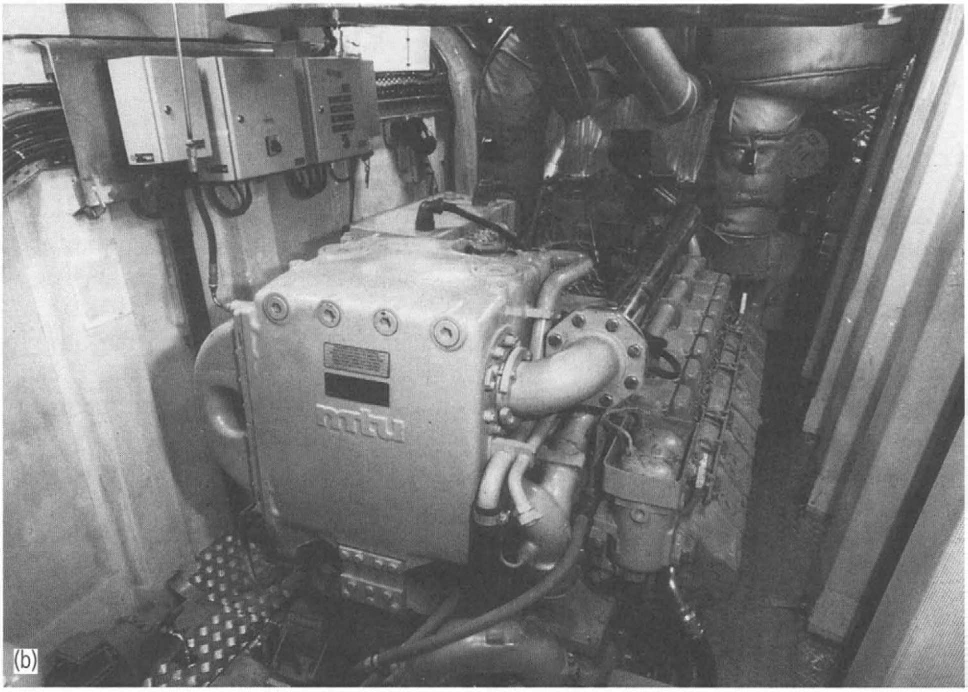


Fig. 16.2(a) Aircooled Deutz diesel installed in Griffon 1500 ACV.



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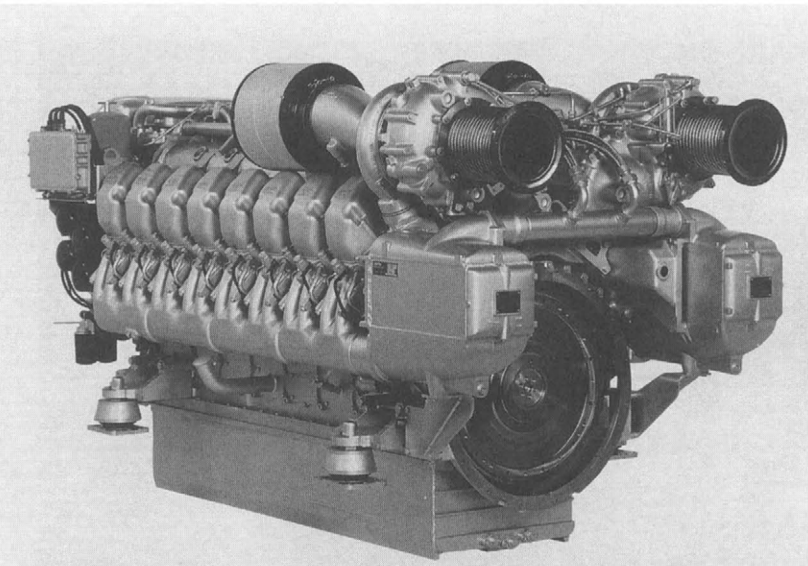


Fig 16.2 (b) MTU TB 396 installed in an SES side hull; (c) MTU 4000 V16 diesel engine.

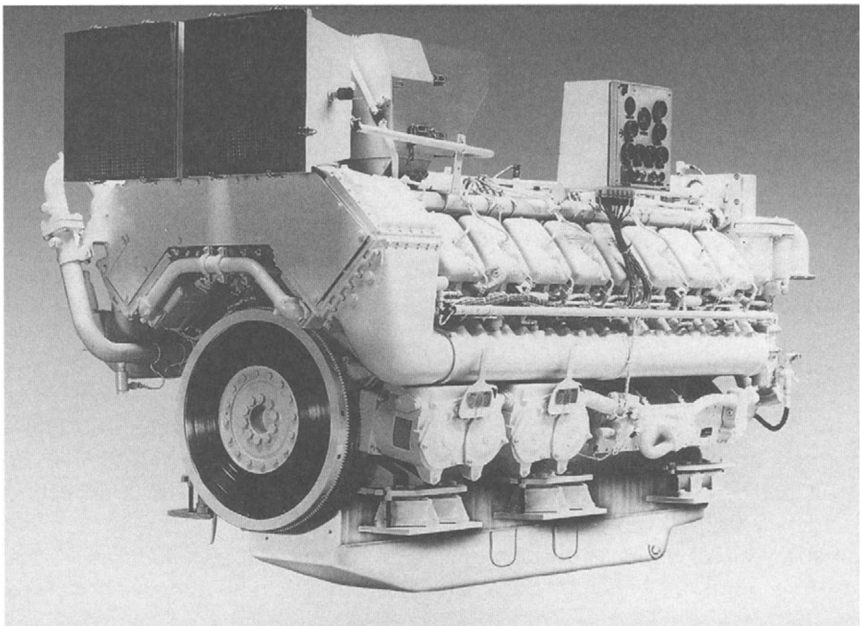


Fig. 16.2(d) Deutz MWM TB 32 V16 water cooled diesel.

heat exchanger, at a penalty of introducing a small drag component from the cooling water intake, and the need to use specifications for the cooling system and generator which are corrosion resistant to sea water.

Above the powering range where a single engine can supply the power for propulsion, it is convenient to install twin propulsion systems. Large SES, similar to fast catamarans, sometimes use two engines per shaft for large water jets, or four engines each driving a separate water-jet system.

Until recently suitable lightweight diesel engines were not available for power ratings above about 3 000 kW; this ceiling is now closer to 6 000 kW, so the break point above which gas turbines are the only option is being raised. For large SES, where power installations of 50 000–100 000 kW are necessary, gas turbines are the only realistic option for the foreseeable future and so interest continues to focus on improving fuel efficiency.

Engine operating characteristics

Diesel engines suitable for primary power use on an ACV have been adapted from industrial plant power units, such as the Deutz air-cooled diesel range, or from truck or heavy vehicle power units which have a closed circuit cooling system, for example Caterpillar diesels. Such engines are not normally run at maximum power and so a designer has to be careful to specify the craft operating characteristics at a power rating consistent with the mission. Most diesels will safely run for long periods (more than 3 hours per day) at 85% maximum continuous rated power (MCR), so this is a safe specification. Above 90% should only be considered for 'burst' operations of 30 minutes or less, or emergency conditions. Diesels are flexible in operation from idle at 15–20% maximum rpm up to cruise rating, and so control of lift and propulsion can be by throttle.

Gas turbines are not flexible in their operating speed. They are specified with a continuous power output, which may be varied in a range +10% and −20% approximately. This does not need to be derated for continuous use in ACVs or SES. Outside this range the available torque drops off rapidly. Gas turbine installations therefore need an independent means of thrust variation. ACVs with gas turbine powering generally have variable pitch propellers or fans. SES installed with gas turbines have thrust control systems fitted to their water jets, or variable pitch propellers.

Transmission configuration

A gas turbine has a very low specific mass (mass/kW), but due to the very high rotational speed of the compressor and power turbine wheels (15 000–30 000 rpm), a reduction gearbox is necessary to reduce this to a suitable speed for a propeller, fan, or water jet (500–3000 rpm).

High-speed diesel engines normally operate in the range 1500–3500 rpm. A gearbox is also often required, but with a reduction of 1.5–2.5. This reduction can also be

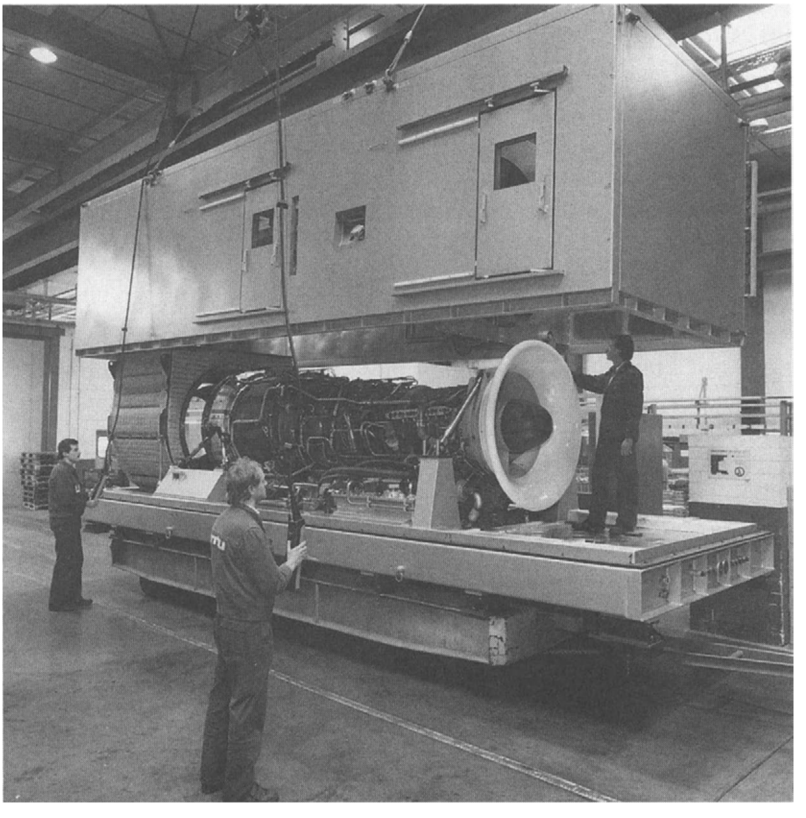
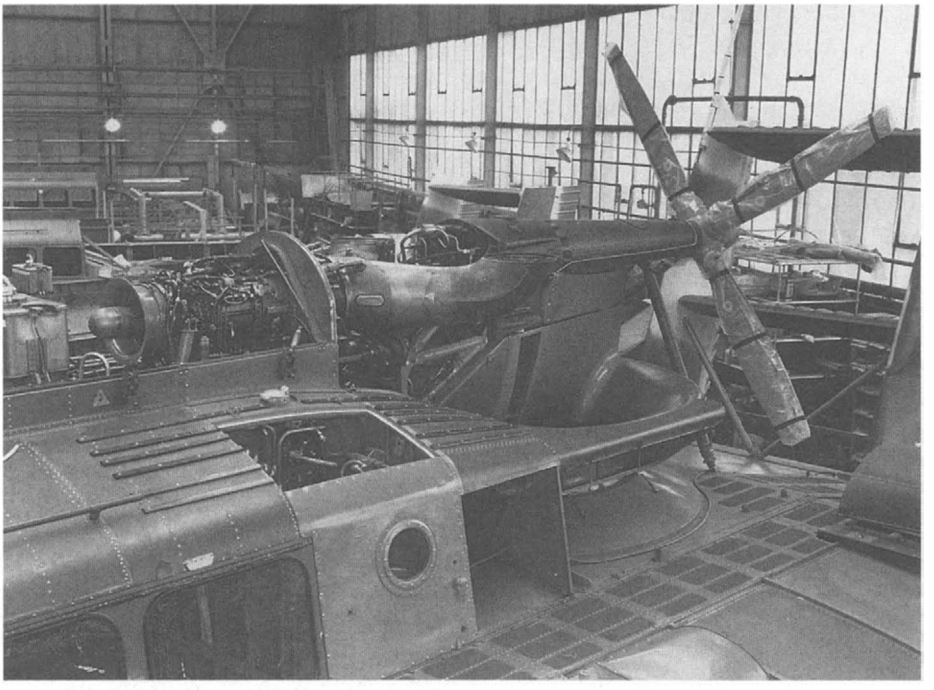


Fig 16.3(a) Kvaemer/GE LM 2500 gas turbine propulsion package.



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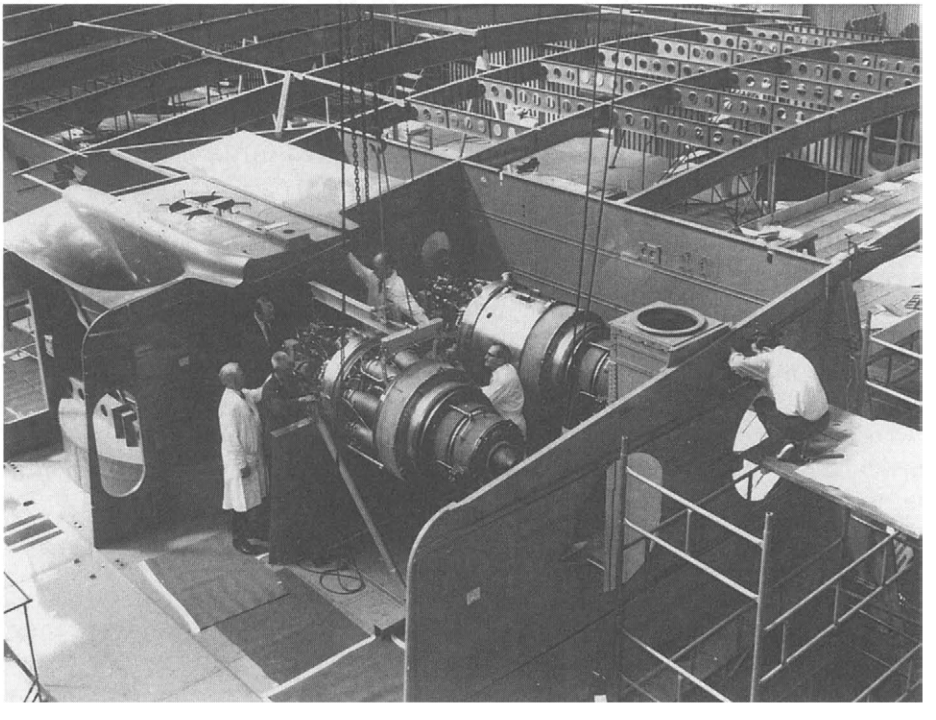


(c)

Fig. 16.3 (b) Rolls Royce Gnome gas turbine installation in SR.N6; (c) Rolls Royce Proteus gas turbine installation in SR.N4.

achieved by using a reduction belt drive for power ratings up to about 600 kW, which is often convenient for lift fans or propellers. Medium speed diesels run at 750–1500 rpm and so for propulsors such as water jets generally no gearbox is needed at all. This is now changing for the largest water jet systems, where a gearbox with a ratio of 1.5:1 is needed.

Each engine may be coupled to both a propulsion device and a lift fan (e.g. the SR.N4 or LCAC), or may be dedicated to a lift or propulsion system (e.g. the AP1.88 or Cirrus SES). Where an integrated system is used, such as on the SR.N4, (see Fig. 6.7), the gearbox and transmission system can be quite complex and has to be designed and constructed specially for the craft. BHC's parent company Westland build helicopters which have similar power trains and so they have the experience and capacity to design and build these. Implementation of bespoke transmission designs of this kind has become very expensive since the mid 1980s and requires a craft build of many units to justify the initial development cost. The trend has therefore been towards using simpler transmission systems based on use of standard marine units.

Gearboxes and transmission systems for diesels are generally also selected from standardized marine or industrial units. The propeller(s) or lift fan(s) therefore have to be designed to fit the available shaft speed and power profile. The advantage is much lower cost, at a penalty of higher weight, as ships are not so sensitive to power train mass.

Some craft have also used hydraulic power transmission on lift systems, where the engine drives a hydraulic pump and the fan is rotated by a hydraulic motor. The Hovermarine HM.2 bow lift fan is one example. This can be useful where, as on the HM.2, the engines are installed at the stern and a lift fan is needed at the bow to optimize cushion flow while minimizing air ducting.

Power loss with increased temperature and engine heating for sub-zero temperatures

Both gas turbines and diesels give reduced power at increased temperature. Typically a gas turbine will give 7% less power for each 10°C temperature increase, while a diesel will reduce by about 2%, compared with the normal standard temperature for measuring power of 20°C. Where a craft is to operate in a hot climate, it is therefore important to specify the engine power rating at the normal operating temperature, rather than standard conditions.

Diesel engines depend on the cooling system, whether forced air, or water, to maintain operating temperature. It is important in this case to specify the engine cooling system based on the maximum expected operating temperature and to obtain guidance from the manufacturer on continuous operating envelope when outside this range. Coolant flow will then be controlled by thermostat for lower temperatures.

At the opposite end of the spectrum, in very cold climates, fuel and engine heaters may be required at least for cold starts. Below about −20°C, special lubricating oils must be used (modern synthetic oils are ideal for this), while below −40°C, in high Arctic or Antarctic, diesel fuel begins to solidify and so must be warmed. Engine powering must be considered for above zero conditions, since for most Arctic logistics applications, summer temperatures will be well above zero.

Costs

Diesel engines are much cheaper to procure than gas turbines – of order 900–1700\$/kW compared with 1200–2250\$/kW at 1996 prices. In addition, so long as a diesel is run within specification (at or below the agreed %MCR), mean time between overhauls (MTBO) can be between 5000 and 20 000 hours for medium- and high-speed diesels in the 500–3000 kW range and up to 60 000 hours for larger engines which operate at constant power for long periods.

Diesels also use fuel which is considerably cheaper than that suitable for gas turbines. Medium- and high-speed diesels use light to medium distillate gas oil with cetane number between 50 and 60. Typically diesel fuel may cost around 70% of the equivalent fuel oil suitable for gas turbine use (approx. \$130 per tonne at 1996 European prices). Gas turbines are currently being developed for heavier fuels, but cleanliness of the fuel will remain an issue for gas turbine power turbines (see below).

It can be seen that diesels lend themselves to utility applications where resilience and maintainability in the field are more important than maximized payload. Gas turbines can be efficient on a regular service for passengers or freight where overhauls can be planned ahead. A craft in regular passenger service can benefit from the additional productivity offered by the increased payload, while a utility craft will benefit most by reduction in capital costs so long as the design mission can be fulfilled.

16.2 Powering estimation

The first stage in sizing a craft is to make an overall weight estimate, as described in Chapter 11. Initial estimates for the known components (payload for example) are grossed up by use of relations for the unknown components based on previous experience. It is also necessary to investigate the craft overall dimensions and cushion parameters (P_c, Q_c) at least in a preliminary way before trying to estimate powering.

A choice between diesel or gas turbine power may be left open at the initial stage, unless the craft mission demands a specific type of power unit, based on the discussion above. The weight data and cushion parameters may then be used to estimate installed power, which in turn can be used to re-estimate total craft weight. If very few parameters are fixed initially, it may be necessary to make several projections before the weight and power estimates converge. The relation used to predict power is typically:

$$P_t = K_t \, W^{0.825} \tag{16.1}$$

where power is measured in shp and W is measured in tonnes. (N.B. shp = kW × 1.34).

Based on statistical analysis of craft from the 1960s and 1970s K_t was found to be close to 165. This has reduced to closer to 125 in recent years for ACVs and to about 100 for SES. The original analysis [4] showed most craft to cluster around the above relationship regardless of design speed, though at this time design speeds were usually in the region of 40–50 knots in calm water. These global coefficients may nevertheless be used as a starting point for craft aimed at typical coastal ferry roles, or equivalent.

Figures 16.4 and 16.5 plot the installed lift and propulsion power as a function of total craft weight × speed (shp/tonne.knot) for a number of existing craft. These may be used for reference where the craft mission is outside 'normal' specifications. These data may be reduced to the relations.

$$P_l = P_c\, Q_c/550\ \ \eta \text{ where } \eta \text{ is normally in the range } 0.6\text{–}0.8 \ldots \qquad (16.2)$$

for lift systems. η is the total efficiency of the lift system including losses in the fans, ducting and cushion; and

$$P_p = K_p\, W^{0.825} \qquad (16.3)$$

for propulsion systems, where K_p varies dependent on the propulsor type (see Chapter 15).

To use these relations to check the initial estimates, the craft cushion system initial design needs to have been carried out (see Chapters 10, 3 and 12, in turn). Further, the craft propulsion estimates need to have been made (see Chapters 4 and 15, in turn). Once the power estimate has been made, an estimate of the engine weight is possible,

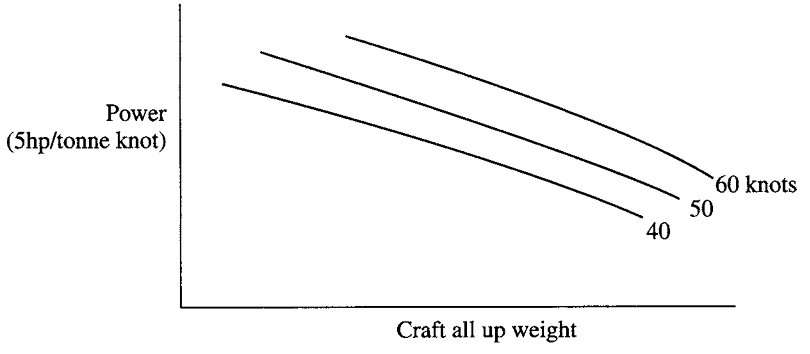


Fig. 16.4 Shp/tonne.knot lift.

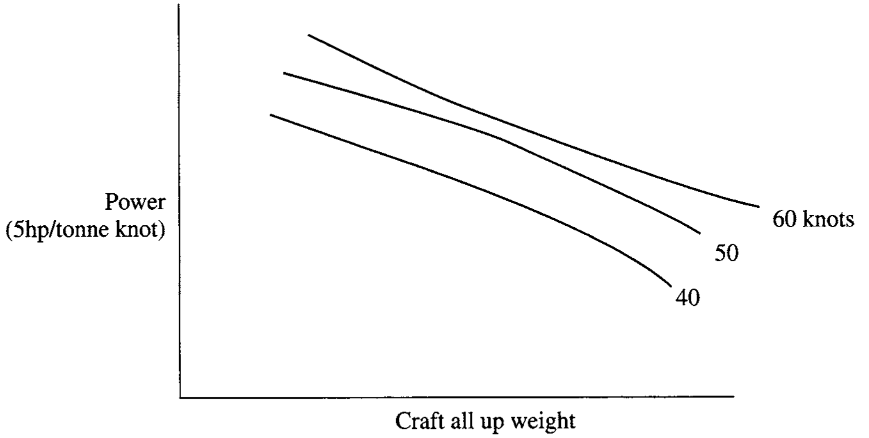


Fig. 16.5 Shp/tonne.knot thrust, and total.

allowing a second cycle of estimation. Initial guidance is given in the table below, based on some data extracted from ref. 119.

Engine Type	Specific Weight (lb/shp)	Gearbox Weight (lb/shp)
Medium speed diesel	$580/P^{0.5}$	0 – assumed direct (750 with aux)
High speed diesel	$250/P^{0.5}$	$100/P^{0.5}$
Air cooled high speed diesel	$200/P^{0.5}$	$100/P^{0.5}$ or $30/P^{0.5}$ if belt drive
Marine gas turbine	$65/P^{0.5}$	$55/P^{0.5}$
Aerospace gas turbine	$14/P^{0.5}$	$55/P^{0.5}$

The next step is an estimate of fuel weight. First we need to assess the fuel consumption depending on the choice of engine type and the installed power. For guidance the following relations may be used:

Engine type	RPM range	Fuel consumption C_f (lb/shp.hr)	Consumption (kg/kWhr)
Medium speed diesel	750–1500	0.34	0.21
High speed diesel	1500–4000	0.35	0.22
Air cooled high speed diesel	1500–4000	0.38	0.23
Aerospace gas turbine	10 000–30 000	0.6–0.25	0.36–0.15
Marine gas turbine	10 000–30 000	0.5–0.2	0.3–0.15
Industrial gas turbine	10 000–30 000	0.5–0.3	0.3–0.18

Diesel engine fuel consumption changes slightly with power output, small/medium diesels consuming 0.2–0.25 kg/kWhr while very large diesels consume 0.18–0.23 kg/kWhr. There is no clear relationship, so it is necessary to seek data from the manufacturers of candidate engines to complete an evaluation. Large gas turbines are significantly more fuel efficient than smaller units, approaching the efficiency of diesels.

The fuel weight can now be estimated, assuming a mission duration T_m and a reserve time T_r in hours. The mission duration in turn can be determined from the craft fixed route, or longest distance between refuelling points:

$$W_f = [C_{f1}\, P_l + C_{f2}\, P_p]\,[T_m + T_r] \tag{16.4}$$

A typical reserve may be 20–100% of the normal mission duration. If fuel is used as ballast for trimming, the higher value may be used as a starting value and optimized later in the design process. Craft operating short ferry crossings where refuelling will be once every 2 to 4 trips might use a 25% reserve, or one leg, while craft for coastal patrol may have a reserve determined in hours of operation, dependent on the greatest distance from a temporary or permanent base.

Once estimates of engine and fuel weight from this procedure have been compared with the craft initial weight estimate, the procedure will need to be repeated by adjusting earlier weight component assumptions and recalculating until convergence is reached. At this point, sufficient data should be available to begin detailed studies of the cushion system and craft drag components based upon the earlier estimates referred to above, so as to obtain a detailed estimate of craft powering, using the methodology in Chapters 2–6.

16.3 Diesel engines

A diesel engine works on the compression ignition principle. The lowest piston position in the cylinder is referred to as bottom dead centre (BDC) and the highest as top dead centre (TDC). The distance BDC to TDC is the stroke. While the piston travels from BDC to TDC the trapped air is compressed by the ratio of the cylinder volume at BDC to that at TDC. This is the compression ratio.

There are two diesel engine types, the 2-stroke cycle and the 4-stroke cycle. The 2-stroke engine completes all four processes of compression–power–exhaust–scavenge for each 360 degree rotation of the crank, while the 4-stroke engine uses a second rotation for exhaust and scavenge. The 4-stroke process allows much closer control of the compression and exhaust processes and so is more fuel efficient, while it requires a larger cylinder swept volume to achieve the same power rating.

Marine diesels have fuel injectors at the cylinder top which inject fuel as the piston reaches TDC. The compression raises the air temperature sufficiently for fuel to burn spontaneously. Injection is continued into the power stroke just far enough to maximize the power generated without leaving unburned fuel in exhaust gases.

A 2-stroke engine relies on the remaining overpressure for exhaust gas to be scavenged. This is assisted marginally by an overpressured air supply system refilling the cylinder with fresh air through valved ports which open when the piston is close to BDC. Cams are positioned so as to open cylinder head valves for the correct period during the piston stroke for exhaust and inlet. A cam shaft is positioned at the side of the cylinder, rotated by gears, chains, or a belt drive from the main crankshaft. The cam shaft rotates at half crank speed on 4-stroke engines.

SES and ACV craft require high speed (for small motors) and medium speed (for higher power ranges) diesels, in order that engine weight is acceptable Medium speed engines are approximately 500–1200 rpm, while high speed diesels are anything higher. Both classes of engine are generally 4-stroke motors having trunk type piston/crank arrangements and a short stroke (stroke to bore 1.0 to 1.5:1). Up to 10 cylinders in line and 24 in vee formation are common.

Most engines are turbocharged and aftercooled. Turbocharging is compression of the inlet air before it is released into the cylinder, increasing the density. The unit is usually a rotary compressor driven by a turbine powered by engine exhaust gas. The higher pressure inlet gas allows greater power to be extracted, while at the same time improving fuel burn and so reducing specific fuel consumption.

Once the power rating is known from the procedure in section 16.2, the designer can consider his design options and check whether his preferences increase or decrease the weight estimate so far.

Number of engines and layout

ACV small craft selection starts on the basis of a single air cooled engine with power outputs for an integrated lift/propulsion ducted fan (Fig. 16.6), or separate propulsor and lift fan (Fig. 16.7 (a), (b)). Larger craft may simply duplicate this arrangement. Utility and small ferry craft begin to employ separate power units for lift and thrust (Fig. 16.8). This has the advantage that the lift motor(s) can be sized to supply

Fig. 16.6 Small craft integrated lift/propulsion from single ducted fan with horizontal splitter plate.

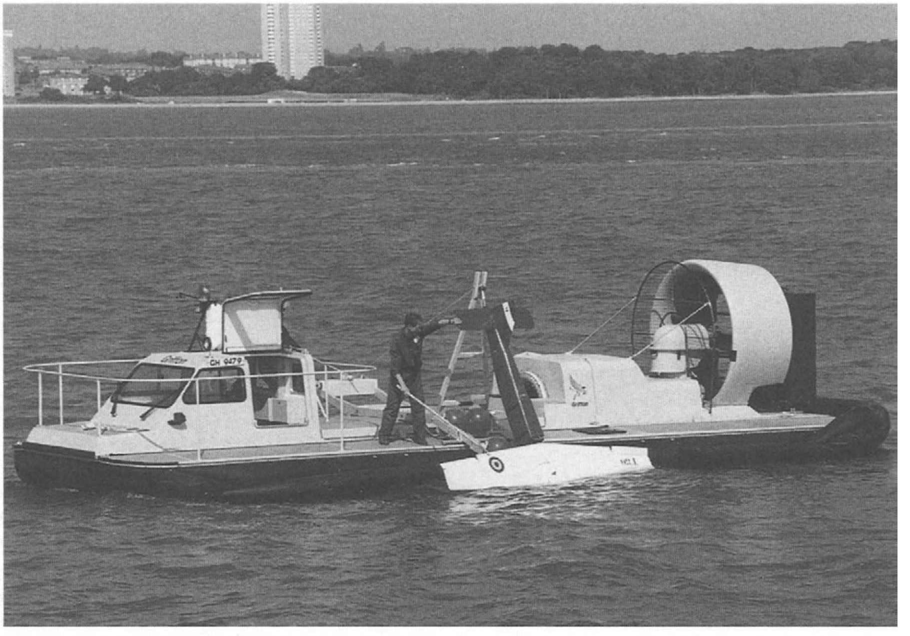
additional air to bow thrusters (see Figs 6.3 and 6.9), as an alternative to variable pitch propellers or fans.

Due to the limited available power range of air cooled diesels, for higher ratings liquid cooled diesels need to be considered. These have been installed in variants of the AP1-88 (Fig. 16.9) and the PUC-22 built by Wartsila in the 1980s (Fig. 16.10). Until recently the high installed weight of liquid cooled engines has meant that payload was significantly reduced, making this choice an inefficient one. This is now changing due to market demands from other industrial users.

Use of multiple engines minimizes transmission requirements, while creating a need for several engine compartments, each with stiff structural support, air intake filtering, maintenance access panels, sound attenuation and fire protection. In general, the optimum selection is that where the minimum possible number of engines is used. Care should also be taken with the craft CG for lightweight operating conditions. If engines are placed too far to the stern, this can increase the requirement for static trimming ballast, which then needs to be accounted for in the craft weight estimates.

The most common diesel engine arrangement for SES consists of two engines each for lift and propulsion (Fig. 16.11). Propulsion engines are best mounted towards midships to minimize VCG and static trimming ballast. The sidewall geometry can be adjusted to accommodate them on smaller craft, so also reducing the shaft inclination, whether for water jets or free propellers.

Lift engines are relatively small for SES compared to craft size and so can be mounted in the same area as the lift fan units, normally somewhere just forward of amidships, with ducting to the bow and stern seals. Care should be taken to effectively sound insulate the lift system compartments.



(a)

(b)

Fig. 16.7 (a) Utility craft integrated lift and propulsion (Griffon 2000); (b) Utility craft integrated lift/propulsion, the ABS M10 (see also Fig. 15.47(c)).

Cooling

ACVs have a choice between air cooled and closed circuit liquid cooled engines. The simplicity of air-cooled engines and their light weight has made them a popular

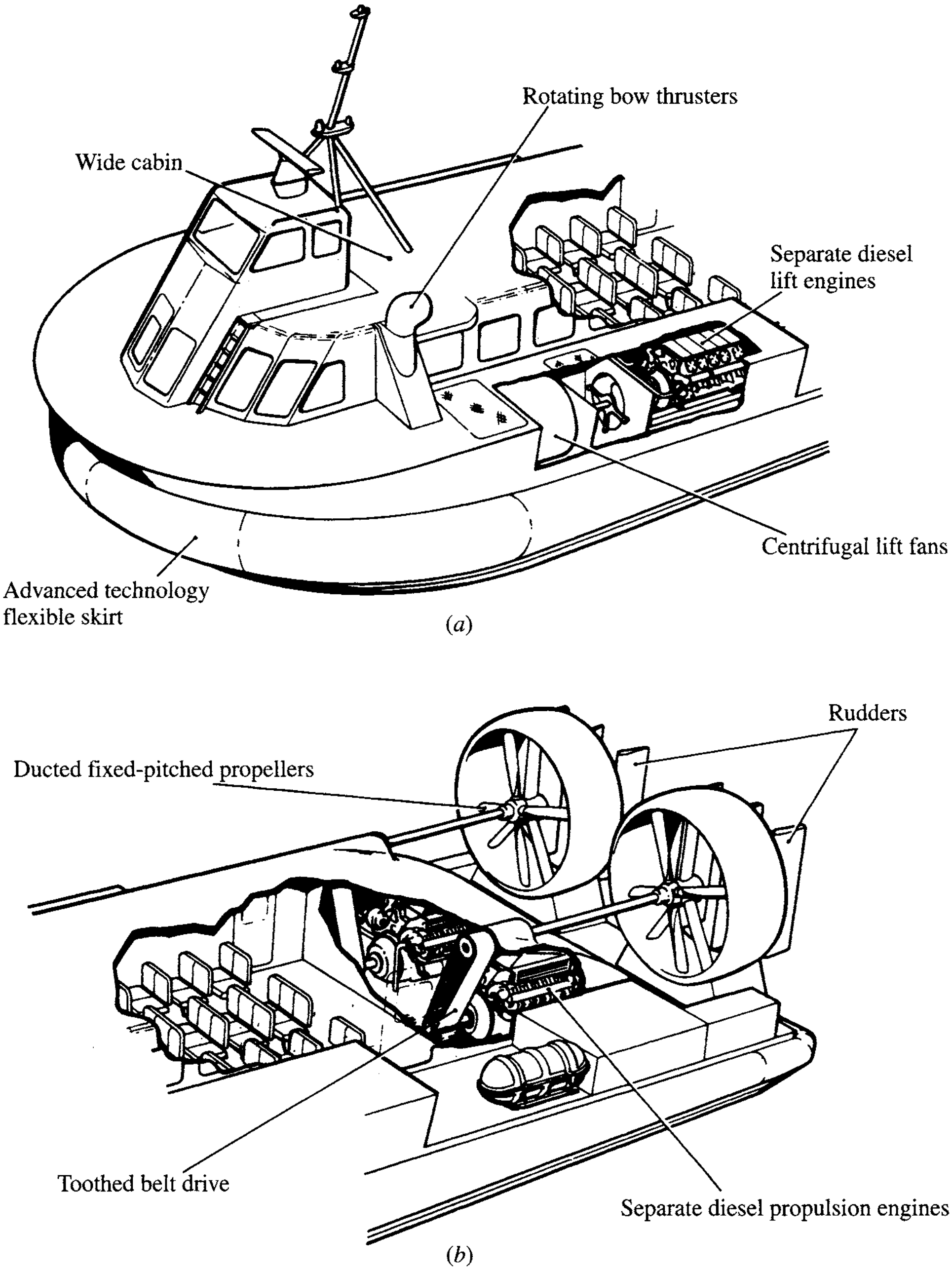


Fig. 16.8 Larger ACV separate power units, the API-88 power system.

choice during the 1980s and 90s. Liquid cooled diesels are becoming available which will extend the power range above that offered by air cooled motors. This should allow designers to develop ACV designs which are larger than the current limit typified by the AP1-88.400 (Fig. 16.12).

Fig. 16.9 AP1.88 Cominco craft.

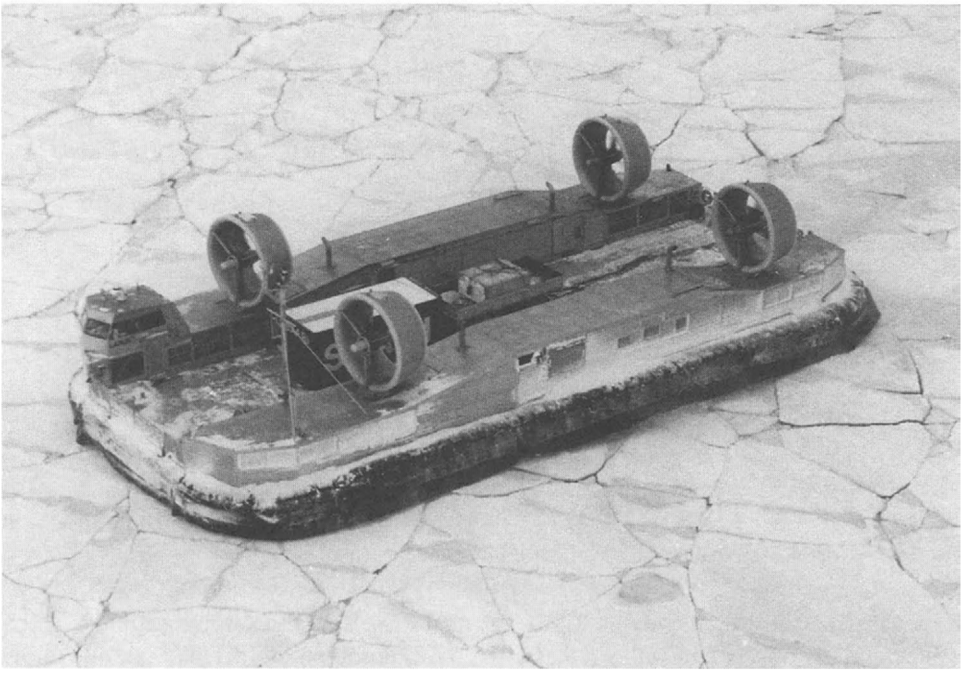


Fig. 16.10 Wartsila PUC-22, with water cooled diesels driving rotating ducted propellers.

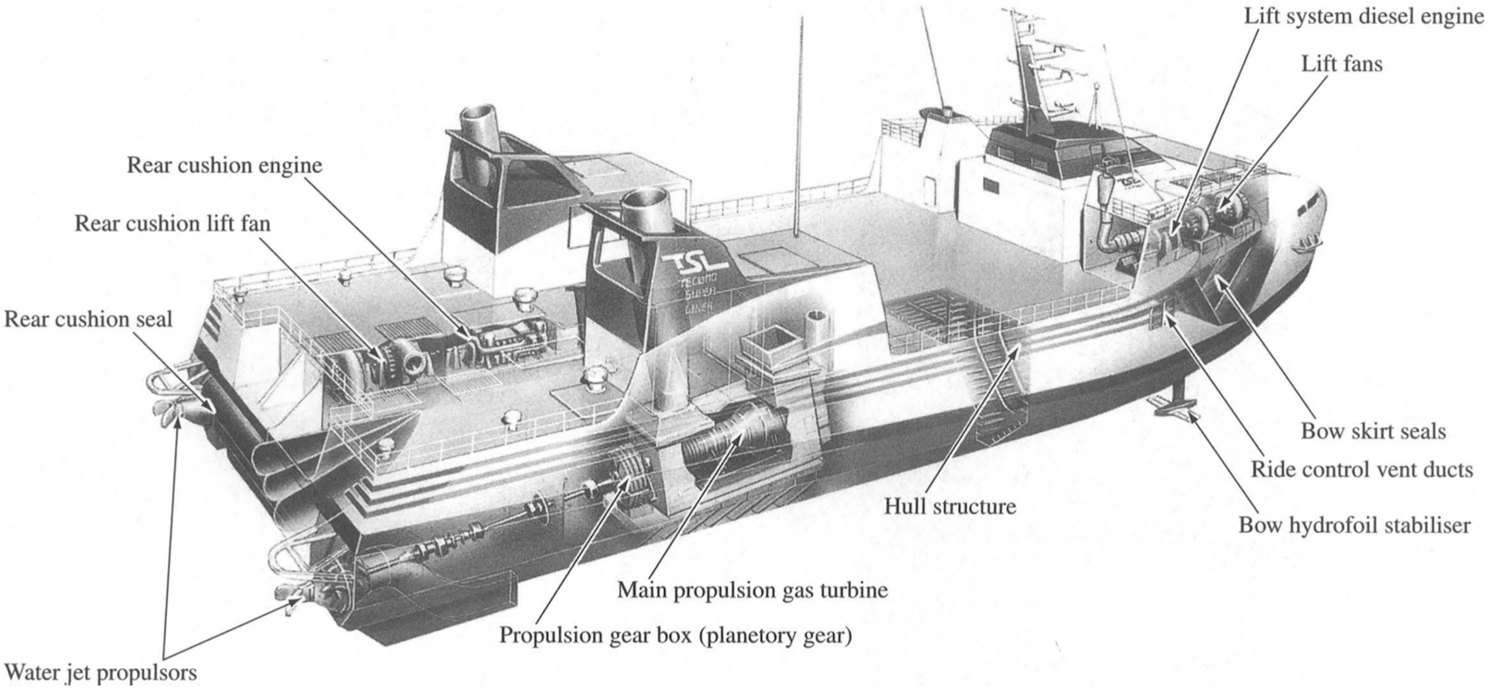


Fig. 16.11 SES power system layout. The TSL-A.

Fig. 16.12 AP1.88 400 design.

SES choice is between closed circuit cooling and open circuit sea-water cooling. Since there is very little drag penalty from a well designed cooling water intake, this is the system of choice. Closed circuit cooling might be chosen for a lift engine on the basis of market availability and cost.

Specific design issues which should then be taken into account during ACV and SES design include:

Vibration characteristics and damping

A diesel main engine is the largest individual mass installed in an SES or ACV. In larger craft it can weigh as much as 30 to 40 t. While larger modern engines with 12–20 cylinders are well balanced, the vibration energy is still significant. Diesel engines are stiff structures, due to the high internal forces developed. Mounting direct to the structure of an ACV or SES will require careful analysis of the local supporting structure to determine its natural frequency and harmonics and response to the engine vibration energy spectrum (see Chapter 14). A resilient mounted engine will also require this type of analysis, with the additional parameter of the resilient mount damping response applied to the engine excitation. Resilient mounts assist to isolate noise transmission from diesel (or gasoline) engines in a metal hull structure. GRP does not transmit noise so efficiently, while foam sandwich panels act as noise attenuators.

In addition to considering engine vibration and noise transmission through the craft structure, it is important to determine the transmission axial and whirling natural vibration frequencies. If there is significant response to any of the main engine vibration frequencies, then stiffness of the transmission shafts or bearing spacing may have to be changed. On small- to medium-sized craft, the damping properties of toothed rubber belt transmission can be used to provide isolation between an engine and a transmission train.

Water-cooled diesel engines generally emit less noise than air cooled diesels, due to the damping of the water jacket. The engine space for an air-cooled diesel may therefore need additional noise absorbing cladding. Forced draft air cooling will also need to be exhausted from the engine compartment in such a way as to ensure it does not recirculate, or become ingested into the cushion air system.

Engine lubrication system

Effective lubrication is particularly important for diesel engines, to ensure rated power is developed and engine life maintained. Most diesel engines operate a duty cycle which includes a significant period at part power or idling conditions. In these conditions, usually slow speed manoeuvring, the lubrication system should be fully effective. It is best to take advice from the selected engine supplier regarding the lubrication system specification for the required craft mission profile.

Exhausts

Engine exhausts should be designed so as to prevent recirculation into machinery space ventilation, or air cushion system intakes. Cooling and exhaust ejection at or under the water-line on an SES can be a convenient way to minimize the in-air noise signature, though non-return flaps are needed to prevent flooding and undesirable backpressure in the exhaust system during start-up. Some military missions such as mine countermeasures may demand exhaust above the water line to minimize the underwater signature.

Relief valves

Diesel engines with bores larger than about 200 mm need to have relief valves installed for relief of excess pressure both in the cylinder head and in the crankcase spaces. Guidance is available from rules such as ref. 116. In this case release into the engine room by opening vent valves needs to be accounted for in designing the ventilation system. This issue should only be significant for large SES craft. Advice can be sought from the engine supplier.

Generators

Generator motors should be rated so as to be able to continuously drive the generators at their full rated output. In addition it is normal to design the system to give an overload power of not less than 110% for 15 minutes or so.

16.4 Gas turbines

A gas turbine is a rotary engine comprising an air compressor, a combustor and a power turbine. The compressor turbine and power turbine can be mounted on the same shaft, or two separate shafts (referred to a spools) may be used, one for the compressor and a power turbine to drive it and one for the main power output. The advantage of this two-shaft arrangement is that it allows the turbine wheels to be separately optimized for maximum efficiency. Some aerospace derivative engines also have low- and high-pressure compressor turbines running on separate concentric shafts to increase compression ratio and further improve efficiency.

The simple gas turbine with free power turbine (Fig. 16.13(a)) can achieve specific fuel consumption as low as 0.25 kg/kWhr for steady operation at design power rating if a compression ratio of 16:1 were used. Marine turbines do not generally operate in this region, 9–12: 1 being more common and with fuel consumption between 0.3 and 0.5 kg/kWhr.

To improve performance a number of measures are possible. The most interesting for fast marine craft is recuperative heating of the compressed air inlet to the combustors by using air from the engine exhaust. This can increase the thermal efficiency by 20–30% so long as the engine is optimized for it.

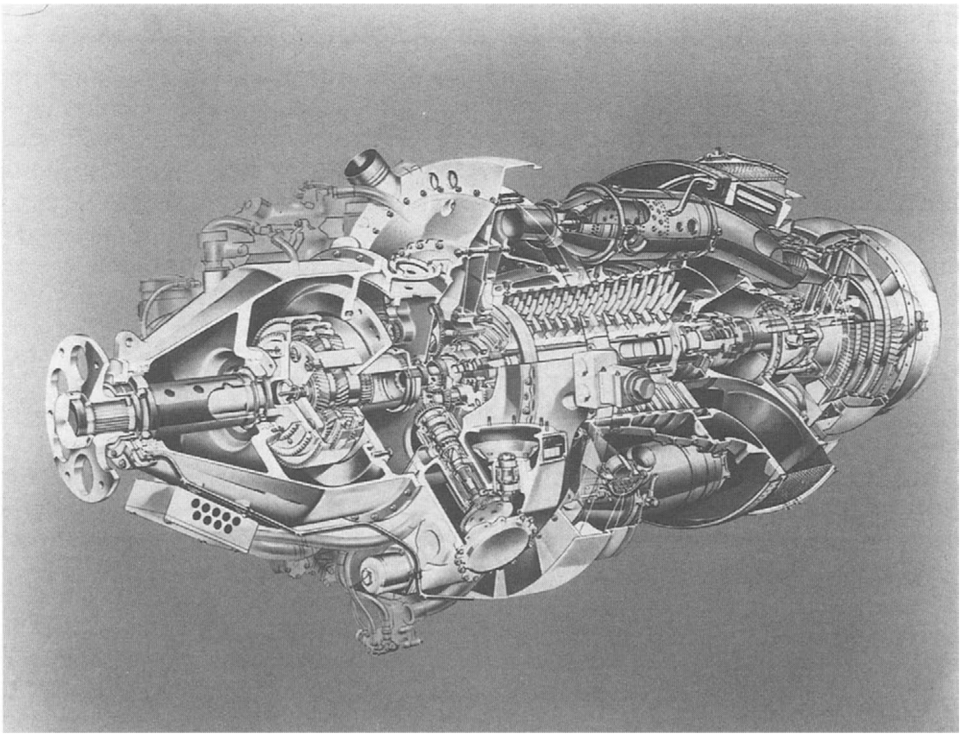


Fig. 16.13 Gas turbine diagrammatic sketches: (a) Rolls Royce Proteus.

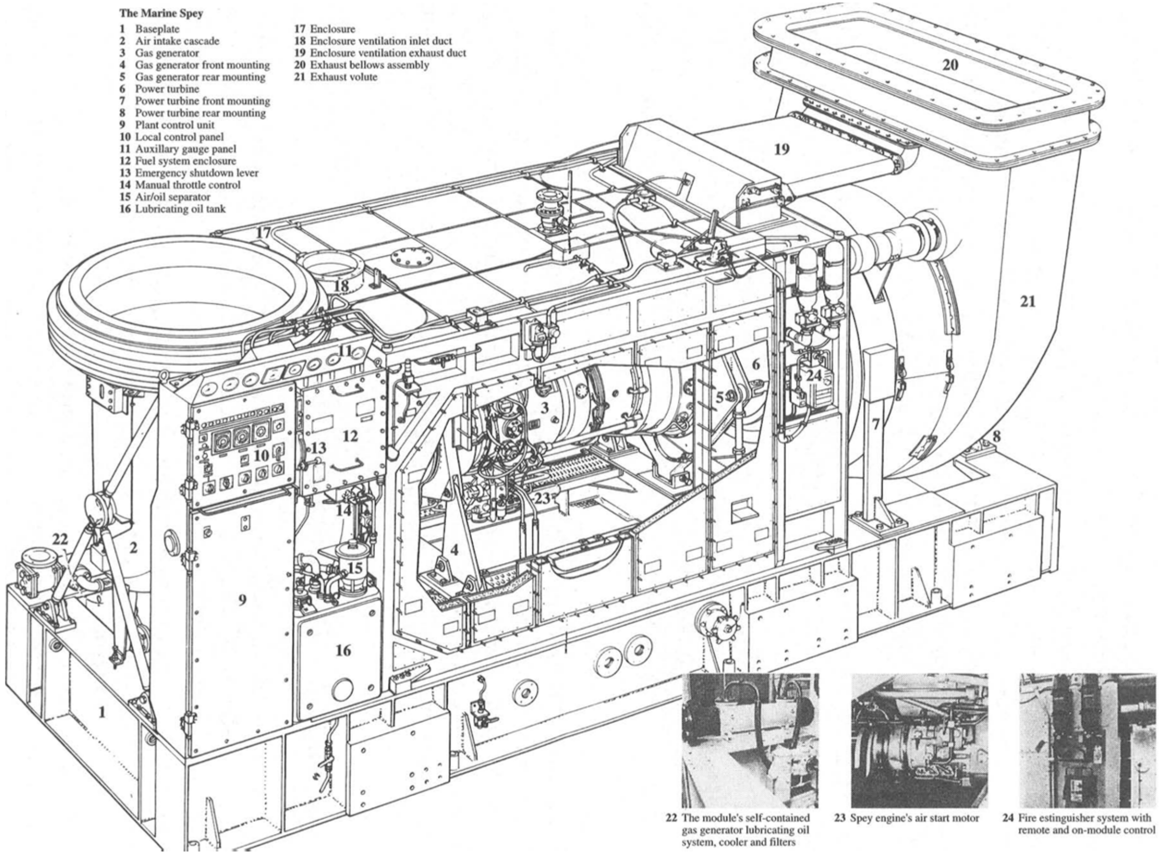


Fig. 16.13(b) Rolls Royce Marine Spey propulsion package.

Gas turbines have a relatively high air volume flow and so pressure losses at the intake and exhaust will significantly affect power generated. A pressure drop of 1% at the inlet will reduce power output by 1.5–2%, while a similar pressure rise at the exhaust due to diffusion will reduce power by 0.5–0.75%. In addition the required thermal energy and so fuel consumption, is increased by around 0.5% in each case. When designing an SES or ACV gas turbine installation, the intake plenum chamber characteristics and exhaust ducting need careful attention. Consultation with the gas turbine manufacturer is recommended!

Axial compressors derived from aerospace machines have limited pressure ratio per disc, resulting in several discs with static straightener vanes for each compressor or turbine stage. This makes for a complex engine and costly major overhauls. In an attempt to simplify engine design a number of manufacturers have produced industrial engines with centrifugal flow compressor stages. At present the power rating available from such machines is limited, but can be expected to improve in the near future.

A gas turbine has to be mounted on a stiff structural skid assembly (see Fig. 16.13(b)) to maintain shaft alignment. In the past this, combined with a need to provide protection against flying debris in the case of rotating disc failure, fire protection and noise suppression, led to development of packaged units. These were fine for displacement ships, but give a weight penalty for fast craft such as ACVs and SES. Consequently gas turbines installed in ACV/SES are normally bare engine/gearbox units, with support frame or skid. The machinery compartment is then designed to fulfil the other functions.

The development of industrial gas turbines has encouraged the design of power units which are modularized, allowing the compressor, combustor or power turbine sections to be removed separately. This is particularly important for larger engines in the 10 000–30 000 kW range, as it also implies exchangeability of modules between engines, leading to reduced spares holding.

There are several design issues which need to be considered when using gas turbines in ACV or SES, as follows:

Layout and engine selection issues

Many of the earliest ACVs used aerospace derivative gas turbines. The SR.N series built at Saunders Roe/BHC developed a design based around an assembly of an engine driving a vertical shaft through a gearbox, which transmitted power to a vertical axis centrifugal lift fan and upwards inside a rotating pylon to a further gearbox and a propeller (Fig. 6.3). This arrangement was light, efficient and scalable but proved expensive to construct.

Bell Textron developed a somewhat simpler power train assembly for the LCAC in the early 1980s, (Fig. 16.14). This is based on a fixed ducted propeller system and separately powered centrifugal lift fans. The LCAC arrangement has similarities to that of the diesel powered AP1.88, except that due to the compactness of the gas turbines, all the machinery is contained in the side structures. Moving the machinery to the sides of the craft allows considerable flexibility for design of the payload area, including the possibility for driving vehicles on and off, as was put to good effect also on the SR.N4. If this is not an issue then the propulsion machinery may be moved into stern

Fig. 16.14 Bell Textron Jeff (B) Showing two sets of 3 TF40 gas turbines driving lift fans and bow thrusters forward, and ducted propellers at the stern. Aerojet General Jeff (A) is in the background.

compartments. An advantage with this arrangement is a lower noise signature in passenger areas. Where fixed ducted propulsion is installed, it is preferable to have a separately powered lift system, with rotatable bow thrusters to give good slow-speed manœuvring.

Until recently only military SES have used gas turbine powering, notably the experimental US Navy SES-100A and 100B in the 1970s. In the 1990s the first major project for a large cargo-carrying SES was started by a consortium in Japan – the Techno Superliner. The half-scale prototype (70m waterline length) for this craft completed trials in 1996. Figure 16.15 shows an artist's impression of the full scale craft while Fig. 16.16 shows the prototype. Machinery installation comprises four gas turbines driving water jets at the stern and four smaller units driving lift fans, two at the stern and two at the bow. In a craft this size the designer is not faced with particular space problems to install machinery. The majority of the outfit may be optimized in stern located areas. The main consideration for an SES is to have 50 to 60% of the lift power located at the bow to feed the bow seal. Machinery should all fit into the sidehull areas, so leaving the centre area free for the mission-oriented layout.

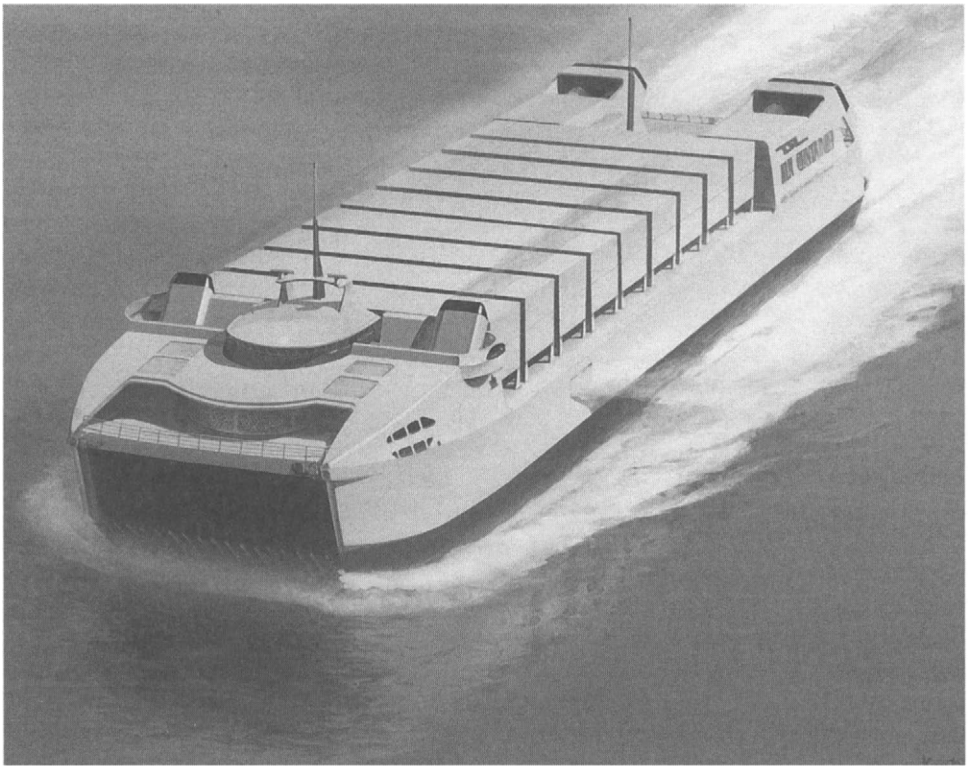


Fig. 16.15 TSL-A full scale short sea cargo SES design.

Air intake flow requirements and inflow distortions

Gas turbines have a high air volume flow requiring careful design of the intake and exhaust systems (see Fig. 16.17(a)). On the intake side there should be sufficient plenum volume so that the air can settle and not cause rapid changes in dynamic head or turbulence, otherwise the engine compressor blade fatigue may be accelerated and in the worst case lead to failure. Current practice is to design an inlet which does not face the craft bow, so as to avoid ram effects, and to aim at 3–5 m/s velocity into the engine intake itself. Engine exhausts are generally a simple stack, see for example Fig. 16.16, if noise is not an issue. The stack should be on an ACV or directed away from propulsors, or comprise a diffuser volute to reduce the exhaust velocity.

Gas turbine power generators are very small, between 0.001 and 0.008 m^3/shp and so the main design issues for this type of power unit are arranging the intake and exhaust, while providing personnel access to the turbine itself for maintenance.

Protection from foreign object damage

ACVs and SES are surface vehicles which often operate in conditions which cause water or sand spray. The air cushion can also throw up other small objects. Spray sup-

Fig. 16.16 TSL-A prototype SES Nissho.

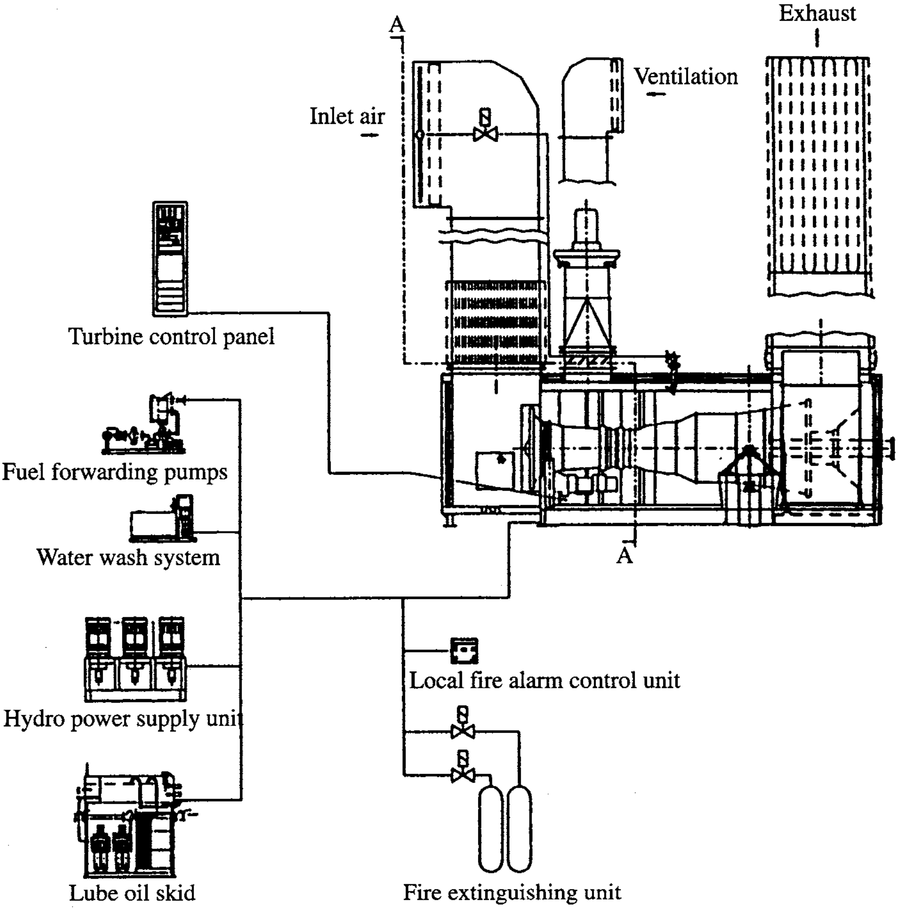
pression skirts can be fitted, but these cannot remove the problem totally. In addition, any debris left in the intake volute after maintenance can be sucked into compressor blading. Such incidents are rare, but have occurred in the past. This problem can be minimized by using ship practice for engine space design, see Fig. 16.17(a), making the intake volute space easy for personnel entry or access and providing effective air intake filtration.

Air intake filtration – protection from salt, sand and snow

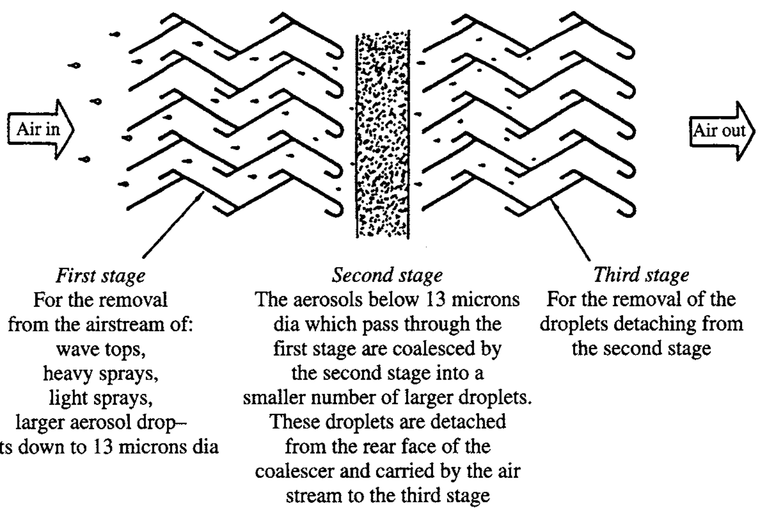
Removal of water droplets, sand particles and debris from the intake air stream demands the use of mesh type filters. Multi-layer nylon or polypropylene knitted mesh, mounted in a configuration so that the entering air flows up through it, has been found effective (see Fig. 16.18). The filter trays can be removed for cleaning out salt or trapped particles on a regular basis. An alternative 3 stage air drying system is shown in Fig. 16.17(b). Systems of this type are installed on military ship gas turbine intakes.

Gas turbine blades are sensitive to the presence of salt, which increases the corrosion rate and fatigue degradation. Reduction to levels as low as 0.01 ppm of salt are needed before engine life is not affected.

Mesh filters will remove droplets, but will not dry the intake air: it is still at 100% humidity and will have some fine water droplets present. Further reduction requires secondary filtration with a finer mesh filter similar to systems used in industrial HVAC systems and possibly also adoption of the strategy used on the BHC craft whereby the



(*a*)



(*b*)

Fig. 16.17 Gas turbine inlet and exhaust system.

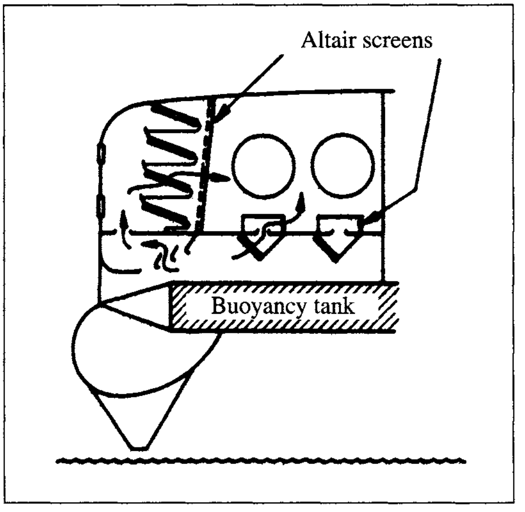


Fig. 16.18 Knitmesh filter diagram.

engine air is supplied from the cushion, as well as having both knitmesh and fine filter screens. Filter systems such as the Primaberg filter are able to meet this requirement (Fig. 16.17(b)).

Eventual salt build-up on gas turbine compressors is inevitable for ACVs and so an effective engine wash or soft blast grit cleaning system is also essential to maximize MTBO, which for the SR.N4 Rolls-Royce Proteus engines is between 2000 and 3000 hours.

Attenuation of engine noise

Gas turbine noise, if not attenuated by muffler systems of some kind, can cause problems in populated areas. Based on sample measurements, Hamilton Standard in the USA proposed a relation as follows:

$$\text{Noise level} = 72 + 8.2 \log P \ \text{dBA at 30m}$$

where P is the engine power rating in shp. The noise level is variable $\pm$ 5 dBA between noisy and quiet engines. This suggests a range between 91 and 105 dBA for 1000 shp class engines without silencing.

From an environmental point of view and to compete with other vehicles such as fast catamarans, external noise levels above 80 dBA close by the vessel would be considered noisy and so would require attenuation. Gas turbine exhaust silencing therefore typically needs to cope with noise power reductions of order 80–90% (approximately 20 dBA). This can be achieved by enclosing the engine itself in an acoustic enclosure (this may be the machinery space itself, suitably clad) and using attenuating cladding at the exhaust ducting.

16.5 General design requirements

When designing machinery systems and spaces on board an ACV or SES the following design requirements need to be taken into account, based on IMO and classification society typical requirements.

Vessel trim and dynamic motions

Machinery and associated systems should be designed so as to continue functioning safely while the craft is rolled and pitched to its design maximum angles for normal operation. Designers should also consider if there is a need for a craft to be able to continue emergency operation if collision damage is sustained. Auxiliary machinery should at least be able to continue operation so as to provide power and pumping capacity. For guidance, Lloyds Register Special Service Craft rules [116] part 9, section 4.2 specifies the following inclinations:

Inclination angle (Degrees)	Transverse inclination		Longitudinal inclination	
	Static	Dynamic	Static	Dynamic
Main and auxiliary machinery	15	22.5	5 or 500/L for craft above 100m long	7.5
Emergency machinery and equipment	22.5	22.5	10	10

Machinery control and remote monitoring

Machinery controls should be from the wheelhouse or control cabin. Larger craft (Category B or cargo vessels in IMO) should have duplicates of the main machinery controls close by the engine room(s). A typical monitoring/alarm scheme may include the following (extracted from Lloyds Register Special Craft Rules). These are the key parameters for engine health monitoring.

Item		Alarm	Notes
Lub oil inlet*	Pressure	Low	Automatic shutdown, medium/high speed engines
	Temp	High	Alarm monitor
Exhaust gas*	Temp	High	Alarm monitor
Overspeed*	rpm	High	Above 20% for main engines, 15% for auxiliary, independent of governor controls if fitted
Piston coolant outlet	Flow	Low	Alarm monitor
	Temp	High	Alarm monitor
Cylinder coolant inlet	Flow	Low	Alarm monitor
Cylinder coolant outlet	Temp	High	Automatic shutdown, medium/high speed engines
Thrust bearing	Temp	High	Alarm monitor
Oil fuel	Temp	High	Alarm monitor
		Low	Alarm monitor
Turbocharger exhaust gas	Temp	High	Alarm monitor
Above 1500 kW:			
Lub oil sump	Level	Low	Alarm monitor

Item		Alarm	Notes
Lub oil filters	Diff. pressure	High	Alarm monitor
Cylinder lubricator	Flow	Low	Alarm monitor
Piston coolant inlet	Pressure	Low	If a separate system
Seawater cooling	Pressure	Low	Alarm monitor
Fuel valve coolant	Pressure	Low	If a separate system
	Temp	High	If a separate system
Oil fuel booster pump	Pressure	Low	Alarm monitor
Charge air cooler outlet	Temp	High	4 stroke medium and high speed engines
		Low	4 stroke medium and high speed engines
Scavenge air	Temp	High	Alarm monitor
Turbocharger lub oil inlet	Pressure	Low	If system not integral with turbocharger
	Temp	High	If system not integral with turbocharger
Automatic engine start	Failure		Lloyds allow 3 attempts at start based on start system design

Gas turbines should have alarms fitted for items marked* and in addition a vibration monitor should be fitted and flame and ingition failure should be monitored. Automatic shutdown should be linked to each of these events, as manual control is unlikely to be quick enough to avoid major machinery damage.

ACV and SES machinery rooms should be designed for unmanned operation. While for smaller craft this may be self evident, for larger vessels this may require a significant outfit of remotely operable machinery and supervisory instrumentation. Outfit will include automatic fire detection and protection and a bilge alarm system in addition to the remote machinery operation systems.

Engines should be protected against overspeed, high temperature, loss of coolant or lubricating oil pressure and overload by safety devices which can be tested. The safety protection devices should not cause complete shutdown without prior warning, except where there is a risk of explosion or major damage. There should be at least two independent means of shutting down machinery at the engine room or space, in addition to the wheelhouse controls.

Starting

It should be borne in mind that ACVs and SES may need to black start while at sea or at an unsupported overnight stop. Equipment for starting the auxiliary and in turn the main machinery, should therefore be self contained and suitable to the craft mission – take care to account for extremes of cold or heat. An FMEA (Failure Modes and Effects Analysis) should be carried out to identify the need for duplicated systems, such as batteries, see below.

Fuel system

In all cases it is important that fuel supply lines are protected from heat from engine cylinders or hot parts. Modern diesel engine fuel injection systems run at relatively high pressures and so these lines are best designed as metallic pipework, shielded by a secondary barrier against heat and to prevent leakage of fuel to engine hot parts in the case of rupture.

Fuel filtering

To minimize wear on diesel fuel injection systems, fuels need to be filtered to remove fine grit which is often present. High-speed engines normally require a fabric or felt filter rather than gauze. If the engine is to run on heavier quality fuel, it is possible that wax may solidify in cold weather and so a fuel pre-heater before filtering may be required.

Gas turbines can also be engineered to run on diesel fuel rather than kerosene, as used in the aerospace industry, where the operating conditions are not as demanding. In this case attention must be given to grit filtering and to both salt water content and sulphur content, which can lead to accelerated corrosion. High speed diesel fuel may have 1.5% sulphur compared with 0.1–0.3% in kerosene fuel.

Failure modes and effects

Both the IMO and other regulatory bodies now require Failure Modes and Effects Analyses (FMEA) to be carried out. This has been encouraged by analysis of a number of high speed ferry accidents in recent years. The *IMO High Speed Code* [118] gives a useful guide to this technique. FMEA of machinery and their control systems is an important task for a designer once the main craft design is complete. This analysis will highlight any weaknesses in the choice of engine type and number, and the control system and its redundancy.

16.6 Machinery space layout

There should be sufficent access space around each engine, gearbox and transmission coupling to allow for the regular inspection and maintenance operations which need to be carried out in place and for removal of items for workshop or remote maintenance. In the case of diesel engines this implies stripping the engine and removal of components, while gas turbines will generally be removed complete, or in modules (LP and HP gas compressors, combustor, power turbine, etc.).

Engine removal normally requires a hatch vertically above the engine itself to allow access for craneage. Gas turbines will need removable hatches, while larger diesel installations may only be removed complete in the case of a major failure. In this case it may be acceptable to design the deck(s) above the engine room in such a way that panels can be cut away for access and re-welded back in place after the engine has been replaced.

Small craft machinery spaces are normally designed for access while standing or kneeling on hull hard structure outside the space after removal of protective panels or access hatches. Daily maintenance operations can be carried out this way, while external cranage or lifting gantry frames are used to remove the main machinery items for major overhaul in a workshop.

Design of machinery spaces should cater for the need to be able to drain engine fuel and lubricating oil lines to a safe place. As a minimum for small craft, drip trays should be installed under items such as fuel and lubricating oil filters, and sump drainage points.

Machinery compartments should be naturally or force ventilated sufficient to maintain a safe environment in normal operation. Air for ventilation will need to be filtered to remove sand, dust, water particles and salt. The filter system will require cleaning by removal and backwashing or replacement. External surfaces of machinery compartments should be suitable for hose cleaning. ACVs in particular operate in conditions where mud and salt can build up.

16.7 Systems and controls

Monitoring and control of engine functions for high speed marine diesels or gas turbines is carried out through a computer system which addresses a series of sensors. Groups of sensors may be linked together into a module via a data bus, and then each module linked to the computer processing unit by a data netword.

The modularization of such a system will allow for simple change out of the components, or uprating of specifications as this technology advances. Redundant systems can also be simply arranged with such a design, which may be important for military craft to allow for some level of damage to a craft in battle. Data from the sensors are processed by the main processor, and then fed out to additional computers which further process the data and present information in a series of screen displays designed to inform the engineer, or the craft driver. A block diagram of this type of system as implemented by MTU is shown in Fig. 16.19. Figure 16.20 shows a drawing of a typical peripheral interface module, comprising a microprocessor motherboard and sockets to receive printed circuit boards containing the logic for a particular sensor group. Each sensor group may include the functions for a particular machine.

The same approach may be adopted by the SES or ACV designer to monitor and control other primary systems on board the craft, such as water jets, cabin heating and ventilation, and safety instrument systems. Adoption of a consistent modularized approach for all such systems will then give minimized maintenance for the craft.

Design and supply of these systems is carried out by the main engine supplier, based on functional requirements provided by the ACV or SES designer. Care should be taken to ensure close liaison between the engine supplier's specialist and the electrical/instrument engineer designing the ACV or SES total craft system.

16.8 Operation and maintenance

Operation

A diesel engine is a relatively dense metallic structure – primarily cast and forged steel and aluminium components. Start-up from cold involves considerable internal heat transfer, and higher wear between moving parts until heated to design operating temperature so that clearances are optimal.

Through the operating period between maintenance activities, gradual degradation of lubrication oils occurs, as abrasion and combustion products from the upper cylinder are absorbed. Abrasion also occurs from particles taken in with the air mixture. Gradual degradation of bearings occurs, leading to increased tolerances and vibration. Fatigue of components due to vibration within the engine gradually increases. Fuel economy will gradually worsen as these effects build up, together with coking of the piston crown and combustion chamber.

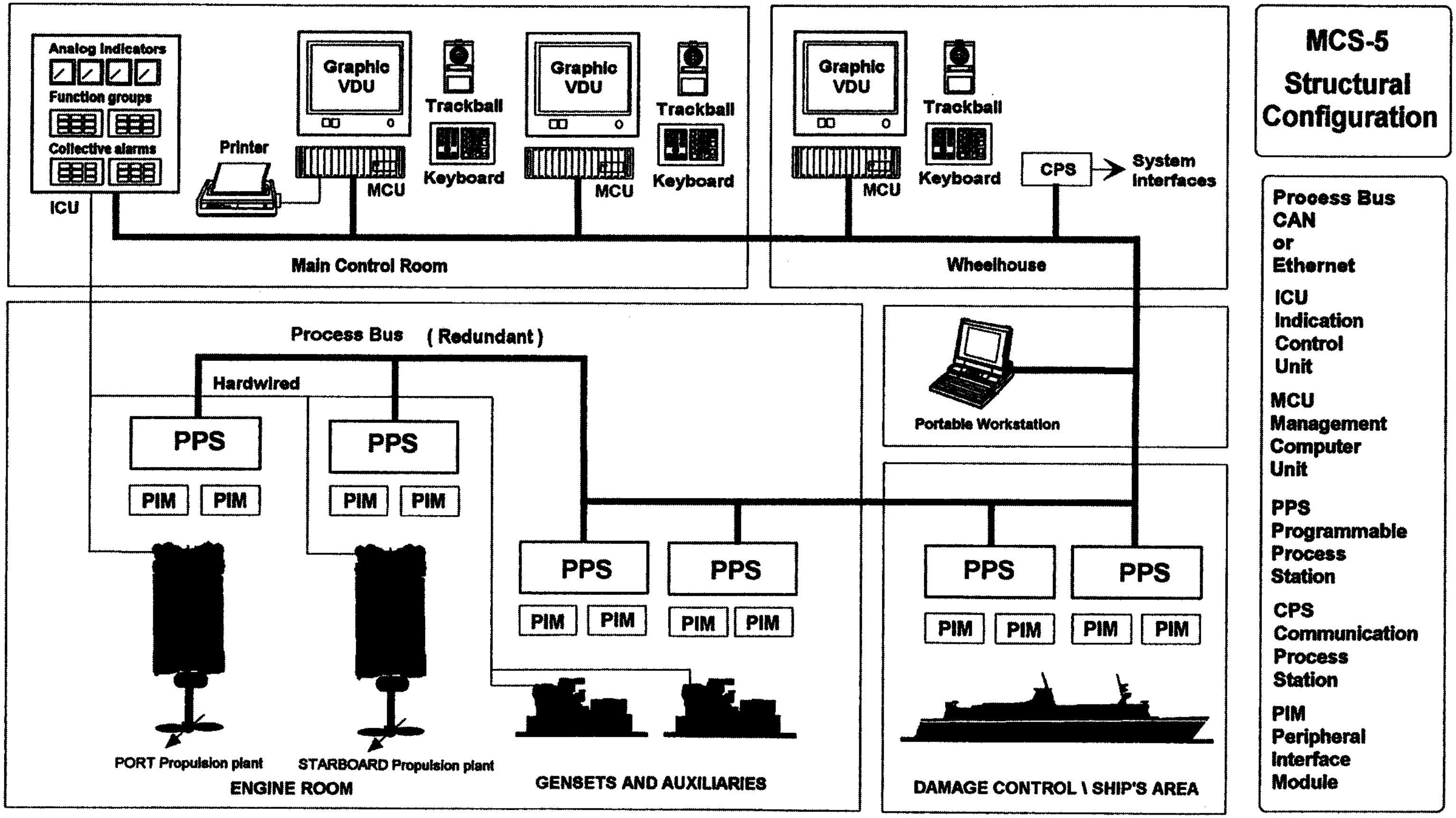
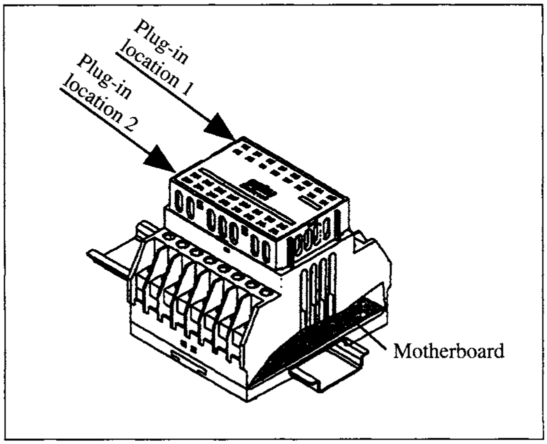


Fig. 16.19 MTU Engine Monitoring and control system example block diagram.

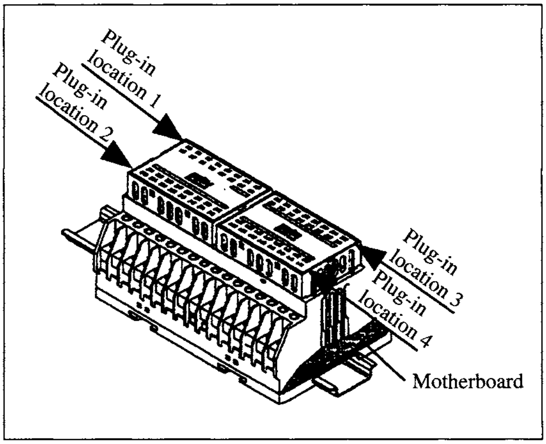
The PIM is available in two versions:



Type: **PIM 1**

The PIM 1 comprise:

- the modular cassette with printed circuit board COB (motherboard)
- plug-in location 1: printed circuit board MPU 23 (microprocessor)
- plug-in location 2: free plug-in location for selected printed circuit board



Type: **PIM 2**

The PIM 2 comprise:

- the modular cassette with printed circuit board COB (motherboard)
- plug-in loaction 1: printed circuit board MPU 23 (microprocessor)
- plug-in location 2, 3 and 4 free plug-in location for selected printed circuit board

Fig. 16.20 MTU Peripheral Interface Module (PIM).

Monitoring of engine vibration, fuel consumption and lubrication oil condition can provide a useful health check, and assist to predict when an overhaul will be required. Operation at above 85% MCR (Maximum Continuous Rating) can lead to very much increased rates of wear and degradation and so craft which require operations above this rating – for example military craft for sprint performance – should be subject to reduced periods between major engine inspections. Manufacturers will give advice on the appropriate procedures.

Engine auxiliaries can be prone to failures when operating in extreme environmental conditions, for example starter motors in low temperatures. Specification of auxiliaries should take this into account where possible. In low temperatures it is also necessary to provide for lubricating oil and fuel heating for start up.

Diesel engines have a wide useable range of rpm, so it is possible to use engine speed to regulate fan or propeller speed, rather than specifying variable pitch rotors for propulsion. The use of rotating bow thrusters can provide adequate slow speed manœuvring. Engines may be left running at idle on bus stop type passenger services to avoid the stress cycle of a shutdown. It is preferable that diesel engines be specified by the ACV or SES designer for normal service speed at 85% MCR or less. This will then ensure that the period between major overhauls is in the range between 5000 and 10 000 hours.

Gas turbines have fewer moving parts than diesels, but operate at much higher rotative speeds – a factor of 5 to 10 higher. Main shaft bearings are sensitive to efficient lubrication and accuracy of rotor balance. Degradation will lead to vibration. Dust particles and salt in intake air will abrade the rotor blades, leading to reduced efficiency and thus increased fuel consumption and additional increased vibration. Operation at reduced power ratings can cause increased deposition of combustion products. Rotors should therefore be cleaned regularly to remove salt and combustion products. Typically a gas turbine is washed weekly or daily, depending on the intensity of operations. Monitoring of engine fuel consumption and vibration is useful as a health monitor, similar to diesels.

Gas turbines operate efficiently over a much smaller rotative speed range than diesels, and so propulsion fans, propellers or water jets will normally be specified with variable pitch, or some other means of varying the thrust independent of engine speed. Greatest efficiency will normally be obtained if a gas turbine installation is designed for normal service speed at about 95% maximum power rating. This will give a suitable power margin for extreme weather conditions, while allowing the turbine to operate close to its optimum for most of the time. This should also maximize the time between major overhauls. Typically a major gas turbine overhaul will be required every 2000 to 5000 operating hours for aero derivative units, depending on the number of starts. Industrial gas turbines generally have MTBO times between 5000 to 20 000 hours where operation is continuous for very long periods. When used in ACV or SES, these periods will be reduced by at least half, due to the number of start cycles.

Maintenance

Diesel engine MTBO is controlled by hours of operation, number of starts, and the operating cycle. The definition will be guided by power loss due to steady build up of coke – ash products from burnt fuel which fuse to the piston and cylinder surfaces. Heavily coked engines tend to smoke, particularly on start-up. Typical regular maintenance operations may be as follows, all based on monitoring performance of the engine during service:

Operating hours	Maintenance
500–1000	Sample lubricating oil and renew if required
	Check cooling water in closed circuits and treat or renew
1000–2000	Check exhaust valve seal, remove and clean, reseat, or replace
	Remove test and recondition fuel injectors
2000–5000	Check cam surfaces, clearances, and reset as necessary
	Check all major nut and bolt security
5000 and upwards	Major overhaul to manufacturer specification
	Main engine bearings and thrust bearing inspection
10 000–25 000	Overhaul of turbocharger, governer (if fitted), engine ancillaries

A major overhaul will usually be done in situ and consists of stripping the cylinder heads, removing and replacing worn parts, particularly valves and sleeve bearings, and de-coking the cylinder head and pistons. To achieve this efficiently, the engine room should have personnel access space around the engines and lifting arrangements/hatches to remove the heavier items to the workshop.

Gas turbine in service maintenance will follow the pattern below.

Operating hours	Maintenance
Each day, or each shutdown between voyages	Engine wash or cleanliness check Backwash air intake coarse filters
500–1000	Sample lubricating oil and renew if required Check cooling water in closed circuits and treat or renew
1000 and upwards	Major overhaul to manufacturer specification
10 000–25 000	Overhaul of governer (if fitted), engine ancillaries

Marine gas turbines in the power range 500 to 5000 kW normally have a maintenance schedule which requires regular attention from mechanics (regular engine and air intake washing to remove salt, etc.) and MTBO in the 2000–5000 hour range. The MTBO will depend on a combination of the number of hours operation and the number of cold starts. Typically, each cold start counts as one hour operation.

Development of marinized versions of high power industrial gas turbines, in the range 10 000–30 000 kW for large fast ferries is leading to much higher MTBO, in the same range as large diesel engines. For these applications the duty cycle includes fewer starts and a higher proportion of constant power output. A gas turbine overhaul consists of a complete strip and clean, rebuilding of main rotors replacing damaged blades, re-balancing and rebuilding. This is a specialist operation which is not normally done outside the suppliers' workshops. Intensive operation of a gas turbine craft will therefore require a spare turbine unit, or an exchange agreement with the supplier. Where an ACV or SES operator has several craft, it may be economically viable to set up an inhouse maintenance organization with mechanics trained by the engine supplier. Engine rooms for gas turbines need to include lifting gear and a removal route for the complete turbine unit.