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# PRELIMINARY EVALUATION OF A COMPOUND CYCLE ENGINE FOR SHIPBOARD GENSETS

June 1986




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**16. Abstract**

This report presents the results of a thermodynamic cycle (SFC) and weight analysis performed to establish engine configuration, size, weight and performance. Baseline design configuration was a 2,000 hour MTBO Compound Cycle Engine (CCE) for a helicopter application. The CCE configuration was extrapolated out to a 10,000 MTBO for a shipboard genset application. The study showed that an advanced diesel engine design (CCE) could be substantially lighter and smaller (79% and 82% respectively) than todays contemporary genset diesel engine. Although the CCE was not optimized, it had about a 7% reduction in mission fuel consumption over today's genset diesels.

The CCE is a turbocharged, power-compounded, high power density, low-compression ratio diesel engine. Major technology development areas are presented.

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## INTRODUCTION

This report presents the results of a preliminary evaluation of a Compound Cycle Engine (CCE) for driving a 1000 kW ship service type generator of the type used on a U.S. Navy FFG-7 class ship. The objective of this evaluation was to determine if an advanced design diesel engine could be substantially lighter and smaller than today's contemporary genset diesel. Basis for this advanced design was a CCE analytical study and component technology program sponsored by the U.S. Army Aviation Systems Command (AVSCOM) for a light helicopter application(1). The helicopter engine concept is used as the basis for the genset evaluation. The AVSCOM CCE helicopter engine design parameters and MTBO hours were changed for the longer life ship service genset application. To accomplish this, the helicopter engine design was derated and the resultant performance potential in genset service identified.

As shown in Figure 1, a CCE combines the airflow capacity and lightweight features of a gas turbine engine with the heavier but highly efficient diesel engine. The compressor of the gas turbine module delivers high pressure air to the diesel core where further compression takes place in the cylinders (as with a conventional reciprocating compressor). Fuel is introduced and burned at very high pressure and temperature in the diesel cylinder and power is extracted on the downstroke of the piston. The exhaust gas, with its remaining energy, is then ducted to turbines that drive the compressor and also augment the output of

(1) GTEC Report 21-5854-2 "Compound Cycle Engine for Helicopter Application"

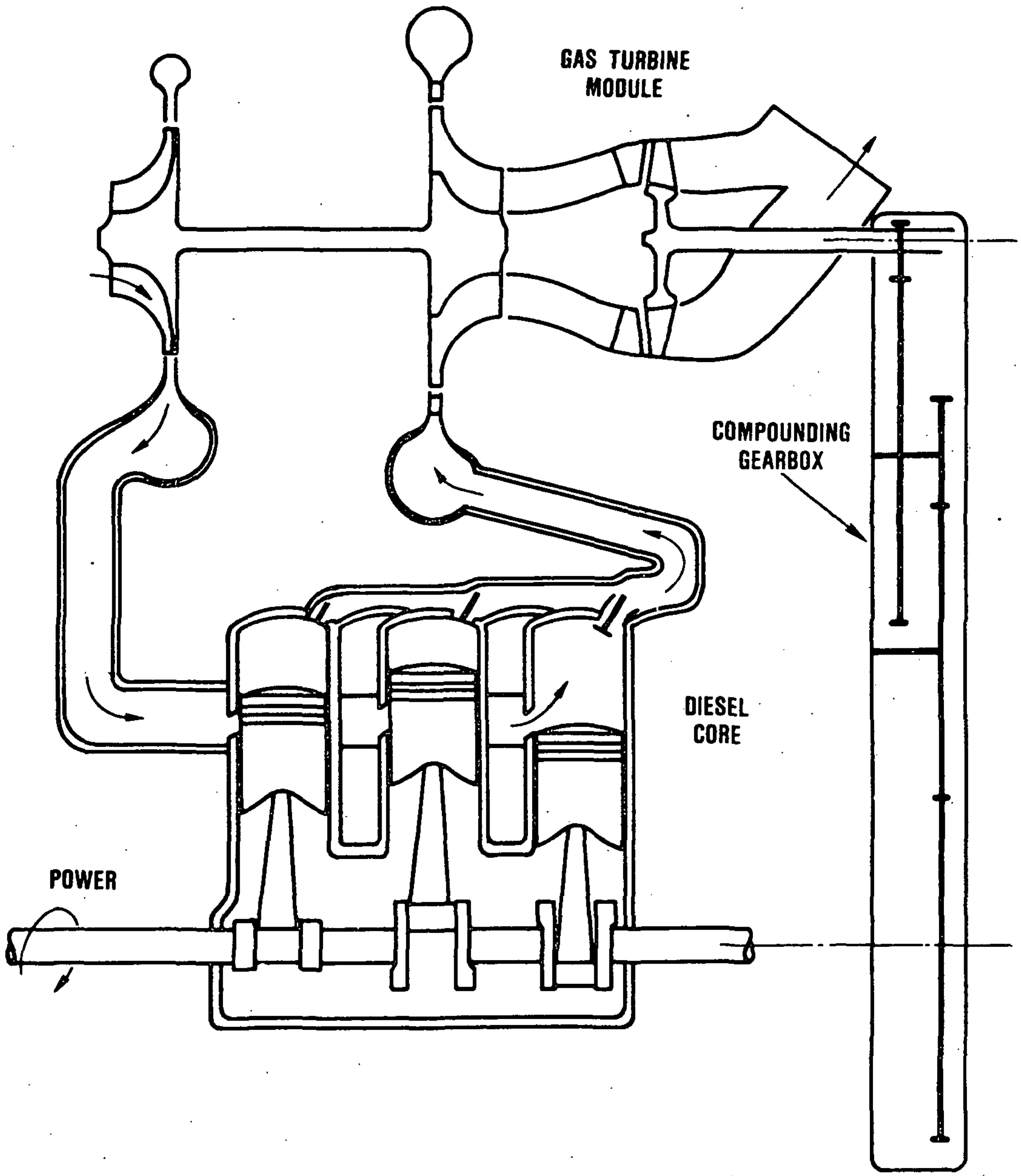



Figure 1. Arrangement of Compound Cycle Engine.

the diesel core. Therefore, the term compound cycle is an expression used to describe the process where additional power is extracted from the exhaust energy by the turbomachinery and compounded through gearing to add to the output of the diesel core.

Diesel powered electrical generator sets are widely used as primary or backup electrical power sources for a variety of marine and ground applications. For shipboard gensets, there have been no major changes for many years in the basic design of the engine driving the generator. Typically for older ships, the engines are low speed, large and heavy, and cannot be easily removed for major maintenance or overhaul. Requirements for recent and future ships dictate that the genset engines must be much lighter, more compact or modular, and easily maintainable or removeable to reduce service and down-time. In order to have lighter and smaller engines, it is necessary to go to different engine configurations or types with higher power densities. The CCE being studied under AVSCOM's Advanced Diesel Engine Propulsion Technology (ADEPT) program for a helicopter application is a very lightweight, fuel-efficient, high power density engine. A small study was undertaken to define a CCE for a shipboard genset using the helicopter engine technology as the baseline.

The AVSCOM CCE helicopter engine 2000 hour MTBO design parameters are redefined and discussed for the 10,000 hour MTBO ship service genset application. An engine thermodynamic cycle parametric study using the redefined design parameters was performed to determine the best configuration based on specific fuel consumption (SFC), performance, and weight. The weight prediction method is also discussed. The CCE configuration is compared to a Detroit Diesel Allison 16V-149TI diesel engine (currently in use) on the basis of size, weight and fuel usage for a typical ship mission. The helicopter engine specific power output was derated to obtain the 10,000 hour MTBO and its performance was then calculated. A discussion of technologies that must be developed for the CCE is also presented.

## Engine Design Parameters

In order to get a five-fold increase in MTBO (10,000 hours) over the CCE helicopter engine for the shipboard genset requirement, it was necessary to reduce the specific power of the engine. This was achieved by reducing thermal loads on the piston (bhp/in$^2$), engine speed, peak firing pressure, and piston top ring reversal temperature. The specific design parameters and the range chosen to implement this study were as follows:

| | | |
|---|---|---|
| o | Power | 1405 shp |
| o | Thermal Load | 8 to 12 hp/in$^2$ |
| o | Crankshaft Speed | 3600 rpm |
| o | Peak Firing Pressure | 3000 psia |
| o | Trapped Equivalence Ratio | 0.50 |
| o | Intake Manifold Air Temp | 200F |
| o | Number of Cylinders | 12 to 16 |

These parameters were arrived at by assessing current diesel 10,000 hour engine technology and then projecting out to the same state of R&T development as the helicopter engine. Engine life rather than performance, dominated over weight considerations in the design parameter selection. An engine speed of 3600 rpm was arbitrarily selected for a 60 Hz synchronous match for direct drive to a generator.

## Parametric Studies

A two-stroke cycle, uniflow engine, the same type as the helicopter engine, was selected as the study baseline. The engine was sized at 100 percent power (sea level, standard day) even though the average engine power level is approximately 50 percent.

Two configurations were investigated: one turbocharged and a 1-1/2 spool configuration with a turbine-driven compressor and a compounding turbine. Calculations were performed for three different combinations of bore, stroke, and number of uniflow-scavenged cylinders. In effect, this covered a range of thermal loading from 8 to 12 bhp/in$^2$. In each case, the piston stroke was selected for a mean piston velocity of 2160 ft/min and the engine speed was fixed at 3600 rpm. Since the power output, peak firing pressure, and trapped equivalence ratio were fixed, effective compression ratios and turbocharger pressure ratios were varied.

The uniflow cylinder porting and valve characteristics were assumed to be identical to those used for the selected helicopter engine. The turbomachinery (state-of-the-art) performance maps were also the same, but only a single stage compressor was required for the lower supercharging pressure ratios. Aftercooler effectiveness was varied as required to deliver 200F air to the intake manifolds at full power. Seawater coolant was used in the heat exchanger, rather than air since this significantly reduces the heat exchanger size. A coolant pumping power of 15 hp was estimated for circulating the coolant.

The design characteristics for the uniflow turbocharged and 1-1/2 spool turbocompound engines are listed in order of increasing thermal loading in Tables 1 and 2, respectively.

The brake SFC increases at the higher thermal loadings since keeping firing pressure constant dictates a reduction in effective compression ratio at higher boost pressures. The same design-point parametric trends are displayed by both the turbo-

TABLE 1. GENERATOR SET TURBOCHARGED ENGINE DESIGN DESIGN POINT CHARACTERISTICS (1405 HP, 3600 RPM)

| | | | |
|---|---|---|---|
| Thermal Load ($hp/in^2$ nominal) | 8 | 10 | 12 |
| Number of Cylinders | 16 | 12 | 12 |
| Bore (in) | 3.750 | 3.875 | 3.500 |
| Stroke (in) | 3.600 | 3.600 | 3.600 |
| Displacement ($in^3$) | 636 | 509 | 416 |
| Air Flow (lb/sec) | 5.67 | 5.84 | 6.22 |
| BMEP (psi) | 246 | 307 | 376 |
| Compressor Pressure Ratio | 4.44 | 5.60 | 6.95 |
| Effective Compression Ratio | 11.32 | 9.18 | 7.51 |
| Trapping Efficiency (%) | 64.8 | 65.0 | 63.9 |
| Diesel Exhaust Temp (F) | 960 | 1006 | 1037 |
| Aftercooler Effectiveness | 0.61 | 0.67 | 0.71 |
| Turbocompressor Speed (rpm) | 51,642 | 56,084 | 59,726 |
| Indicated Thermal Efficiency (%) | 46.5 | 44.3 | 41.9 |
| SFC (lb/hp-hr) | 0.334 | 0.345 | 0.361 |
| Installed Weight Estimate* (lb) | 2364 | 2054 | 1820 |

*Weights were estimated to be twice the calculated weight of aircraft engines because of the expected extensive use of cast iron in the genset engine construction.

TABLE 2. GENERATOR SET 1-½ SPOOL TURBOCOMPOUND ENGINE DESIGN POINT CHARACTERISTICS (1405 HP, 3600 RPM)

| | | | |
|---|---|---|---|
| Thermal Load (hp/in$^2$ nominal) | 8 | 10 | 12 |
| Number of Cylinders | 16 | 12 | 12 |
| Bore (in) | 3.750 | 3.875 | 3.500 |
| Stroke (in) | 3.600 | 3.600 | 3.600 |
| Displacement (in$^3$) | 636 | 510 | 416 |
| Air Flow (lb/sec) | 5.15 | 5.20 | 5.35 |
| BMEP (psi) | 237 | 291 | 353 |
| Compressor Pressure Ratio | 4.79 | 6.13 | 7.46 |
| Effective Compression Ratio | 11.08 | 8.95 | 7.48 |
| Trapping Efficiency (%) | 68.4 | 69.4 | 68.8 |
| Diesel Exhaust Temp (F) | 1059 | 1114 | 1160 |
| Aftercooler Effectiveness | 0.64 | 0.69 | 0.72 |
| Turbocompressor Speed (rpm) | 53,305 | 57,600 | 60,970 |
| Diesel Power (hp) | 1357 | 1334 | 1319 |
| Brayton Power (hp) | 48 | 71 | 86 |
| Indicated Thermal Efficiency (%) | 45.6 | 43.0 | 41.1 |
| BSFC (lb/hp-hr) | 0.330 | 0.339 | 0.346 |
| Installed Weight Estimate* (lb) | 2405 | 2105 | 1874 |

*Weights were estimated to be twice the calculated weight of aircraft engines because of the expected extensive use of cast iron in the genset engine construction. The use of lightweight materials would substantially reduce engine installed weight, but it is not known what the effects of lightweight materials usage might have beyond 2000 hours to the 10,000 hour MTBO requirement.

charged and turbocompound engines. The efficiency gain associated with compounding for the genset is smaller than it was for the helicopter engine because of the lower boost pressure and trapped equivalence ratio. Table 2 shows that, for the initial engine configuration, the power turbine contributes relatively little net output power due to low diesel exhaust temperatures and pressures.

The effect of turbocompounding SFC is shown in comparison with a turbocharged engine in Figure 2. Turbocompounding is clearly beneficial and therefore was selected for mission fuel consumption computations.

Engine Cycle Selection

A detailed thermodynamic cycle analysis on the selected 16 cylinder, 1-1/2 spool, turbocompound aftercooled engine configuration indicated that a better part load SFC and power split between the diesel and turbine could be obtained by using different turbomachinery and rematching the components. Valve timing was also adjusted for the 3600 rpm operation. This adjustment also reduced engine airflow, blowback fraction, and scavenge ratio. A comparison of the rematched genset engine with that used for the parametric study is shown in Table 3. During the helicopter study, engine data for power density ($hp/in^3$) and thermal loading ($hp/in^2$) versus mission life (Figures 3 and 4 respectively) were plotted for a wide range of diesel and spark ignition engines. It can be seen that the genset power density, Figure 3, of 2.2 $hp/in^3$ and thermal loading, Figure 4, of 8 $hp/in^2$ fell within the projected CCE values for 10,000 hours.

The cycle conditions and mechanical power distributions for the 1-1/2 spool CCE for 100 and 50 percent load are shown in Figures 5 and 6 respectively. The beneficial effects from compound-

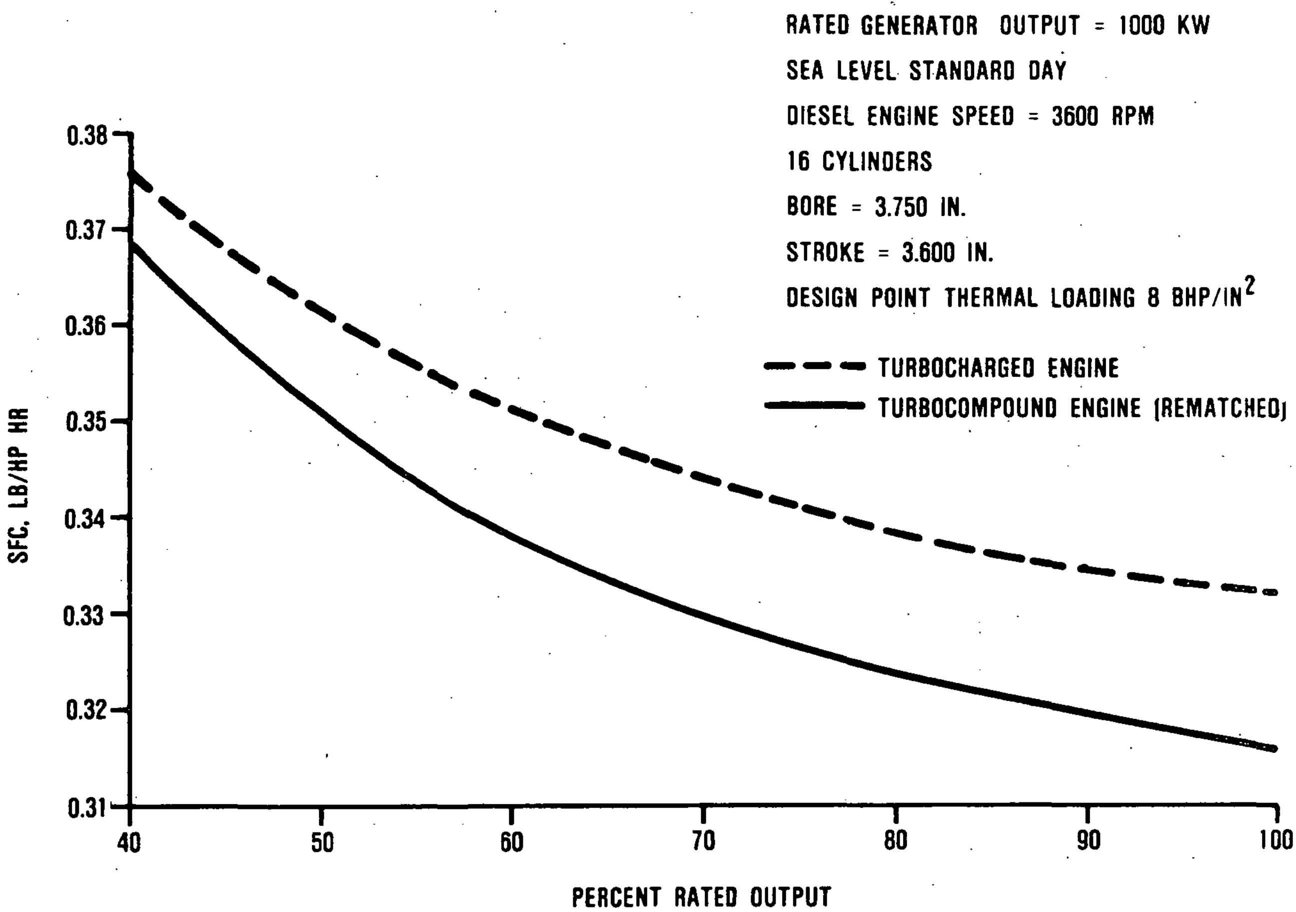



Figure 2. Generator Set Off-Design Performance.

TABLE 3. COMPARISON OF REMATCHED ENGINE

| Engine Parameters | Initial | Rematched |
|---|---|---|
| Air Flow (lb/sec) | 5.15 | 4.11 |
| BMEP (psi) | 237 | 226 |
| Compressor Pressure Ratio | 4.79 | 5.16 |
| Effective Compression Ratio | 11.08 | 11.60 |
| Diesel Exhaust Temperature (F) | 1059 | 1178 |
| Turbocompressor Speed (rpm) | 53,305 | 54,670 |
| Diesel Power (hp) | 1357 | 1291 |
| Brayton Power (hp) | 48 | 114 |
| Compressor Efficiency | 0.75 | 0.79 |
| HP Turbine Efficiency | 0.845 | 0.842 |
| LP Turbine Efficiency | 0.807 | 0.817 |
| Inlet Port Opens (ATDC) (degrees) | 126 | 133 |
| Exhaust Valve Opens (ATDC) (degrees) | 90 | 101 |
| Exhaust Valve Closure (ATDC) (degrees) | 239 | 227 |
| Scavenge Ratio | 0.850 | 0.631 |
| Blowback Fraction | 0.048 | 0.050 |
| SFC | 0.330 | 0.316 |
| Bore | 3.750 | 3.750 |
| Stroke | 3.600 | 3.600 |
| Displacement ($in^3$) | 636 | 636 |
| Thermal Loading ($hp/in^2$) | 8 | 8 |
| Power Density ($hp/in^3$) | 2.21 | 2.21 |
| Peak Firing Pressure (psi) | 3011 | 3020 |
| Weight (lb) | 2405 | 2367 |
| Relative Density ($lb/in^3$) | 3.78 | 3.72 |

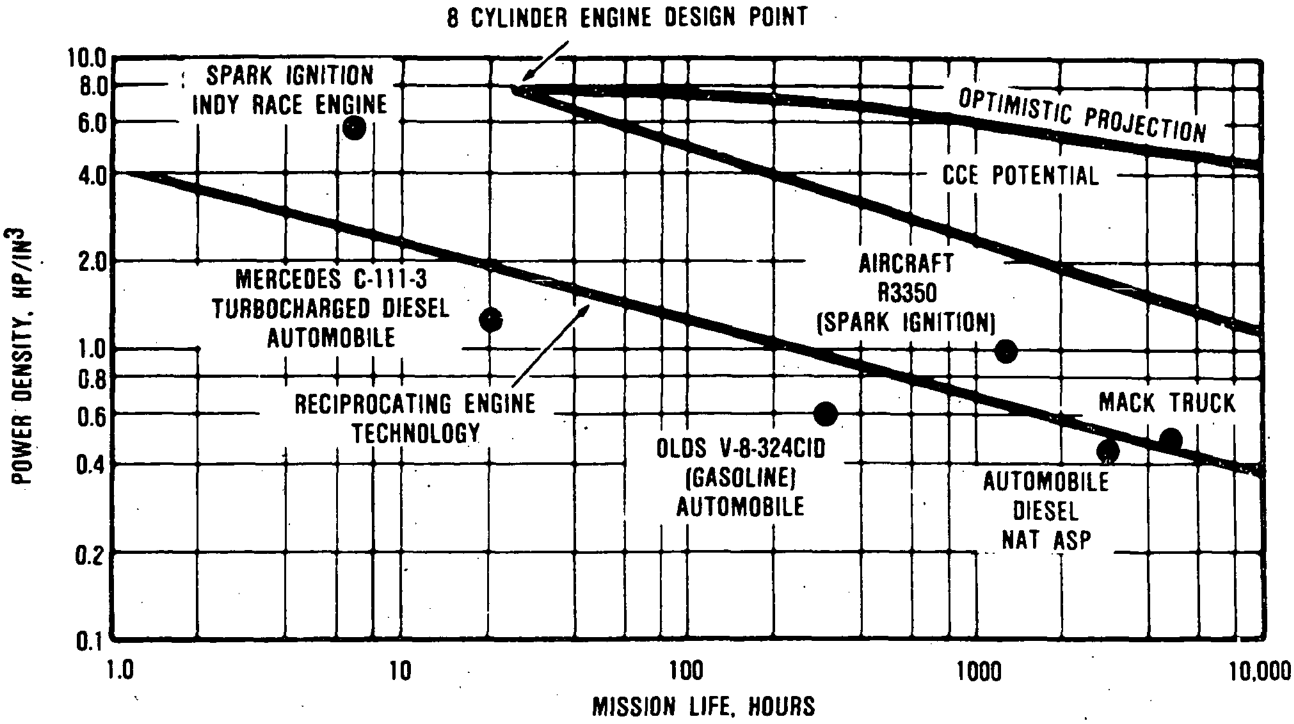



Figure 3. Power Density Versus Mission Life.

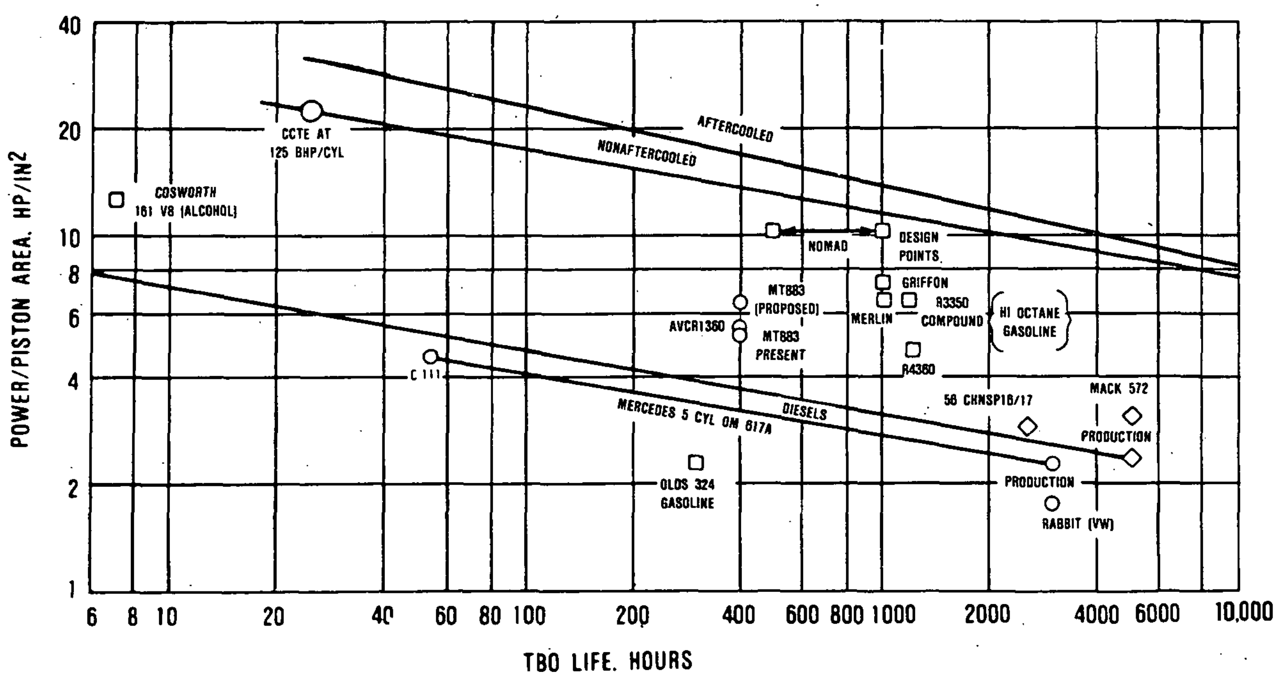



Figure 4. Engine Life Tradeoff.

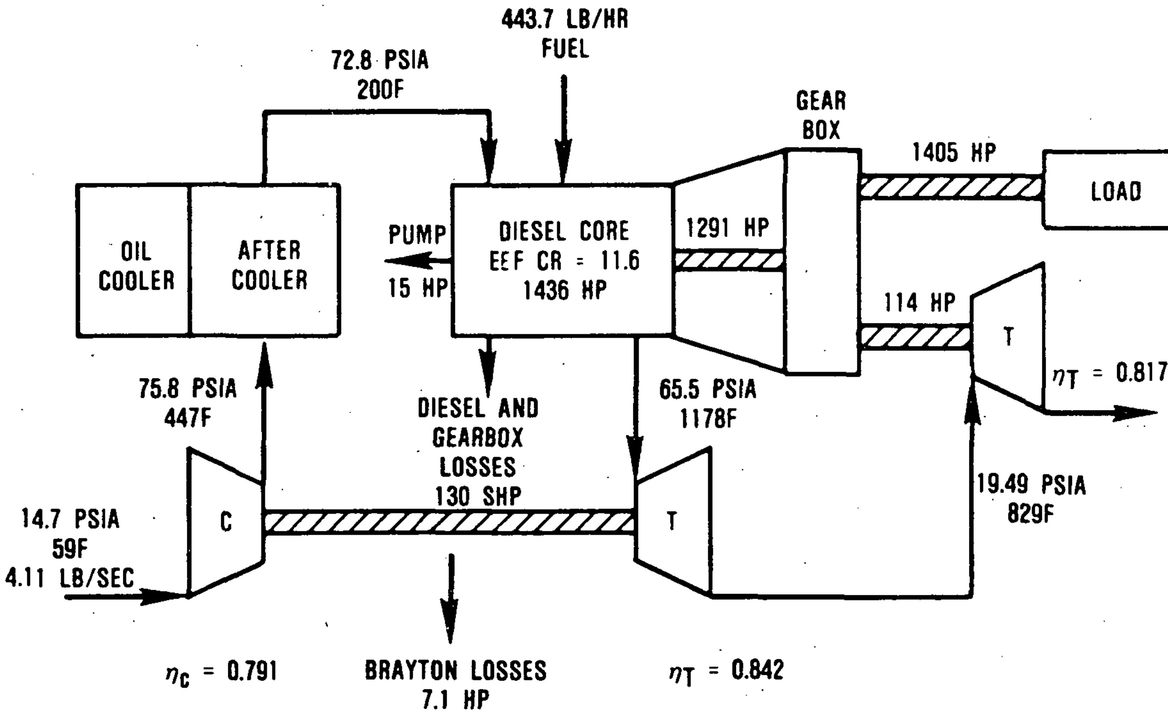



Figure 5. Design Point 1-1/2 Spool Compound Cycle Engine, Sea Level, Standard Day Operating Conditions.

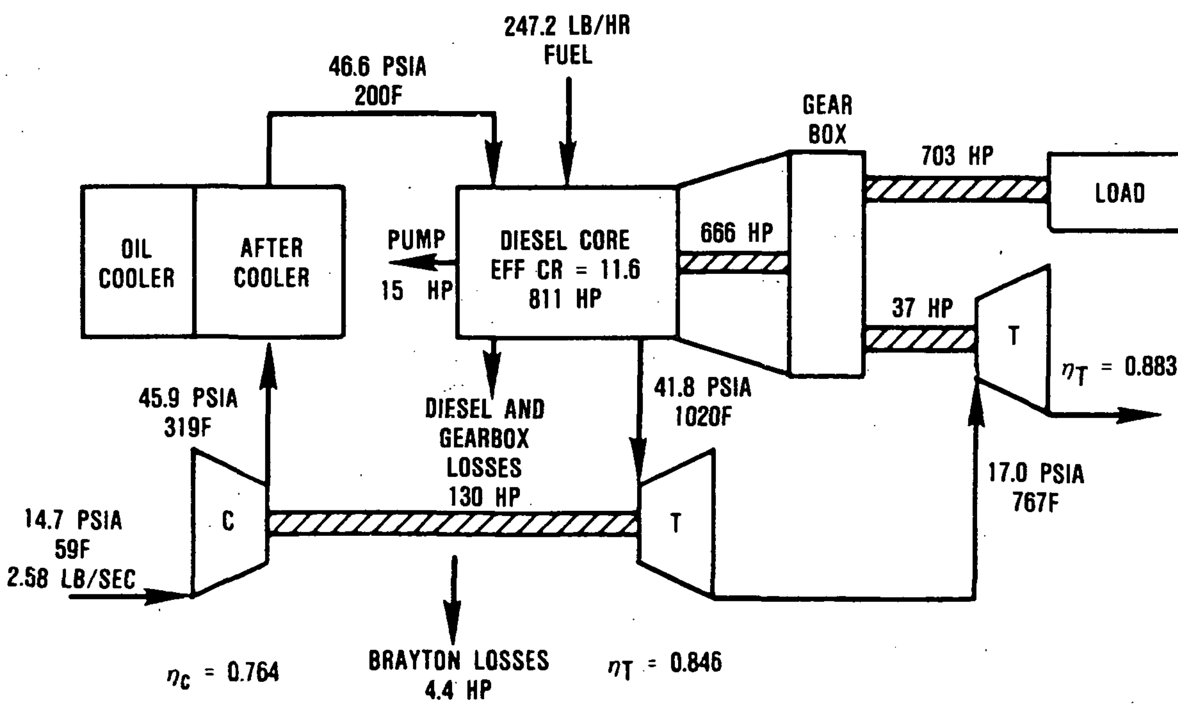



Figure 6. Fifty Percent Power, 1-1/2 Spool, Compound Cycle Engine, Sea Level, Standard Operating Conditions.

ing decreased as the electrical load is reduced but there is still a positive gain of 32 hp at 50 percent load. In a more detailed study, the engine would be optimized and designed at the 50-percent load (nominal operating) condition for 10,000 hour MTBO. This would result in a higher compounding power output and reduced SFC.

## Mission Fuel Consumption

The average load power level for a shipboard genset is about 50 percent and was used to calculate annual fuel consumption. There are four 1000 kW diesel gensets per ship. Two of the diesels are run concurrently for 5300 hours per year or 2650 hours per engine per year. The four engines would therefore accumulate 10,600 engine hours per year. A fuel consumption curve (Figure 7) for the 16V-149TI engine was generated by extrapolating DDA Curve No. E4-9165-32-34, dated January 9, 1984, which was obtained from a local Detroit Diesel Allison distributor. A comparison between the CCE and the 16V-149TI indicates that a potential exists for saving 7 percent of the mission fuel consumption (7370 gallons per engine or 29,480 gallons of fuel for four engines, each operating 2650 hours).

## Engine Volume and Weight

It was assumed that the genset 16 cylinder CCE would consist of two 8 cylinder modules coupled in-line for ease of removal and to reduce the hatch size required to remove them from the ship. Engine weight was calculated using equations developed during the helicopter study and modified slightly for this application. The calculated engine core weights were arbitrarily doubled because it was thought that cast iron engine construction would probably be used in the genset application. The weight equations are discussed in detail in the CCE helicopter engine study final report[1]. Figure 8 from the helicopter engine study, is a com-

(1) GTEC Report 21-5854-2 "Compound Cycle Engine for Helicopter Application"

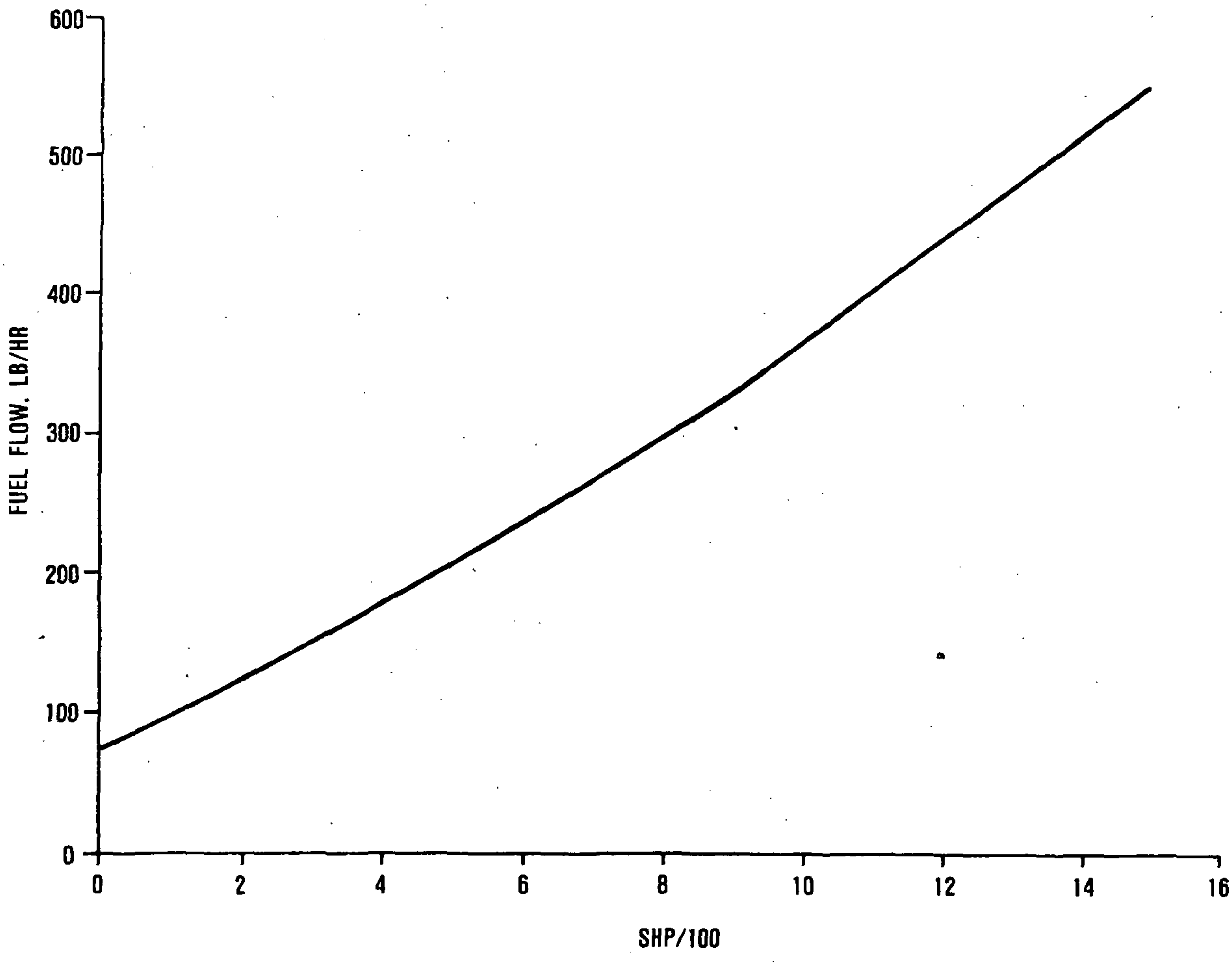



Figure 7. Estimated Fuel Consumption of 16V-149TI Engine.

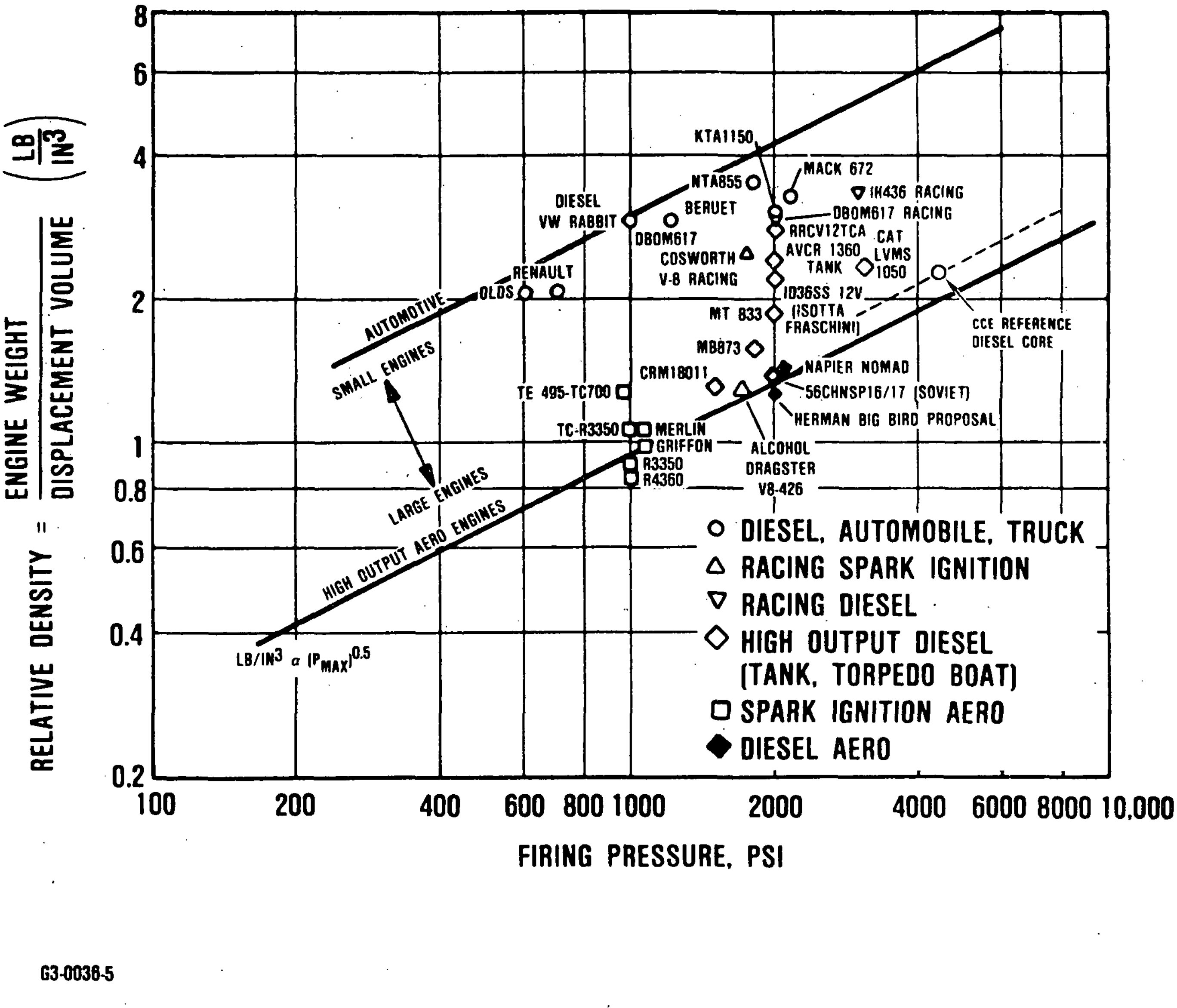


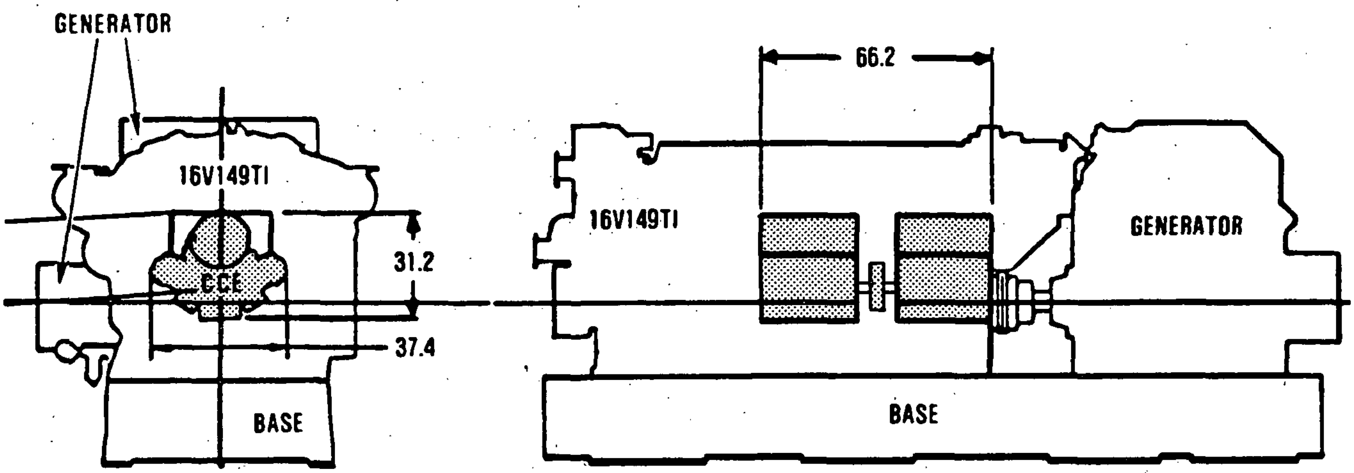

Figure 8. Effect of Firing Pressure of Engine Weight.

pilation of engine relative density (engine weight/displacement volume, lb/in$^3$) versus maximum firing pressure (psi) for a wide range of diesel and gasoline engines. Trend lines are shown for automotive, high output aero and CCE reference core engines. Figure 8 shows at the genset maximum firing pressure of 3000 psi, genset engine weight specific density of 3.72 lb/in$^3$ displacement volume is conservative relative to high output aero engines, but is more in line with that of high performance truck or tank engines. A more accurate estimate of engine weight would require a conceptual design effort that was beyond the scope of this study. Engine estimated weight and volume for the compound cycle engine are shown for comparison with the 16V-149TI diesel engine in Figure 9. At the power density selected, the engine box volume would be reduced approximately 82 percent from 254 to 45 cubic feet and engine weight could potentially be reduced 79 percent from 11,200 to 2,367 pounds.

Cross sections of the V-6 cylinder helicopter engine conceptual design are shown in Figure 10. The scope of this study effort did not allow for any conceptual design effort on the genset engine. However, it is reasonable to assume that the genset engine configuration could be similar (Vee form) to the helicopter engine.

## Engine Life

It is impossible at this time to accurately predict or quantify engine life. However, the engine selected is thought to be a reasonable selection of key engine design parameters to meet the long life objectives for the genset application. Speeds, loads, pressures, and temperatures have been substantially reduced from those selected for the helicopter application. An indication that the engine design is in line with the criteria used in the helicopter engine study can be seen in Fig-




| | 16V149TI** | CCE TECHNOLOGY |
|---|---|---|
| ENGINE SPEED, RPM | 1800 | 3600 |
| ENGINE BOX VOL $FT^3$ | 254 | 45 |
| ENGINE WEIGHT, LBS | 11,200 | 2367* |
| BSFC LB/HP-HR | 0.360 | 0.316 |

*WEIGHT = 2 x A/C ENG WEIGHT EST.
(100 PERCENT CAST IRON/STEEL)
**SAE 851243

Figure 9. 1000 kW Generator Set Study Shows Potential for CCTDE Derivative Engine.

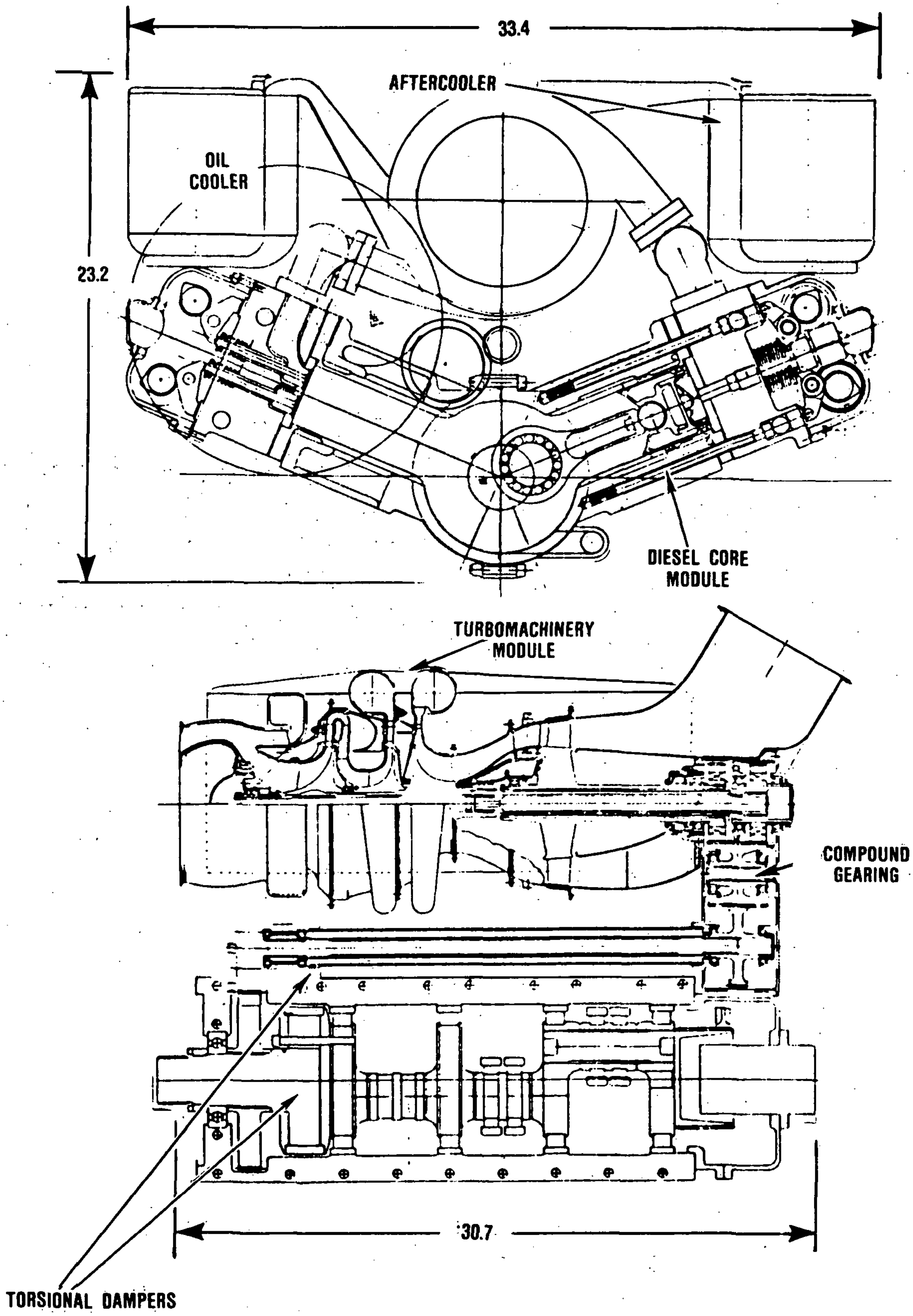



Figure 10. Helicopter Engine Conceptual Design.

ures 3 and 4. These figures show the engine power density (hp/in$^3$) and thermal loading (hp/in$^2$) life (MTBO) trends for a wide range of diesel and gasoline engines. At 10,000 hours, the genset engine is in line with CCE projected performance levels. A comparison of the helicopter and genset engine design parameters is shown in Table 4 for sea level, standard day operation at rated power. Genset operational parameters at 50-percent power are also shown. In addition, engine operational parameters for a derated version of the helicopter engine designed to meet a 10,000 hour MTBO are shown. For a genset application, the helicopter engine turbomachinery would be considerably different since it would only have to operate at sea level conditions.

## Major Technology Development Areas

The turbomachinery module consists of state-of-the-art technology components. The diesel core configuration follows nominally conventional design practices for two-stroke engines, but the operating pressures, temperatures, and speeds are somewhat higher and therefore beyond today's demonstrated diesel engine technologies.

Based on the helicopter engine study, three major technology development areas have been identified for the diesel core. These are in the order of considered importance:

- o Piston ring/liner interface wear life
- o Exhaust valve life
- o Fuel injection with high heat release rate combustion

## Piston Ring/Liner Interface Wear Life

The primary development or life limiting factor of most concern is the wear rate of the piston ring/liner interface materials. Factors that influence this wear are:

TABLE 4. HELICOPTER AND GENSET ENGINE COMPARISON

| Engine | Referenced Helicopter 100% Pwr | Derated Helicopter 100% Pwr | Genset 100% Pwr | Genset 50% Pwr |
|---|---|---|---|---|
| Estimated TBO (hours) | 2000 | 10,000 | 10,000 | 10,000 |
| Rated Power (shp) | 1000 | 363 | 1405 | 703 |
| Engine Speed (rpm) | 6125 | 3600 | 3600 | 3600 |
| Inlet Air Temp (F) | 435 | 200 | 200 | 200 |
| Equivalence Ratio | 0.68 | 0.62 | 0.50 | 0.42 |
| Exhaust Gas Temp (F) | 1750 | 1260 | 1178 | 1020 |
| BMEP (psi) | 393 | 284 | 226 | 118 |
| Piston Velocity (ft/min) | 3000 | 1764 | 2160 | 2160 |
| $HP/in^2$ Piston Area | 22 | 8 | 8 | 4 |
| $HP/in^3$ Disp. | 7.5 | 2.7 | 2.2 | 1.1 |
| Peak Firing Pressure (psi) | 3360 | 2018 | 3020 | 1971 |
| No. of Cylinders | 6 | 6 | 16 | 16 |
| Installed Weight (lb) | 432 | 432 | 2367 | 2367 |
| Compressor Efficiency | 0.79 | 0.75 | 0.79 | 0.77 |
| HP Turbine Efficiency | 0.85 | 0.85 | 0.84 | 0.85 |
| LP Turbine Efficiency | 0.85 | 0.74 | 0.82 | 0.88 |
| Bore | 3.101 | 3.101 | 3.750 | 3.750 |
| Stroke | 2.940 | 2.940 | 3.600 | 3.600 |
| Displacement | 133 | 133 | 636 | 636 |
| SFC (lb/hp hr) | 0.330 | 0.361 | 0.316 | 0.352 |

- Piston velocity and engine speed
- Piston ring/liner geometries
- Surface topography
- Material composition and properties
- Oil film type and thickness
- Operating pressures and temperatures
- Contamination (foreign and self generated) and filtration
- Lubricant type and additives
- Time between oil changes - oil condition

The generator set engine has a 10,000 hour TBO requirement which is five times greater than that of the helicopter engine. The engine operating conditions have been reduced for the generator set application as compared with the helicopter engine, thereby easing the piston ring/liner interface, P, V, T conditions. The following tabulation shows a comparison between the helicopter, genset and commercial engines. With the exception of the 3600 rpm engine speed, the other parameters are generally only slightly higher than those of commercial generator set applications.

| Parameter | Helicopter Engine | Genset Engine | Commercial Engine |
|---|---|---|---|
| TBO - (hours) | 2000 | 10,000 | 10,000 to 20,000+ |
| Engine Speed (rpm) | 6000 | 3600 | 1800 to 1200 |
| Piston Speed (fpm) | 3000 | 2160 | 1800 to 1200 |
| BMEP (2 Stroke) (psi) | 393 | 226 | 140 to 200 |
| Exhaust Gas Temperature | 1750 | 1178 | 1200 to 1000 |
| Equivalence Ratio | 0.68 | 0.50 | 0.50 maximum |
| $hp/in^2$ Piston Area | 22 | 8 | 4 to 3 |

Complex interactions between the different operating parameters make it difficult to quantify overall effects on engine life. However, the qualitative effects are well understood. A great deal of experience is available on low power density diesel engines, but it is quite limited in its extension into some of the design regions of the CCE discussed here. The extensive single cylinder engine testing that will be performed under the helicopter engine program will provide considerable parametric information at the generator set engine operating conditions. These tests will be made under controlled conditions using the best lubricant formulations and tribological couples which are available in order to establish a technology baseline for CCE wear-life predictions.

Exhaust Valve Life

The exhaust valve life is the second most important item for CCE development. The exhaust gas valve temperature at full power is within the range of current experience, and the temperature at 50 percent power is lower than at full power, but the frequency of operation is two to three times higher. A combination of both metallurgical and kinematic investigations will be required to validate the required life of 10,000 hours. A low heat rejection (LHR) engine design would increase the exhaust energy available for compounding power but would increase exhaust gas and valve temperatures. Tradeoffs would have to be performed on heat rejection/installation versus exhaust valve life.

Fuel Injection/Combustion

Fuel injection with high heat release rate combustion is considered to be the third most important area for development. The primary requirement for the fuel injection equipment for a direct-injected diesel is to distribute a uniform, finely atomized charge of fuel throughout the combustion chamber, at the right time and in the correct quantity. If not, excessive peak cylinder pressures could occur, exhaust smoke would increase and engine life might be shortened. The injection frequency is two to three times greater than that of current genset engines and the unit injector camshaft-follower relationship and wear will require both metallurgical and kinematic investigations. High speed requires high injection pressures for increased heat release rate combustion over a shorter duration. A high pressure (>20,000 psi) electronically controlled hydromechanical type fuel injection system is considered the prime candidate for both the helicopter and generator set applications.

## Conclusions

It is evident from this preliminary compound cycle engine evaluation study that advancing the state-of-the-art of diesel engine technologies offers dramatic potentials for reducing installed genset engine weights and volumes. There is also a potential fuel savings payoff of a CCE when compared with the 16V-149TI turbocharged diesel, but it is less dramatic than the weight or volume savings. However, the fuel savings might be considered significant under some operating scenarios.

The CCE payoffs indicated in this study are also indicative of what might be expected for today's mobile ground/marine applications such as LCAC (landing craft, air cushion) vessels which are weight and volume limited.

It is impossible at this time to accurately quantify high power density engine life. In order to conserve or maximize returns on critical R&D funds, every effort should be made to coordinate diesel core engine development and life work currently underway by various government agencies. This information should be disseminated among the various investigators to eliminate any unnecessary duplication of efforts between interested parties.

## LIST OF SYMBOLS

| | |
|---|---|
| $hp/in^3$ | Horsepower per cubic inch |
| CR | Compression Ratio |
| EFF | Effective |
| F | Fahrenheit |
| hp | Horsepower |
| $hp/in^2$ | Horsepower per square inch |
| hr | Hour |
| in | Inch |
| $in^3$ | Cubic inch |
| kW | Kilowatt |
| lb | Pound |
| lb/sec | Pounds per second |
| MTBO | Mean time between overhaul |
| psi | Pounds per square inch |
| psia | Pounds per square inch absolute |
| PVT | Pressure/velocity/tempertaure |
| rpm | Revolutions per minute |
| shp | Shaft horsepower |
| > | Greater than |
| % | Percent |
| $\eta$ | Efficiency |