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Intercooled/Recuperated Shipboard Generator Drive Engine

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ABSTRACT

Adverse consequences of losing electrical power to complex electronic and fire control equipment, or of the sudden variations of shore power, cause naval combatants to operate two generators most of the time, each at light load where specific fuel consumption of simple-cycle gas turbines is particularly high. The recuperated gas turbine with variable power-turbine nozzles has a much better specific fuel consumption, especially at part load. Herein described is a compact recuperated gas turbine with variable power-turbine nozzles designed for marine and industrial use, suitable with or without intercooling. These features yield a specific fuel consumption that is comparable to marine diesels used for generator drive, and essentially flat across the entire usable load range.

HISTORY

Ever since gas turbines have been considered for marine and industrial use, the advantages of recuperation have been recognized. The unsuccessful gas turbine of the French engineer Stolze in 1872 had axial compressors and turbines - and a recuperator. The various merchant marine main-propulsion units developed in the 1940's and 1950's were generally recuperated, and many were intercooled. Significant numbers of industrial gas turbines have been recuperated. Almost invariably these recuperated units have been large and heavy, with long start-up times and susceptibility to recuperator cracking and leakage if subjected to other than gradual load changes.

Marine generator drives and naval main propulsion units must respond to frequent and large load changes. The constant and insidious presence of salt, plus the inevitable sulfur in marine fuels, make crevice corrosion and cracking a constant hazard. The wracking of the ship and the gas turbine ducting in a seaway add shifting physical strains to the normal thermal strains in the recuperator. Intercooling, which from a thermodynamic viewpoint is particularly advantageous in a high-temperature recuperated machine, adds both thermal and condensation complications. As a result, intercooled and recuperated marine units have been singularly unsuccessful, especially in the applications which are particularly subject to sudden and large load changes.

BACKGROUND

With the above in mind, the Caterpillar Tractor Co. has been working for more than 20 years to develop a gas turbine which will be competitive with its diesel engines, and which will meet the demanding conditions of the marine environment. In addition to continuous in-house work and development, extensive talent and experience were gained through acquisition of Boeing's gas turbine activity in 1966, and acquisition of Solar Turbines Incorporated in 1981. The combined experience has culminated in the present Model 5650 gas turbine and its derivatives.

A most important feature is the recuperator design. This is a modular primary-surface folded-metal-sheet recuperator whose elements can slide relative to each other over most of their geometry, thus avoiding destructive strains. All welds are at the recuperator ends, where they can be readily inspected and easily repaired, if required.

Another somewhat unique feature of this engine is the variable-geometry power-turbine nozzle which is particularly applicable to overcoming or avoiding problems that have caused previous recuperated marine gas turbines to be unsuccessful. This not only makes quick load response practical, but it also provides a reasonably constant recuperator hot end inlet temperature, thus minimizing thermal strains as load changes.

A third important feature is the relative simplicity and conservatism of the design, with particular attention to the many details of requirements of operation in the marine environment, as accumulated by decades of experience in designing, manufacturing and servicing prime movers and ancillary equipment for this demanding application.

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GENERAL FEATURES

The 5650 gas turbine engine, shown in Fig. 1, is unlike any other gas turbine power plant currently available. It achieves a thermal efficiency over a wide range of applied load with about the same footprint as simple-cycle gas turbines of the same power range. Its fuel efficiency exceeds that of these simple-cycle turbines by as much as 30% at full load and by over 50% at half load. The overall thermal efficiency of the machine was set as a primary goal of the design, and it is intended to emulate that of the best reciprocating engines in both overall level and in characteristic. The 5650 engine has the following features:

- Marine and Industrial Gas Turbine
- Modular Major Components
- Recuperation
- 2-Stage Centrifugal Compressor
- 1-Stage Gas Producer Turbine
- 1-Stage Power Turbine
- Variable-Geometry Power-Turbine Nozzle

A major design guideline was overall compactness or engine size. This constraint caused design trade studies to favor a very compact but highly effective heat exchanger, the elimination of interconnecting ducts, and the creation of a unit smaller in bulk than competing reciprocating engines, and not significantly greater volume than less efficient simple-cycle gas turbines in the same power class.

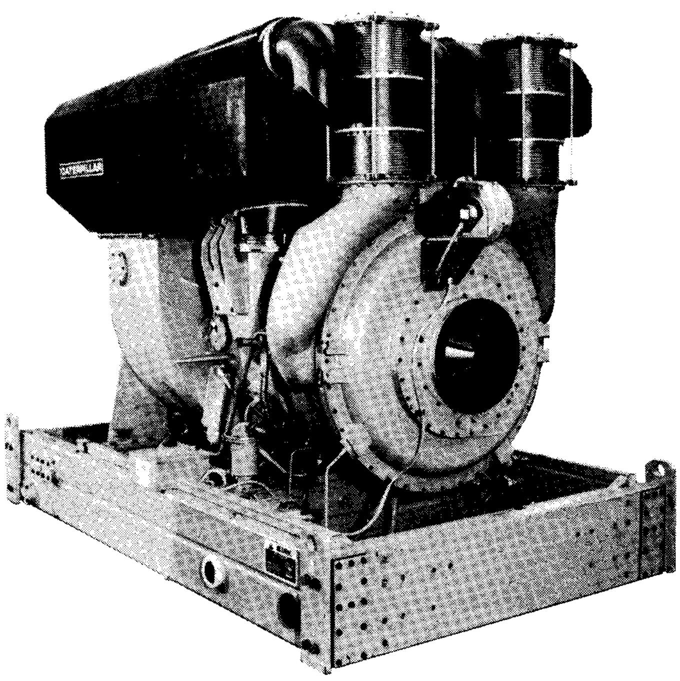


Figure 1. Model 5650 Marine/Industrial Gas Turbine

Other major considerations of the 5650 design are its serviceability and maintainability. As shown in Fig. 2, the engine is designed for the rapid and easy removal of major modules for inspection or repair. The module containing the compressor, combustor and gas producer turbine can be extracted by breaking one splitline. The parts can be inspected or replaced, and the module can be reinstalled in 8 hours or less. The power turbine module can be removed in a similar manner, as can the recuperator module. Thus, the engine is configured from the initial design for ease of serviceability.

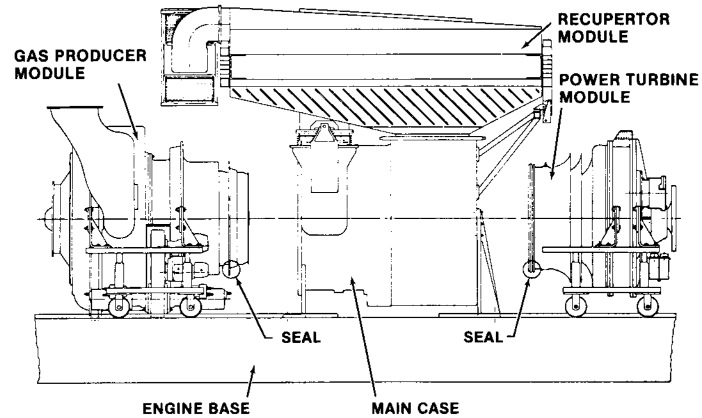


Figure 2. Engine Maintainability Features

COMPONENTS

Compressor

The gas producer module contains the compressor, the combustion chamber and the first-stage (gas producer) turbine. Fig. 3 shows the cross-section of the nonintercooled compressor. Fig. 4 shows the intercooled compressor configuration, discussed in more detail later.

The two-stage centrifugal compressor has a pressure ratio of 6.5 to 1, an airflow of 37 lb/sec (16.8 kg/sec) and an overall adiabatic efficiency of 82%. The stages have been designed and matched for nearly constant operating efficiency over the broad range required to maintain excellent part-load economy. The mechanical design features rugged blading with generous fillet radii and low operating stress levels to ensure long life and trouble-free operation.

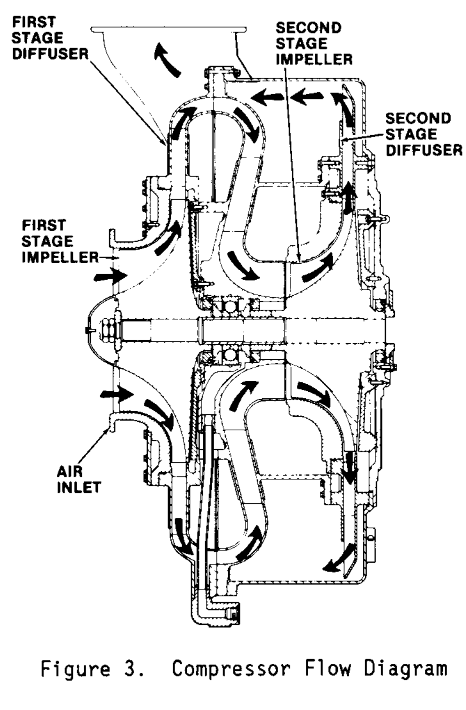


Figure 3. Compressor Flow Diagram

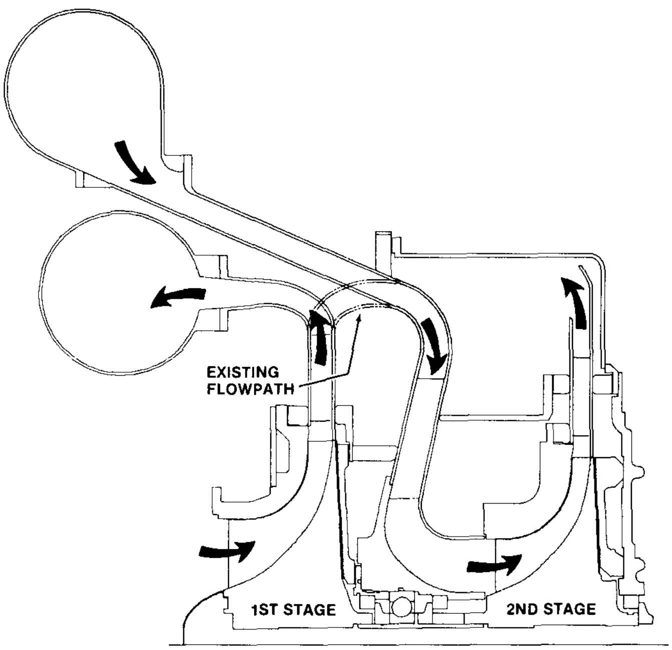


Figure 4. 5650 Intercooled Compressor

Combustor

The original annular vaporizing combustor has worked excellently on natural gas and acceptably on liquid fuel (see Fig. 5). It is small by simple-cycle standards, but is adequate for the low temperature rise needed for this highly recuperated engine with variable power turbine vanes. A new low NOx combustor with capability for handling a wider range of liquid fuels is in preliminary design.

Gas Producer Turbine

The compressor is driven by a single-stage turbine with cooled vanes and blades. The rotor blade tip

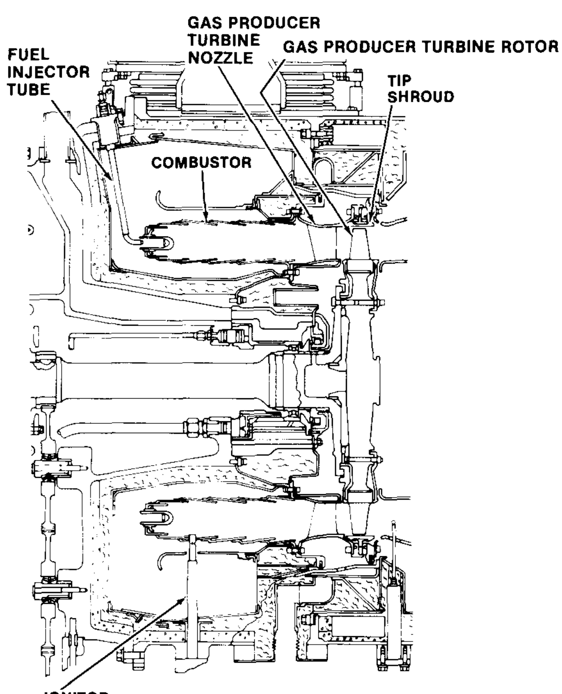


Figure 5. Combustor and Gas Producer Turbine Assembly

stationary shroud is also actively cooled so as to respond rapidly to operating condition changes. This maintains tip shoe roundness and diameter so that blade tip clearance is minimized over the engine operating range. An accessory gear drive between the compressor and the gas producer turbine provides for lube and fuel pump drives, and for the starter drive.

Main Case Module and Variable Power Turbine Nozzle

The main case module, Fig. 6, contains the variable power turbine nozzle, Fig. 7. This rugged design has proven highly satisfactory and trouble free in over 130,000 hours of varying and demanding service. The variable power turbine nozzle is essential for the part-load fuel economy of the 5650 gas turbine. The vanes are designed to rotate about their radial axes to provide control over the amount of energy extracted from the power turbine. Vane stems protrude through the bearing and shroud and are attached to individual gear segments which, in turn, are engaged by a common ring gear so that movement of the ring results in uniform movement of all vanes. The vanes are actuated by a hydraulic cylinder coupled to the vane linkage mechanism which positions the vanes as required for maximum fuel efficiency. Vane position is controlled automatically by the electronic gas turbine control.

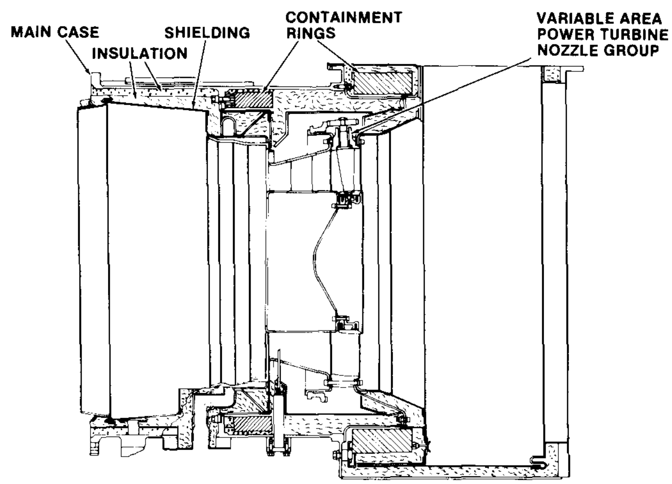


Figure 6. Main Case Module

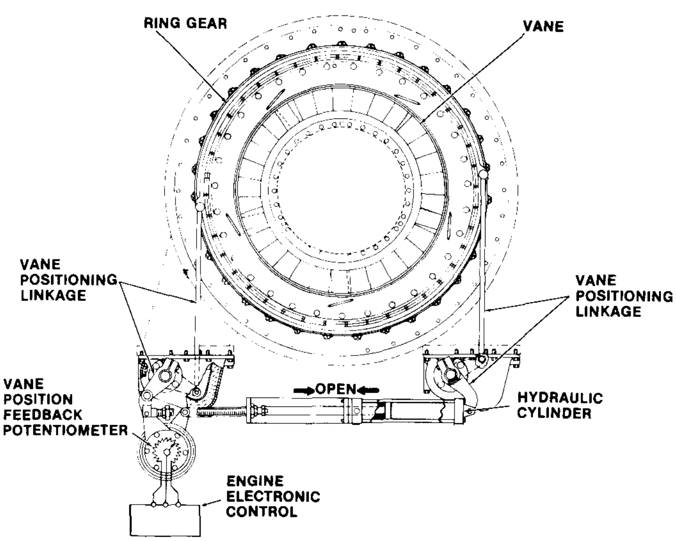


Figure 7. Variable Power Turbine Nozzle

In addition, the variable nozzle significantly improves the response characteristics of the two-shaft gas turbine by permitting the gas producer to operate over a much smaller speed range during load changes than conventional, two-shaft, fixed-geometry gas turbines. As gas producer speed range is decreased, transient response improves, approaching that of a single-shaft gas turbine. The current 5650 gas turbine can accept load changes of up to 50% within acceptable frequency recovery times.

The variable nozzles maintain recuperator hot end inlet temperature at a reasonably constant level, thus minimizing thermal stresses during load changes and extending recuperator life.

Gas turbines typically have external surface temperatures as high as 700°F (370°C) to 1000°F (540°C). A fire hazard is created when liquid fuel or oil comes in contact with these high-temperature surfaces. The use of external blankets to insulate the gas turbine does not eliminate this fire hazard. The 5650's main case is internally insulated so that surface temperatures are kept below 400°F (200°C) over the major portion of the gas turbine.

Recuperator

The most unique component of the 5650 is the primary-surface recuperator, which due to its compact size, is designed as an integral part of the basic gas turbine. The recuperator recovers much of the otherwise unused energy from the turbine exhaust and transfers it to the compressor discharge air, preheating the air before it enters the combustor. As a result, less fuel is needed to power the turbine engine, resulting in a substantial improvement in overall thermal efficiency. Hence, the more effective the recuperator, the less fuel required by the gas turbine. The 5650 design provides over 90% effectiveness with minimum flow losses.

The recuperator is made of thin sheets of high-quality stainless steel folded into a corrugated pattern, Fig. 8. Several patented processes are used to form this pattern without overstressing the metal. The corrugated pattern maximizes the primary-surface area in direct contact with exhaust gas on one side and compressor discharge air on the other. Pairs of these sheets are joined to form air cells which then are welded together to form the core which constitutes the "heart" of each recuperator module. By contrast, conventional recuperators use a plate-fin or a shell-and-tube design, either of which yields a low ratio of primary surface to overall recuperator size. They also use spacers and/or tube racks which add weight and bulk and which require welds inside the recuperator core.

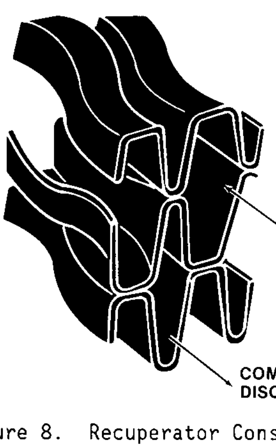


Figure 8. Recuperator Construction

Each 5650 recuperator module contains 5900 square feet of primary surface. These air cells are joined by external, high-strength welds into a compact, rigid module. All welds are easily inspected, Figs. 9 and 10.

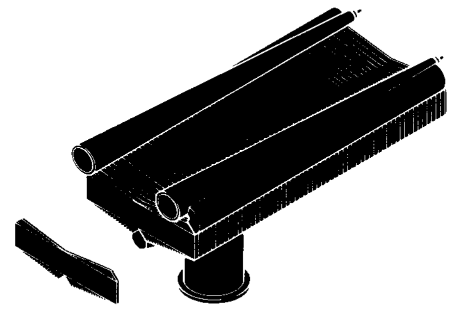


Figure 9. Recuperator Assembly

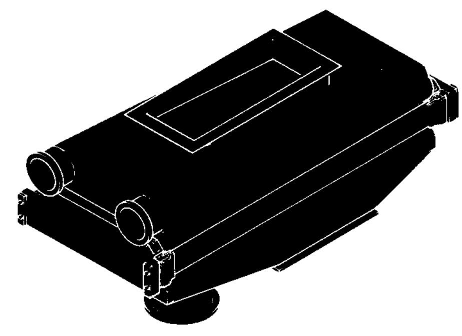


Figure 10. Recuperator Module

Power Output Module

The single-stage power turbine rotor is contained in the power output module, Fig. 11. No cooling is required for nozzles or blades. Overall power turbine adiabatic efficiency is over 89%. A high recovery curved and vaned diffuser guides the exhaust gas to the hot end of the recuperator passages.

The output planetary reduction gear reduces the power turbine shaft's 10,620 rpm to 1800 rpm (or to 1500 rpm by simple replacement of sun and planet gears) for generator drive.

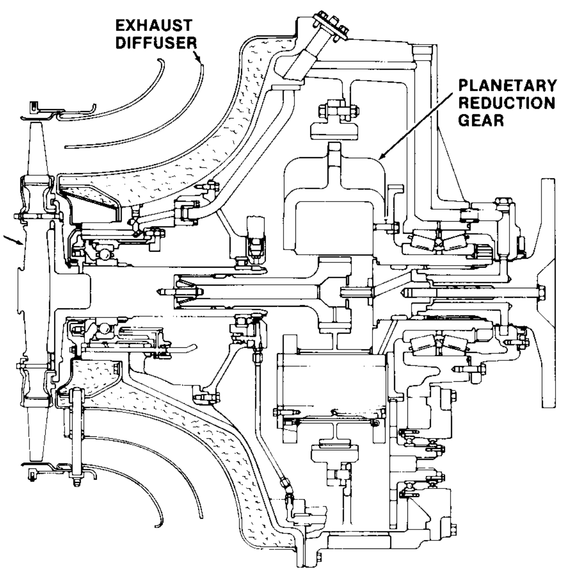


Figure 11. Power Output Module

5650 DEVELOPMENT HISTORY

Development of the 5650 turbine up to and including a pilot production run of 11 engines was carried out by Caterpillar Tractor Co. With the acquisition of Solar as a wholly owned subsidiary, Solar has assumed administration of an extensive field evaluation program as well as further development.

The achievement of specific reliability goals was established as a program requirement at the start of development. Achievement of these goals is illustrated in Fig. 12. The target of 0.144 events per 100 hours of operation is below that set for new diesel engines entering service, and was specifically set to reflect a higher goal for gas turbine equipment. An event is defined as any imperfection in the engine system which requires maintenance and includes engine control items (mechanical and electrical) as well as the reliability/durability of the basic flange-to-flange engine.

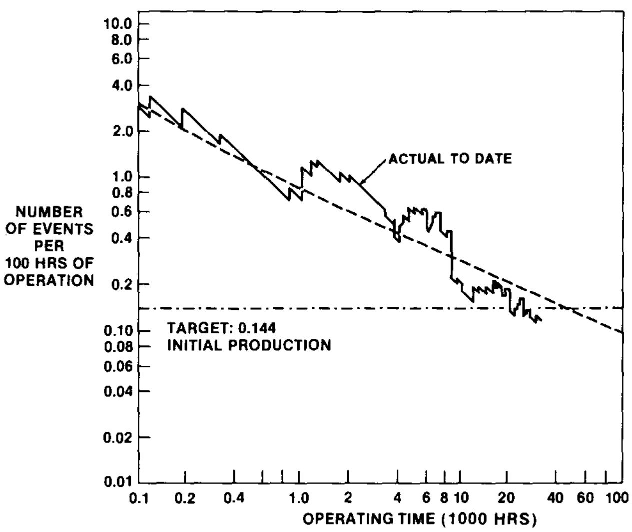


Figure 12. 5650 Engine Reliability Development

The target event rate was reached after some 20,000 hours of laboratory and field testing of three prototype engines. This achievement then triggered the start of the pilot production run.

Two of the pilot production engines are retained at Solar for laboratory development work and the remaining nine have accumulated over 130,000 operating hours at a variety of field evaluation sites. All are in generator sets, normally fueled with natural gas. Several, however, include dual-fuel systems wherein liquid fuel is available in the event of curtailment of the gas fuel supply. These field sites include:

- Northern Illinois - A total energy power plant at a manufacturing facility operates a 5650 in parallel with multiple natural-gas piston engines, Fig. 13. Gas engine jacket water and exhaust heat plus exhaust-heat recovery from the 5650 provide building heat and air conditioning. The high time pilot production engine has accumulated 17,500 hours at this site. Prior operation of prototype engines brings the total 5650 experience at this site to over 30,000 hours.

- Central Florida - Two 5650 generator sets are used for daily shaving of electrical power peaks at a citrus fruit processing plant. Process steam is generated by exhaust-heat recovery on one of the units. The frequent starting of these engines has provided for accelerated evaluation of several improvements relating to thermal shock and fatigue.

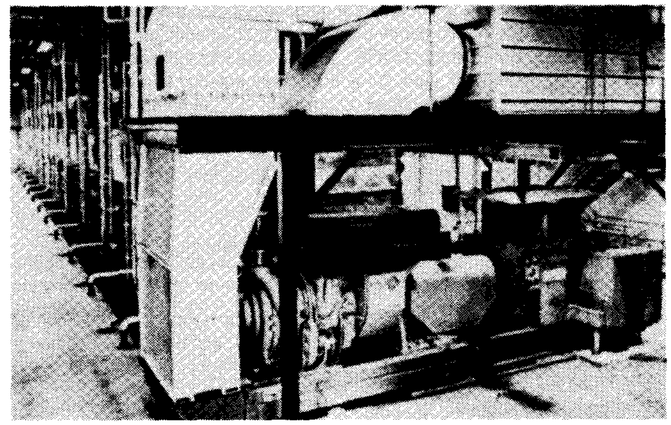


Figure 13. 5650 Generator Set in Field Service

- Central Illinois (discontinued due to rate changes) - A public utility operated a 5650 generator set for two years in an experiment relating to the addition of incremental capacity at remote points in their grid. The unit was located at a rural, unmanned substation and was started and operated via telephone lines from a dispatch office some 10 miles distant.

- Northern California (discontinued due to plant closure) - A 5650 generator set served in a cogeneration installation at a manufacturing facility, which has subsequently been closed. An exhaust-recovery unit provided hot water for plant processes. NOx reduction by water injection was used successfully to comply with local air quality regulations.

- Southern California - A 5650 generator set provides continuous electrical power at varying loads for a manufacturing facility, laboratory and office complex. Local utility economics are such that cost avoidance exceeding $100 per hour is realized without the use of exhaust-heat recovery.

- Southern California - Three 5650 generator sets power a cogeneration plant at a telecommunications computer facility and office building. Exhaust-heat-recovery units provide chilled water for building air conditioning. All three units are on continuous duty at full load and the 5650 units consistently exceed 1000 hours between shutdowns for maintenance or repairs. Availability (ratio of actual to scheduled operating time) at this site has exceeded 97% versus the 85% initially estimated by the using facility's designers.

During 1984, frequency response of the 5650 was demonstrated over a range of no-load gasifier speeds. An unmodified 5650 engine was coupled to a 4160-volt, 60 Hz generator loaded by resistive load banks.

Since data was recorded incident to other testing in progress at that time, the results are not totally consistent. However, Table 1 illustrates that increasing no-load gas producer speed markedly improves the response to step-load changes. Selection of an increased no-load speed for improved load response, or return to the lower, more economical no-load speed is accomplished by simply moving a selector switch on the control panel.

Table 1. Improvement in Transient Load Response

Gas Producer Speed at Load Change Onset, %	Load Change, KW	Frequency Deviation, Hertz	Recovery Time, Seconds
61	0-1680	> 10	--
61	0- 400	4.8	12
91.5	0- 800	1.8	20
80	600-1400	3	6
91.5	600-1400	0.9	2
76	1200-1600	4.8	32
80	1200-1600	4.8	16
80	1400-1600	1.5	8

Although increasing gas producer speed increases the transient load response, it also increases fuel consumption in the 25% to 75% load range in which marine electrical generating sets generally operate. However, the penalty of higher part-load fuel rate in order to achieve excellent transient load response lessens the 5650's substantial competitive advantages, vis-a-vis the simple-cycle gas turbine and the diesel engine for marine generator set drive. This leads to the necessity of modifications to improve transient response. As one example, the existing relationship between acceleration and steady-state temperature schedules is being modified to provide additional acceleration differential at critical points in the acceleration process, as shown in Fig. 14. The flexibility afforded by the variable nozzle and its closed-loop control logic allows an improved acceleration schedule to be tailored within all related constraints such as engine metal temperature limits and surge margins.

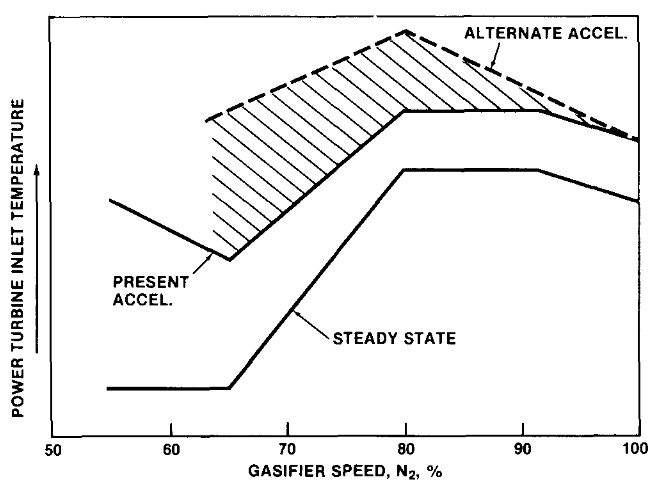


Figure 14. 5650 Alternate Acceleration Temperature Schedule

Another improvement includes minor modifications to certain hardware to quicken the variable nozzle response to control system signals. Further, the current control system responds to frequency change. Adding anticipatory logic based on load demand will improve response. Other modifications are being studied. In total, past tests, current modification and future changes are leading to transient response <u>and</u> part-load fuel rate comparable to modern marine diesels of this power class.

Examination of test data reveals that the response time of the 5650 turbine generator set to both load additions and load removals is independent of the thermal response time of the recuperator. This feature is another contribution of the variable nozzle, which together with its closed-loop control logic, operates the engine at whatever off-design condition is required to compensate for the transient temperature error in the recuperator. For example, in a test not shown in Table 1, frequency recovery was completed 5.4 seconds following a 2000 kW load dump while the variable nozzle did not reach a final steady state position until approximately 64 seconds following the load dump. The 64 seconds represents the length of time for stored heat to be removed from the recuperator before its cold side outlet temperature is compatible with no-load operation. Thus, the variable nozzle also functions to eliminate recuperator thermal response time as a factor in engine load response time.

Exhaust-Stack Gas Temperature

As shown in Fig. 15, maximum exhaust-stack gas temperature from the recuperated 5650 engine is 580°F (305°C), approximately 300°F (165°C) lower than from a typical simple-cycle engine operating at similar firing temperatures. This reduced stack temperature is of general advantage in any marine installation since the size and cost of exhaust ducting and insulation is reduced.

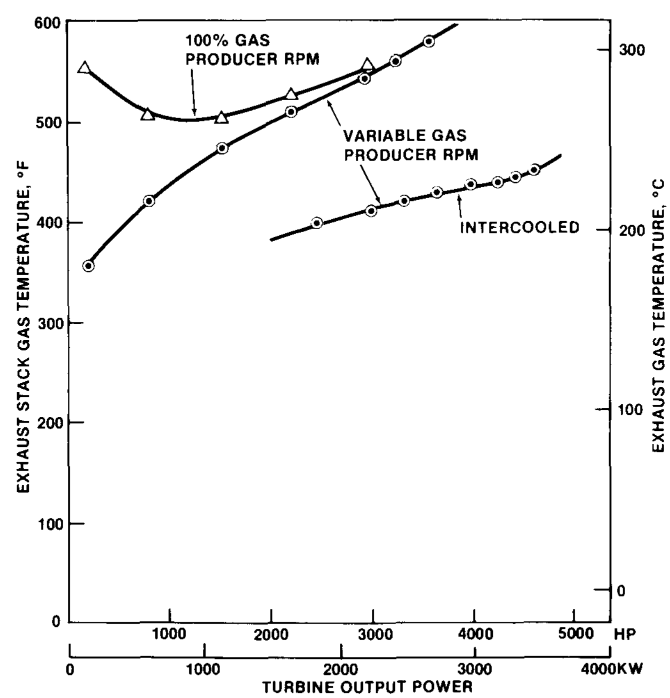


Figure 15. 5650 Exhaust Stack Gas Temperature Corrected to ISO Conditions, Zero Duct Loss without Reduction Gearbox

It is of specific military advantage as a reduced contribution to infrared signature. Fig. 15 also shows that high stack temperature is attainable at low generator loads by selecting higher minimum gas producer speeds. This feature, made possible by the variable nozzle, can be of advantage when the engine is fitted with exhaust-heat-recovery equipment in that exhaust-heat production is decoupled from generator output. Relatively large amounts of exhaust heat can, by simple control systems demand, be produced as desired to obtain the operationally most effective balance between electrical and heat output, automatically or by manual adjustment.

Compressor Air Bleed

The availability of increased minimum gas producer speeds made possible by the variable nozzle also improves the 5650's ability to supply compressed air for engine starting, masker, systems or other ship requirements. A portion of the excess engine air flow attained at gas producer speeds higher than that required to support a given electrical load is available for bleed.

Intercooling

The 5650 gas turbine was designed with an integrated recuperator and a variable power turbine nozzle. This resulted in a 6.5 to 1 compression ratio, lower than typical gas turbine compression ratios found in units designed originally for simple-cycle operations. Other design considerations led to the development of a compressor with two centrifugal stages. This differentiates the engine from most other gas turbines in this size range, which typically have axial compression stages.

Because of the two centrifugal stages on the compressor, with radial discharge from the first stage and radial entry to the second stage, an intercooler is readily accommodated between the two compressor stages. This results in a gas turbine with three of the most important features (recuperator, variable power turbine nozzle and intercooled compressor) to achieve part-load and full-load efficiencies that will compete directly with those achieved by reciprocating engines of similar power.

Problems which have contributed to lack of success with previous intercooled gas turbines are:

- Excessive erosion (and formation of deposits) on the compressor blades downstream of the intercooler
- High pressure drops to and from the intercooler
- Control problems under transient operating conditions

Axial compressors, with numerous thin airfoils, are much more susceptible to damage due to water droplets than centrifugal compressors. In a moisture-laden environment, water droplets form as a result of cooling the compressor air in the intercooler. The effectiveness of the intercooling will play a role in this water formation, and a value over 70% will generally produce some water droplets. The 5650's rugged centrifugal compressor is particularly well suited to coping with this problem.

Additionally, the pressure drop associated with exiting the first-stage impeller and entering the second-stage impeller will be lower with the "radially out - radially in" configuration used in the 5650 than with axial-flow compressors. Particular design effort has been applied to minimizing these intercomponent losses.

The use of microprocessor controls and the excellent success achieved by the 5650 to date with its programmable control bode well for readily handling control problems that proved difficult for earlier intercooled engines.

A logical first step in adding intercooling to the 5650 engine cycle was to examine the results to be expected from the simple addition of intercooling without major revisions to engine components beyond the compressor. This approach represents a vertical excursion between the two top curves in Fig. 16, which depicts the effect on optimum pressure ratio of recuperation and intercooling. Optimization of intercooled cycle compression ratio would later become a logical future improvement, especially in view of the advanced state of development of the present regenerative (nonintercooled) 5650 cycle and engine components.

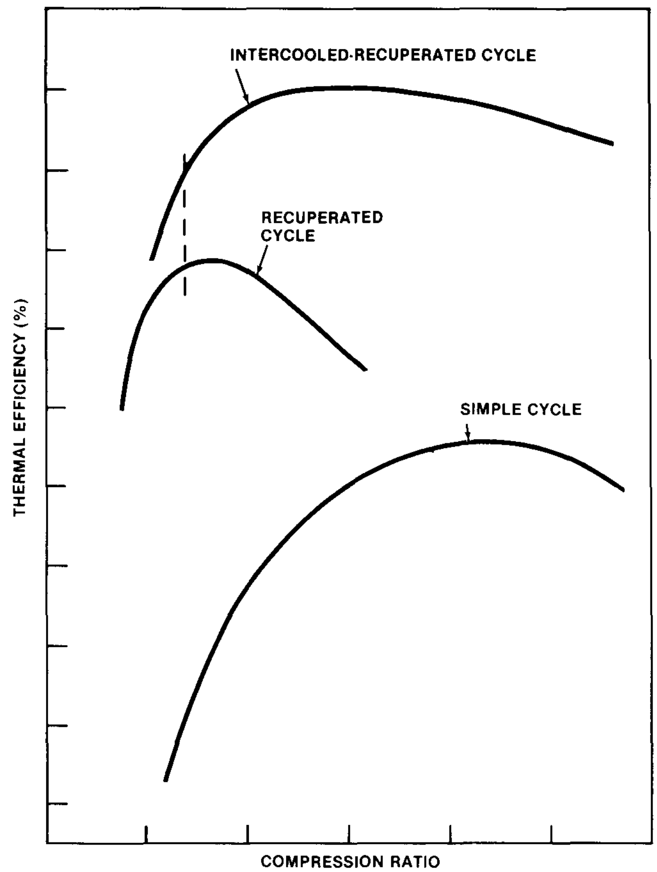


Figure 16. Effect of Recuperation and Intercooling on Gas Turbine Thermal Efficiency

Revised inlet conditions to the compressor's second stage were calculated for an intercooler thermal effectiveness of 90% and the addition of 4% static pressure loss to the interstage flow path. Second-stage and overall compressor performance at these conditions were based on demonstrated conventional performance. Compressor maps were generated for selected second-stage impeller options.

Cycle performance calculated from the finally chosen configuration is summarized in Table 2. The recuperated cycle performance is based on data obtained in tests of the prototype engine. (The current design 5650 has two to three percentage points better efficiency.)

Table 2. Cycle Performance

	Recuperated Cycle	Intercooled/Recuperated Cycle
Maximum power (ISO)	3710 hp (2768 kW)	4780 hp (3568 kW)
Specific fuel consumption (lb/hp-hr)		
at maximum power	0.412 (eff. 33.5%)	0.381 (eff. 36.2%)
at maximum efficiency	0.401 (eff. 34.4%)	0.365 (eff. 37.8%)

As would be expected from Fig. 16, the gain in thermal efficiency is modest, but nevertheless of interest to users who place value on fuel consumption. The greater attraction is a gain of nearly 30% in output power obtained at no expense to the core engine in terms of temperature-, pressure- or speed-related stresses.

Sensitivity plots of intercooler effectiveness and static pressure loss suggest that the 5650 cycle can be intercooled by a wide variety of heat transfer devices and illustrates that the physical design provides great flexibility in adapting to this variety. For example:

- In most marine applications, the intercooler can be directly cooled by seawater, drawing on the accumulated body of knowledge and experience relating to seawater-cooling devices.
- Air-to-air intercooling, while not as compact as liquid-to-air, may be applicable in certain situations (oceanographic research or ultra-quiet anti-submarine operations) where extremely low waterborne acoustic signature is highly important.

Examination of the 5650 compressor first-stage exit conditions reveals a similarity to compressor exit conditions in a turbocharged piston engine and suggests a physical similarity between a 5650 intercooler and a piston engine charge air cooler. Similarity of design point operating conditions is shown in Table 3. Thus proven heat transfer devices used in the charge-air cooler application are eligible for consideration for 5650 intercooling when sized to the air flow rate of the 5650.

Fig. 4 illustrates the in-and-out configuration of the 5650 compressor. Note that all rotating elements of the 5650 compressor remain unchanged and only two major structural components are replaced by new parts. Fig. 17 defines the current basic 5650 driver package (including air inlet plenum) for comparison with an intercooled version shown in Fig. 18.

Table 3. Design Point Operating Conditions

	5650 Intercooler	Typical Piston Engine Charge-Air Cooler
Air in, pressure	47.7 psia (3.24 ata)	44.7 psia (3.04 ata)
Air in, temp.	303°F (151°C)	347°F (175°C)
Coolant in, temp.	85°F (29°C)	122°F (50°C)
Effectiveness	90%	84%
Hot side Δp/p	2.0%	1.1%
Vibration environment	moderate	severe

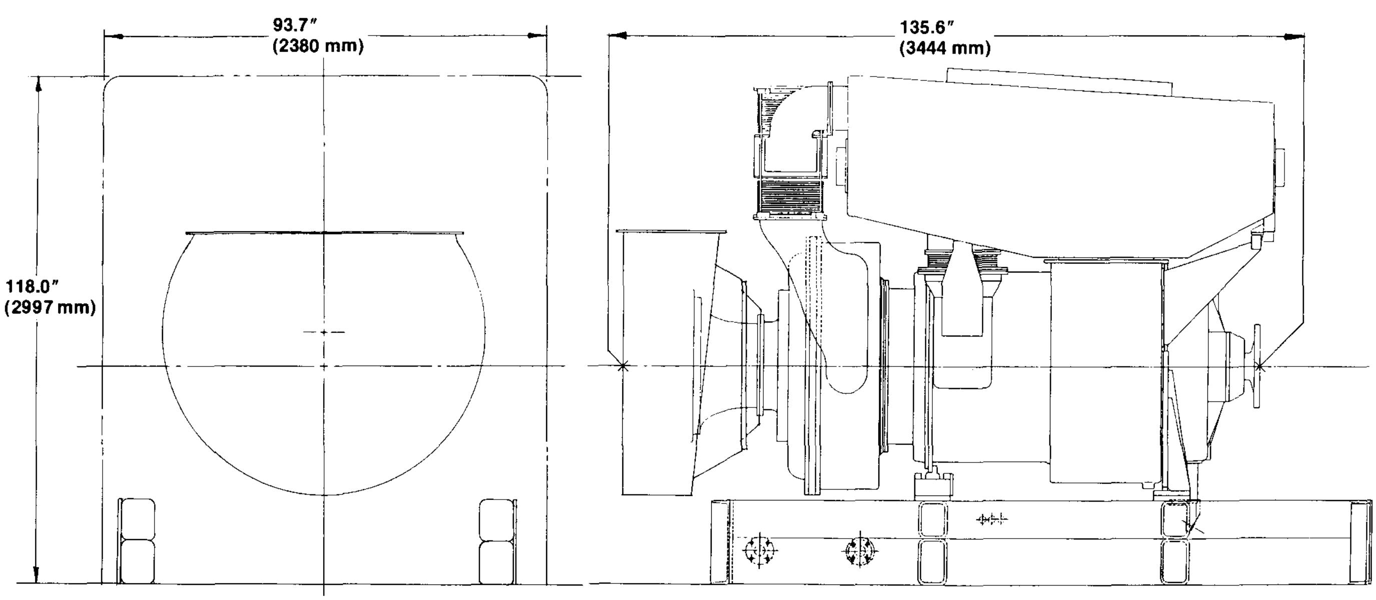


Figure 17. Basic Driver Package

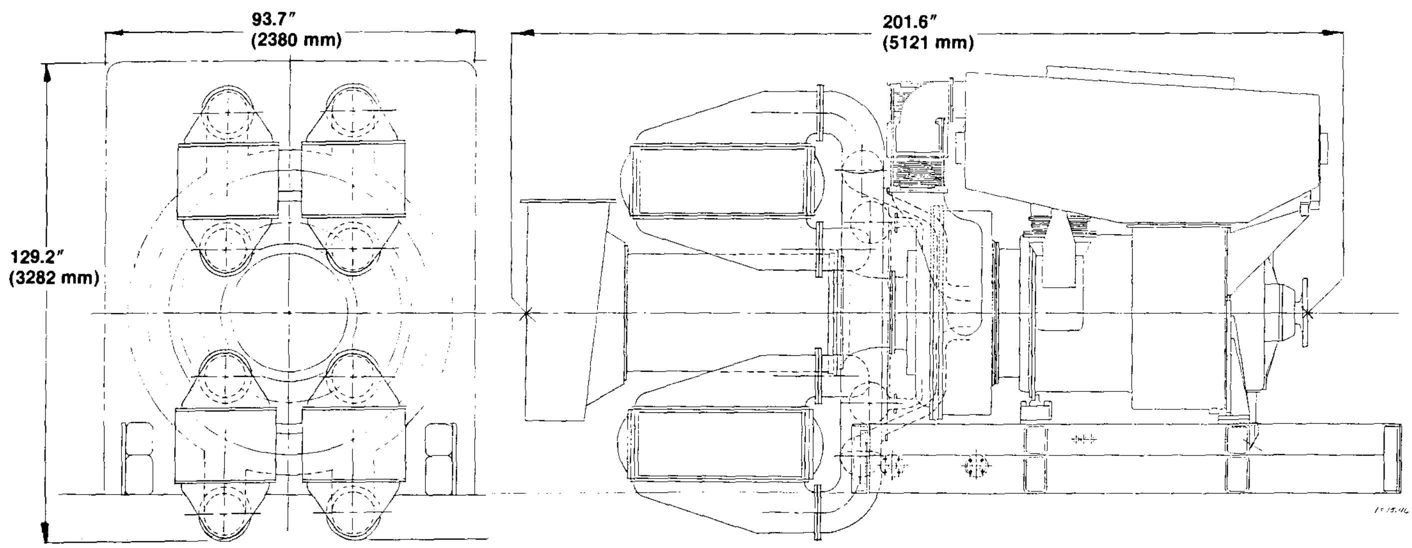


Figure 18. 5650 Driver Package - Four Liquid Cooled Intercooler Cores

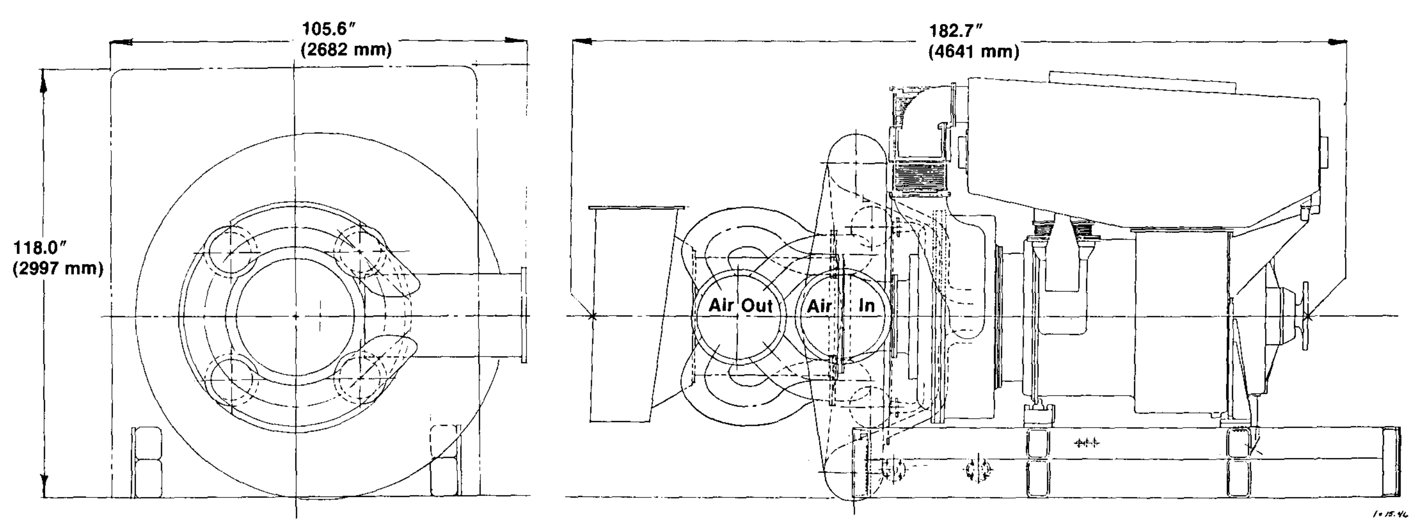


Figure 19. 5650 Basic Driver Package Adapted for Off-Skid Intercooler

This intercooled version of the 5650 uses 4 liquid-to-air intercooler cores of conventional fin-and-tube construction designed specifically for this application by a manufacturer of piston engine charge-air coolers. The core is based on existing high-volume tooling. All tube-to-fin and tube-to-header joints are mechanical with no soldering or brazing, a design that was developed to survive in the severe vibratory environment of railway service. Either direct seawater cooling or the use of a secondary coolant coupling the unit to a seawater cooler may be used. Intercooler effectiveness for this arrangement exceeds 90% and static pressure loss is less than 2%.

Fig. 19 shows an optional arrangement wherein the on-skid intercooler package of Fig. 18 is replaced by manifolding for piping air to and from a remotely mounted intercooler. In a marine installation this arrangement grants considerable freedom to the ship designer in locating the intercooler. The air manifolds are independently rotatable for a full 360 degrees around the engine centerline. The basic compressor structure of Fig. 4 is common to both on-skid and remotely mounted intercooler packages.

5600 GAS TURBINE FAMILY

This paper has discussed the basic 5650 turbine as it exists today and as it may be significantly upgraded by simple addition of intercooling without redesign to optimize for the intercooled cycle. There are multiple avenues to improved performance, all within existing technology and some with basic development work already accomplished:

- The 5650 has built-in capability for thermal uprating from the current 1775°F (970°C) TRIT to 1950°F (1065°C) by merely replacing the gas producer turbine with a revised design. This uprate was planned into the original design and initial engine testing of the revised turbine stage has already been completed. This gives a 6000 hp engine for generator drives of up to 4000 kW, with a fuel rate of 0.32 lb/hp-hr (thermal efficiency of 43%).

- Fig. 20 plots the maximum thermal efficiencies in comparison to efficiencies of all other currently available recuperated gas turbines, as listed in the 1985 edition of the Gas Turbine World Catalog.

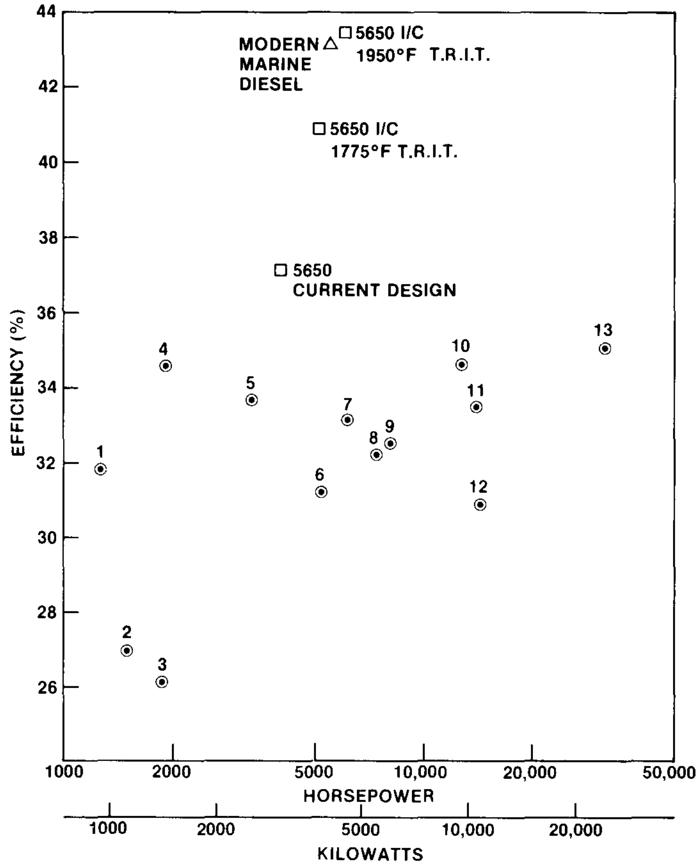


Figure 20. Recuperated Gas Turbines

- Of much greater importance for marine generator sets is comparison of part-load performance, since shipboard generator sets seldom operate at full load, which is the maximum efficiency point for simple-cycle engines. Fig. 21 graphs competitive engine performance. Note particularly the comparison with one of the best marine diesel engines available in this power range.

- Fig. 22 shows that the 5650 intercooled/recuperated generator package, largely due to its integrated reduction gear, will fit in approximately the same space as current shipboard gas turbine gensets. Overall package weight is comparable to existing units that recover exhaust heat with a waste heat boiler.

- Fig. 16 shows that an intercooled and regenerated turbine cycle has a higher optimum compression ratio than a basic regenerated cycle.

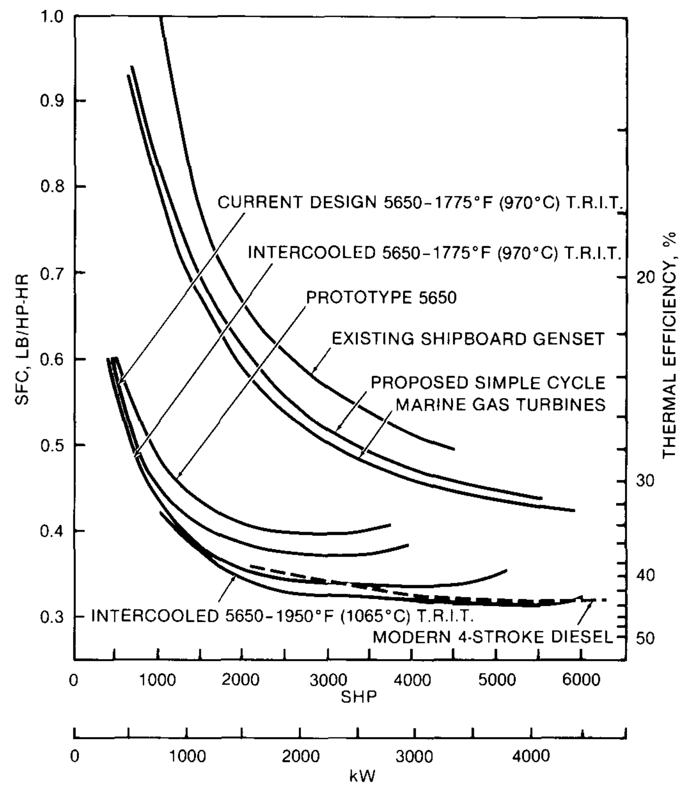


Figure 21. Marine Generator Sets

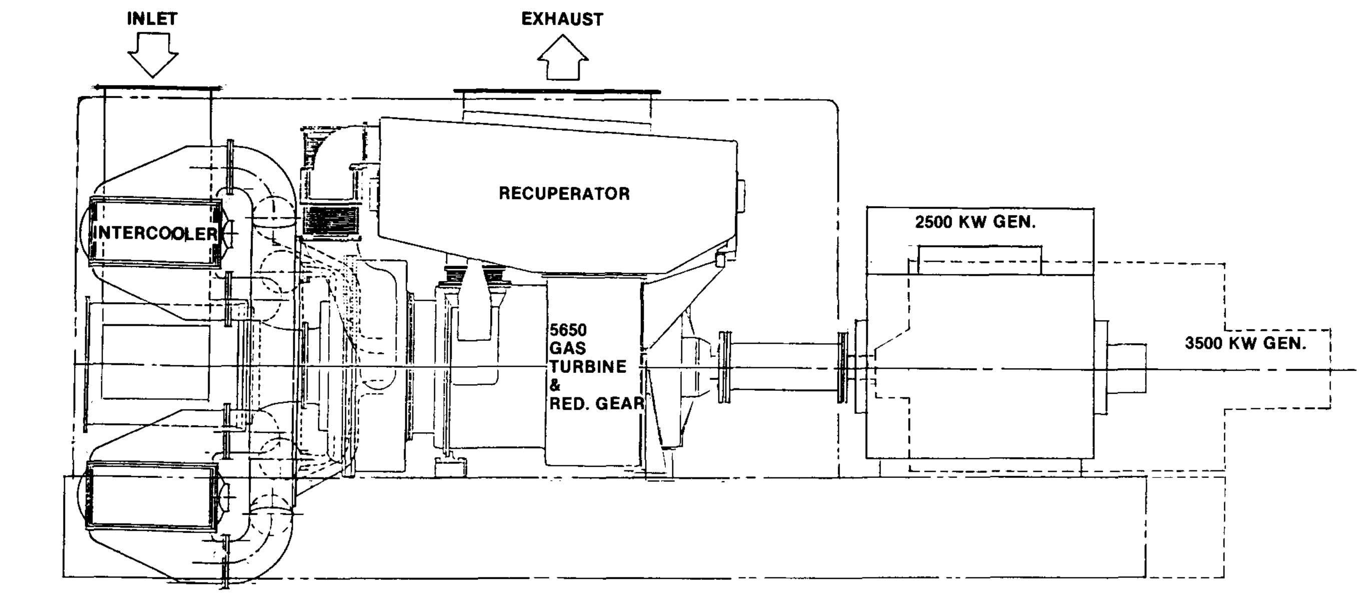
Further component development will allow the simple intercooled version of the 5650 to be developed toward this cycle optimum. Fuel rate would be superior to any of the data of Fig. 21.

- Design work has been completed on a high-flow version of the 5650 which has been designated Model 5670. Compared with the 5650 gas turbine, the 5670 gas turbine has:

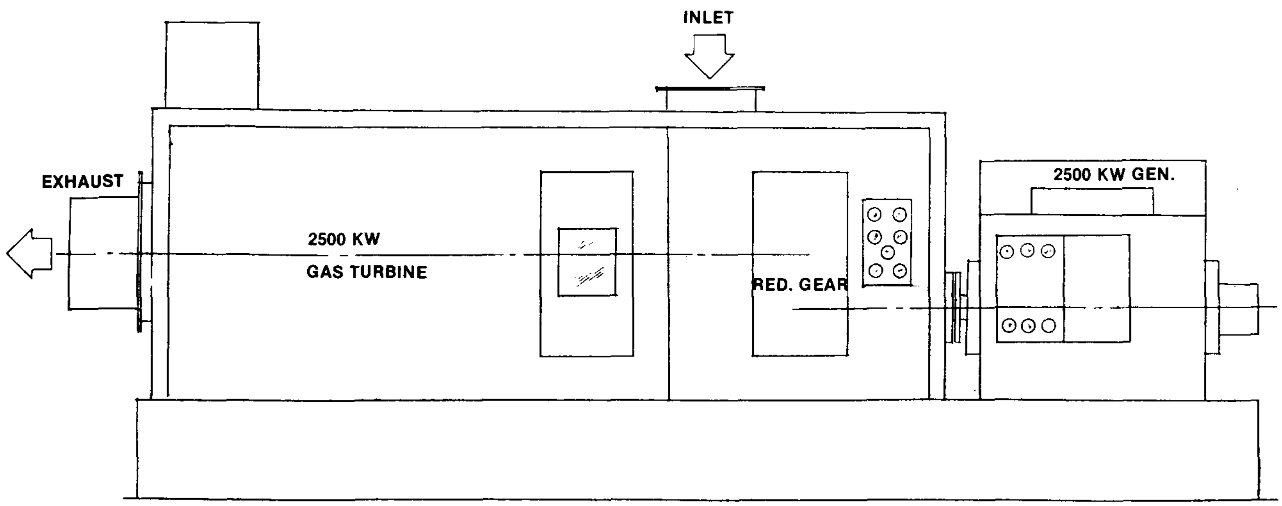
  - High-flow compressor
  - Longer power turbine diffuser
  - New combustor
  - Longer recuperator (30%)

- In all other respects the two engine models, 5650 and 5670, have extensive commonality of parts. Maximum air flow of the 5670 (and achievable power level) is approximately 33% greater than that of the 5650. Substantial testing of 5670 components has already been completed.

A development program based on these ingredients is capable of producing a future member of the 5650/5670 family rated up to 8000 hp (6000 kW) and operating at even better specific fuel consumption.



5650 INTERCOOLED/RECUPERATED MARINE 2500/3500 kW GENERATOR SET



EXISTING SHIPBOARD 2000/2500 kW GENERATOR SET

Figure 22. Shipboard Gas Turbine Generator Set Comparison