High Speed Sealift Technology Workshop
Propulsion Machinery Technology
Working Group Summary

Introduction

On Oct. 21 - 23, 1997 a High Speed Sealift Technology Workshop was conducted at the Naval Surface Warfare Center, Carderock Division, Bethesda Maryland. In support of this effort, people from industry, the government and academia participated in a Propulsion Machinery Technology Working Group.

Objective

The objective of the working group was to identify and investigate powerplants to meet the specified performance parameters.

Assumptions

The working group discussed power generation by means of diesel and gas turbine engines and fuel cells, and power transmission by mechanical means and electric drive. The machinery discussions were guided by the transport requirements presented at the opening of the workshop. This approach bounded the power levels needed, and focused the consideration of current engines and future candidates.

At the outset of the effort, the working group made assumptions which served as guidance/criteria for the subsequent discussions. The assumptions included the power level and time frames the discussions should considered and are summarized below.

- Power level
    - min - 50000 hp/Propulsor
    - - 2 Propulsors/ship or more
    - >30 Knots - Water Jet Propulsion

- Time Frames
    - Near Term - 0 to 5 yrs.
    - Mid Term - 5 to 10 yrs.
    - Far Term - > 10 yrs.

Key Parameters

A goal of the working group was to develop estimates for key parameters associated with power generation and transmission technology for the three time frames given above. The key parameters considered include the following: output power, specific fuel consumption, specific power and specific volume, cost per horsepower, fuel alternatives, propulsion system considerations, emissions, maintenance and complexity.

Gas Turbines

The working group discussed large gas turbine engines (> 20000 hp) currently in production for marine propulsion applications; examples include: the Asea Brown Boveri GT35 and the General Electric Marine & Industrial LM2500 Series. Published performance data is as follows:

Manufacturer	Model	ISO Rating* Continuous (hp)	SFC* (lb/hp-hr)
ABB	GT35	22630	.428
GE M&I	LM2500	33000	.372
GE M&I	LM2500+	39000	.356

The Northrup Grumman/Rolls-Royce WR-21 was also discussed. The WR-21 (intercooled, recuperated gas turbine engine with a power turbine variable area nozzle) is currently undergoing development and testing for the naval propulsion application. This configuration engine provides efficient operation over a broad power range. Published performance data is as follows: ISO rating continuous = 33850* hp; SFC = .329* lb/hp-hr.

The working group also discussed two large, aero-derivative, simple cycle gas turbine engines, namely the General Electric Marine & Industrial LM6000 and the Rolls-Royce Trent. While both engines are in service for industrial applications, neither is currently used in a marine application. It was indicated a marine version of the LM6000 is available. Performance data for the two engines is as follows:

Manufacturer	Model	ISO Rating Continuous (hp)	SFC (lb/hp-hr)
GE M&I	LM6000PC	57330*	.329*
Rolls-Royce	Trent	67050[1]	.329[1]

In considering this application, the working group concluded that gas turbine engines exist in the 43 - 50 MW power range with an associated SFC of approximately .33 lb/hp-hr.

* Data Source: Gas Turbine World 1997 Handbook; ISO rating continuous; SFC based on Lower Heating Value.

1 Data Source: performance data indicated during working group discussion.

Operational Profile

The operational profile for an engine in a high speed sealift application was discussed by the working group in general terms. The engine operational profile and ambient operating conditions would be dependent on the specific shipping route, which is undefined at this time. The working group surmised that the majority of ship operating time would be at high speed with an associated high power requirement. Also, the time when a lower ship speed was required could potentially be met by operating on a reduced number of propulsion engines, thereby attempting to continue to operate the remaining units at a high power level. (It was also suggested that a diesel engine could be considered for slow speed operation.) In this scenario, efficient high power engine operation would be very important and the efficiency of part-power operation would be less of an issue. The operating profile would impact the engine design. For example, incorporation of features which enhance part-power efficiency, such as variable geometry or a recuperator (i.e., regenerative cycle) may not be useful for the high speed sealift application described above. Again, in the above scenario, the engine would need to be designed for a significant amount of time at high power level/high turbine inlet temperature operation.

Discussion on Potential Future Engines/Improvements

The working group considered approaches to obtaining higher output power capability and improved efficiency. The following is a brief summary of the discussions. (Note: Potential further efforts in this area would need to also consider numerous additional factors associated with each approach considered as well, such as: life cycle costs, reliability, maintainability, durability, technical risk, size, weight, manning, additional complexity, suitability for use in a marine/military application, etc.)

It was estimated that the development of a new engine could cost on the order of $ 1 Billion or more, thus the rational of deriving an engine from another application, such as aerospace. An aeroderivative engine has the benefit of high power density, an important consideration in the weight sensitive high speed sealift application.

During the course of the discussions, it was indicated that the core from an existing aircraft engine could be used in the development of a 100 MW aero-derivative engine (estimated SFC of .3 lb/hp-hr). This is given in the following Table as occurring in the Mid-Term (5 - 10 time frame). It was suggested that a market for this size engine does exist and that the engine could be developed in 5 years if the funding was made available. A ROM (rough order of magnitude) estimate was given as $300 - 500 M.

The working group discussed the concept of adding an intercooler to an aeroderivative gas turbine engine (Intercooled Aero-Derivative Gas Turbine - ICAD). This configuration engine would consist of a simple cycle aeroderivative engine with the addition of a heat exchanger for cooling the compressed air between stages within the compression process. Advantages of intercooling include reduced power required for the compression process and increased output power. Intake cooling was also discussed (heat exchanger reduces the engine inlet air temperature). It was suggested that through using intercooling and intake cooling, an estimated 15% improvement in SFC and doubling of output power could be obtained (relative to operating with a high ambient temperature/high engine inlet air temperature). This was considered to be a near term approach, if determined to be feasible for this application.

The combined cycle was discussed. In the combined cycle, gas turbine engine exhaust heat is used to make steam for powering a steam turbine, thereby increasing output power by an estimated 25% and efficiency by an estimated 20%. The basic gas turbine engine is not altered. It was suggested that this may be better suited for use in marine applications that have other uses for steam (i.e. cruise ships). It was noted the Navy has been moving away from the use of steam. This was considered to be a near term approach, if determined to be feasible for this application.

The air bottoming cycle was discussed. Gas turbine exhaust is used to heat the air in a separate air turbine (via a heat exchanger) after it has exited the compressor and prior to entering the turbine. It was estimated that the output power would be increased by 25% and efficiency by 20%. The basic gas turbine engine is not altered. It was indicated that this was in development for the LM2500. This was considered to be a near term approach, if determined to be feasible for this application.

The regenerative cycle was discussed. Heat is recovered from the exhaust gas flow for pre-heating compressor discharge air, reducing the amount of fuel required. As mentioned above, the regenerative cycle enhances part-power efficiency and may not be useful for the high speed sealift application as previously described above.

Engine operation with higher turbine inlet temperatures (and subsequent improved efficiency) through using advanced hot section materials and coatings was discussed. It was felt further development would be required to incorporate materials (i.e. ceramics, etc.) and thermal barrier coatings into the large engines in the mid term.

With regard to emissions, gas turbine engines meet current standards. It was felt that gas turbine development for industrial applications will drive combustor development and marine engines can use what was developed. Development of dry low emissions technology for liquid fuels is nearing completion.

The following table of key parameters for the three time frames was generated by the working group.

Table 1. Primemover Characteristics - Gas Turbines

Key Parameters	Near Term (0-5 years)	Mid Term (5-10 years)	Far Term (>10 years)	Defense Range (NT)
Power (kHP)	70	125-130	125-130	80
BSFC (lbs/hp-hr)	0.33	0.30	0.26	0.33
Lbs/hp*	1.0	1.0	1.0	1.0
Ft^3/hp*	0.1	0.1	0.1	<0.1
Fuels	Distillate/ Natural gas	-------------------	--------------------	------------->
Emissions	Meets Stds.	-------------------	--------------------	------------->
MTBO (khrs)	12.5-25	-------------------	---------------->	1-2

* Engine Only

Diesel Engines

The objective of this working group was to identify powerplants to meet the specified performance parameters, one of which was a minimum hp level of 50K per propulsor. Allowing for two engines per propulsor would still require an engine of at least 25K hp which rules out the use of high speed diesels, the largest of which are in the 4K hp range. Slow speed diesels could easily provide the 50K hp level but are too heavy and voluminous for use in a high speed transport application. This leaves medium speed diesels as the best choice for the requirements. Table 2 represents the groups consensus on the commercial evolution of medium speed, four stroke diesel engines over the three time frames specified for this workshop with the Near Term parameters presenting the currently available state of the art. The main drivers in the commercial diesel market are the customer demands for improved brake specific fuel consumption and lower engine weight and cost.

With the addition of significant government funding (ROM $300-500 M) some of the projections change. The Near Term parameters would not change as there would be insufficient time to introduce new technologies. However, the development of the commercial evolution Far Term engines could be accelerated so that they would become available in the Mid Term time frame and the Far Term would bring about engine parameters that are a generation beyond what was predicted for the commercial market as shown in Table 3.

Advancements in several key technology areas will have to occur for these parameters to be achieved. First, turbocharger technology will have to improve so that higher efficiencies can be achieved with greater flow capability and higher pressures. Secondly, improved materials/designs must be incorporated into components such as connecting rods, pistons, rings, cylinder liners and cylinder heads to withstand the increased pressures and temperatures associated with higher specific outputs. Finally bearing technology will have to be improved to withstand increased unit loads, otherwise sizes for components such as crankshafts and blocks will have to grow which will negatively impact on gains in specific weight and volume.

Tables 2 & 3 deal with the evolution of commercially viable engines which would operate on HFO or distillate and have a MTBO in the 10-20k hour range. The working group then focused on what parameters could be achieved in the Near Term (5 years) for a specialty, military only, engine with a high output but limited service life. The defense rated engine would require a large amount of government funding and would operate on distillate fuel only. The defense rating parameters are detailed in Table 4. As can be seen, the defense rated engine represents an increase in power output of roughly 50% over that of current medium speed diesels but this results in a MTBO of only 1-2k hours. Even though the engine would be designed for a limited service life, the maximum increase in power is capped by the need to maintain minimum component safety factors and eliminate the possibility of catastrophic failures. In addition to the previously detailed technology development, the defense rated engine would require camless valve actuation technology in which the intake and exhaust valves for each cylinder are moved hydraulically rather than mechanically with a conventional camshaft arrangement. Electronic control and hydraulic actuation allow greater flexibility in valve event timing and speed which results in greater airflow capability and improved cylinder component cooling schemes.

The commercially rated diesels have excellent fuel flexibility with the option of operating on HFO, distillate or natural gas. The most economic fuel is HFO, which at half the price, would represent a 50% daily fuel cost savings over distillate or natural gas. However, HFO operation results in a larger and heavier balance of plant relative to operation on distillate due to the more complex fuel system (strainers, separators, heaters) that is required to condition HFO prior to its use in the engine. Natural gas operation adds a level of complexity in fuel storage and safety considerations. Also, a pilot diesel fuel system is required in addition to the gas fuel system.

Table 2. Medium Speed Diesel Commercial Evolution

Key Parameters	Near Term (0-5 years)	Mid Term (5-10 years)	Far Term (>10 years)
Power (kHP)	40-50	50-64	57-71
BMEP (PSI)	400	450	500
BSFC (lbs/hp-hr)	0.29	0.27	0.26
RPM	300-400	300-400	300-400
Lbs/hp*	25-30	22-26	20-25
Ft^3/hp^*	0.3-0.5	0.25-0.45	0.2-0.4
Fuels	All Available	----------------------	---------------->
Emissions	Meet Stds SFC may rise	----------------------	---------------->
MTBO (khrs)	10-20	10-20	10-20

* Engine Only

Table 3. Medium Speed Diesel Evolution with Government Funding

Key Parameters	Near Term (0-5 years)	Mid Term (5-10 years)	Far Term (>10 years)
Power (kHP)	NC+	57-71	80-100
BMEP (PSI)	NC	500	600-700
BSFC (lbs/hp-hr)	NC	0.26	0.24
RPM	NC	300-400	500
Lbs/hp*	NC	20-25	10-15
Ft^3/hp^*	NC	0.2-0.4	0.2-0.4
Fuels	All Available	----------------------	--------------->
Emissions	Meet Stds SFC may rise	----------------------	--------------->
MTBO (khrs)	NC	10-20	10-20

* Engine Only + No Change

Table 4. Defense Rated Engine Parameters

Key Parameters	Near Term (5 years)
Power (kHP)	60-70
BMEP (PSI)	600
BSFC (lbs/hp-hr)	0.30
RPM	300-400
Lbs/hp*	15-20
Ft^3/hp*	0.2-0.4
Fuels	Distillate
Emissions	Meet Stds SFC may rise
MTBO (khrs)	1-2

* Engine Only

Fuel Cells

Fuel cell technology has evolved from systems originally developed for the space program. The fuel cell stack, consisting of separation plates and catalyst, converts fuel and oxidant directly into DC electric power. Each individual cell produces approximately one volt, and they are stacked together in series for the required voltage and power level. The stack fuel conversion efficiency is quite high, however, the balance-of-plant (BOP) must be taken into account when comparing fuel cell system efficiencies with other power converters. Several fuel cell types are in various stages of development. The solid oxide (SO) and molten carbonate (MC) types operate at high temperatures (1800 deg F and 1200 deg F respectively), and offer high efficiency potential. The proton exchange membrane (PEM) is light weight at low temperature and is being developed extensively for automotive applications. The phosphoric acid (PA) is already commercially produced for land based applications, producing reliable, “clean” power where needed.

All fuel cell systems operate on a fuel rich gas stream. As such the BOP is dedicated to fuel processing, or “reforming” the various hydrocarbon gases and liquids. Considerable effort is being directed to he reforming of NATO F-76 distillate fuel for use in fuel cell systems. Several processes are being investigated, including steam and autothermal reforming, and partial oxidation reforming. These processes require energy input, and as such the overall plant efficiency must take them into account. With any of these processes, other byproducts such as soot, sulfur and CO must be controlled. Sulfur, for example, is poisonous to the fuel cell stack at trace levels. The degree of fuel reforming required impacts significantly on the BOP and the resulting fuel cell system size, weight and power density. These key values are summarized in the table below.

Table 5. Achievable Fuel Cell Characteristics

Fuel Cell Technology	SFC (net)	LBS/HP	CU-FT/HP
PEM	0.34-0.31	4-9	0.14-0.22
SO (PLANAR)	0.31-0.22	7-10	0.21-0.60
SO (TUBULAR)	0.29-0.22	15-22	0.45-0.89
MCFC	0.33-0.24	30-45	0.73-1.57
PAFC	0.35-0.31	22-34	0.69-1.12

There are several fuel cell development programs underway for marine applications. They involve the Coast Guard, Maritime Administration and the U.S. Navy; and different types of fuel cell systems. Fuel cells offer high fuel conversion efficiencies, quiet and clean operation, and produce electrical power directly. Marine systems, however, have not yet been constructed operating on marine liquid fuels. Demonstration systems scheduled for the year 2000 are being designed as ship service units of 2.5MW. Fuel cell systems are most attractive when used in electric drive configurations. However, propulsion size systems (>50MW) are many years away placing them, as candidate primemovers, in the far term development category.

Transmission Systems

As horsepower requirements rise dramatically for the proposed high speed transport vessels, delivery of large amounts of power to the propulsors becomes a significant challenge. The key parameter for the transmission system is the propulsor speed (RPM). Currently projected at 100-200 RPM, this requires large reduction ratios, especially with gas turbine engines. The drive ratio governs the size of the equipment. For mechanical drives, the lightest weight and volume can be obtained with epicyclic gears (a sun and planet type arrangement), however, there available size is currently limited to approximately 20,000 hp. Doubling the power, as would be required, would require significant development effort for bearings, gear design and loading, and advanced light weight materials, such as composites. Power transmission efficiencies for gears are relatively high at .97 to .98, and a single gearbox could be designed to connect a gas turbine or diesel directly to a propulsor.

Electric transmission systems are gaining popularity commercially in applications requiring arrangement flexibility and large transfers of electrical power between ship service and propulsion. Induction type low speed motor technology has reached 44MW as represented by the propulsion motors on the Queen Elizabeth II. These are extremely large and heavy machines that are easily accommodated in such a large ship. Power generation is usually produced by a large number of diesel or gas turbine gen sets, which are brought on line by the varying demand. Electric transmissions have inherent inefficiencies as do mechanical gears. There are, however, more components in the drivetrain. Gas turbine/diesel powered systems require a generator (eff:.98), switchgear and frequency converter (eff:.94-.97) and a propulsion motor (eff: .97-.98). The resulting overall transmission efficiency is .92-.96. These values are lower than geared systems. An additional gearbox may be required ahead of the propulsor, further reducing efficiency. A high speed generator, directly coupled to a single spool gas turbine without a free power turbine, would be significantly more compact. These generators have not been built in propulsion sizes, nor at speeds greater than 7000 RPM. Incorporating these features would require significant investment of development funds. Permanent magnet technology is currently under development and offers high power densities, resulting in a more compact systems. Again these machines have not been constructed in propulsion sizes. Some of the technical areas requiring further attention include thermal management (heat removal) and power electronic switching technology.

Fuel Flexibility

Fuel flexibility was considered in discussions of each primemover. Diesel engines offer the greatest flexibility by accepting heavy fuel oils (HFO), distillate fuels (NATO F-76), and natural gas. The impact of this range of fuels on diesel design and operation, is described in the previous section. For a nominal 100,000 hp plant, the most economically acceptable fuel would be HFO at $100/ton. Typical operating costs would be $31,000 per day. Gas turbines can be operated successfully on distillate and natural gas fuels. For the above power level, distillate at $200/ton would be preferred, resulting in an operating cost of $62,000 per day. Fuel cell plants currently operate on gaseous fuels. Development described previously, is currently underway to accept liquid fuels. Propulsion size processing systems, are currently not being demonstrated, and scaling factors may be an issue. For the above plant, natural gas at $200/ton would be preferred with a cost of $56,000 per day. In summary, all primemovers could be operated on a variety of fuels, however, fuel treatment and engine modification could be extensive. The over-riding issue with alternative fuels, is the logistic supply system and subsequent availability worldwide. To properly design a HS transport vessel, the fuel/primemover/transmission should be considered as a total system whereby tradeoffs in BTU/cu ft can be made with hp/lb and hp/cu ft.

Summary

The working group summarized the power density comparisons for each primemover, by including all of the propulsion machinery (designated Group 2) for each candidate system. The results for near to mid term type systems are presented in the following table.

Table 6. Propulsion System Specific Weights

Propulsion System	Mechanical Drive	Electric Drive
Diesel	40 lbs/hp	48 lbs/hp
Gas Turbine	10-12 lbs/hp	18-20 lbs/hp
Fuel Cells	-------------	20-23 lbs/hp

Note: Electric drive offers the potential for shorter below-the-waterline machinery spaces.

The following conclusions can be drawn given the limited time available for the working group.

1. With government funding, market-driven evolution of engine technology could accelerate some mid-term and far-term parameters by five years. This gain would come, however, at a rough-order-of-magnitude estimate of $300 to 500 M. This estimate is consistent with current major engine development programs.

2. Electric drive transmissions have a higher specific fuel consumption, specific weight and volume than mechanical drive systems, but has advantages in arrangement which may compensate for these disadvantages. Advanced technology motors can be located very close to and on line with the propulsors, at the extreme aft end of the ship, or in external pods. Electrical generator sets can be optimally spaced around the ship and electrically connected. In the longer term, combined with fuel cells, SFC, specific weight and volume are comparable with gas turbine and diesel primemovers for direct drive systems.

3. Diesel engines offer fuel costs savings of 50% if heavy fuels can be used, and if emissions can be maintained at acceptable levels. Maintenance may include engine modifications such as dual fuel capability for in-port use, water injection, and timing retard, and exhaust treatment such as selected catalytic reduction and oxidation catalysts. Heavy fuel use also requires careful selection of cylinder material and lube oil to retain high MTBO.

4. Weight sensitive ship designs favor gas turbines and projected light weight fuel cell powerplants such as PEM. Heavier fuel cell

systems and diesels represent larger machinery and structural weight.

5. Hull volume/shape sensitive ship designs may favor electric drive, if the components are compact enough to be located in thinner hulls and appendages.

6. All primemovers are potentially compliant with emerging emission requirements, however, complexity for achieving compliance varies with primemover and fuel type. Diesels require the most attention to emissions control followed at some distance by gas turbines, where ultra low emissions levels have been achieved for land-based systems. Fuel cells emit the lowest levels of pollutants of all the primemovers.

In summary, in the mid to far term, advances can be made to improve fuel efficiency and, to some extent, power density for the primemovers discussed. These advances, as represented in the preceding charts, are not revolutionary, but represent the evolution of present designs. Relatively modest gains can be made, but dramatic improvements by a factor of two, for example, are not achievable without enormous expenditures for design, development and testing, far beyond commercial market needs.