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Compound Cycle Engine Program

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SUMMARY

The Compound Cycle Engine (CCE) is a highly turbocharged, power compounded ower plant which combines the lightweight pressure rise capability of a gas turbine with the high efficiency of a diesel. When optimized for a rotorcraft, the CCE will reduce fuel burned for a typical 2 hr (plus 30 min reserve) mission by 30 to 40 percent when compared to a conventional advanced technology gas turbine. The CCE can provide a 50 percent increase in range-payload product on this mission.

A program to establish the technology base for a Compound Cycle Engine is presented. The goal of this program is to research and develop those technologies which are barriers to demonstrating a multicylinder diesel core in the early 1990's. The major activity underway is a three-phased contract with the Garrett Turbine Engine Company to perform: (1) a light helicopter feasibility study, (2) component technology development, and (3) lubricant and material research and development. Other related activities are also presented.

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INTRODUCTION

A program is being conducted to establish the technology base for a compound cycle engine (CCE). The program goal is to develop those technologies which are barriers to demonstrating a multicylinder gas generator, or core engine, during the early 1990's. A major part of the technology program is a three phase contractual effort being conducted by the Garrett Turbine Engine Company, under the sponsorship of the U.S. Army Aviation Systems Command: the first phase is an analytical feasibility study of a compound cycle engine for a light helicopter application; the second is a component technology development program; and the third is a lubricant and materials research and development program. Other related program elements are also underway in an effort to accomplish the 1990's demonstration of a multicylinder diesel core.

Recent studies have shown that fuel is 70 percent of the tonnage shipped by the Army for supply and support under battlefield conditions. Another study, reference 1, showed that a compound cycle engine, with its superior fuel efficiency, when installed in a Blackhawk helicopter and operated over a typical 2-hr mission, could have a specific weight as high as 0.76 pounds per horsepower (lb/hp) and still be competitive with a gas turbine engine in terms of range-payload product. This result assumed the same take-off gross weight, and balanced the CCE's increased engine weight against its lower fuel consumed plus tankage weight.

This paper summarizes the status of the current CCE activities. The feasibility study predicted that the 1000 horsepower (hp) helicopter engine would have a specific weight of 0.432 lb/hp and a specific fuel consumption (SFC) of 0.33 pounds per horsepower-hour (lb/hp-hr). The state of the single cylinder component development program and of the lubricant/materials research will also be presented. The paper will conclude with other related activities outside the scope of the initial three-phase contract. All these elements taken together comprise the long range plan to meet the 1990's diesel core, multicylinder demonstration date.

BACKGROUND

A compound cycle engine, shown schematically in figure 1, combines the airflow capacity and light-weight pressure rise features of a gas turbine with the highly efficient, although heavier, diesel. The compressor of the turbomachinery module delivers a highly pressurized charge of air to the diesel cylinders. Within the cylinders, further compression, fuel injection, combustion, and expansion takes place, as in any conventional reciprocating engine, but at substantially higher pressures and temperatures. Power is extracted during the expansion stroke and the exhaust gases are then returned to the turbomachinery module. The exhaust energy available is in excess of what is required to drive the compressor, and that excess power is extracted in a free turbine and combined with the diesel output through a gear train. This combined output comprises the total cycle output, hence the name compound cycle engine.

As outlined in reference 2, the 1940's and early 1950's saw considerable interest in compound cycle engines being applied to aircraft. During the early 1950's, the most fuel efficient internal combustion engine ever flown, the Napier Nomad, demonstrated an SFC of less than 0.35 lb/hp-hr in flight, reference 3. The engine used a highly turbocharged, power compounded cycle to reach this level of performance. It delivered 3050 hp output at a weight of 3580 lb. The advent of the gas turbine, however, coupled with the low cost of fuel at the time and the drive toward faster speeds, brought an end to the Nomad. This technology stagnated while gas turbines flourished in the 30-plus intervening years.

The Army/NASA Small Engine Technology program, reference 4 indicated that performance increases of significant magnitude for the year 2000 turbomachine will require improved cycles incorporating the results of intensive research and development efforts, mainly in materials, that is ceramics, and secondly in component aerodynamic design. Efforts in other areas will provide payoffs of a smaller magnitude. The reduction in fuel burned predicted for the year 2000 rotorcraft application was dependent on all the key technologies reaching the applications phase, references 5 and 6.

Economic and logistic pressures have forced us to reconsider more efficient power plants such as the compound cycle. The already mentioned tonnage which the Army must supply and support under battlefield conditions, and the need for a deep penetration capability, are examples of the drivers toward better fuel efficiency. It is estimated that by adapting the Napier Nomad to a helicopter mission and incorporating modern technologies into its 35 year old design, this compound cycle engine could be made to run at an SFC in the range of 0.35 lb/hp-hr and weigh 0.6 lb/hp or less. The weight reduction would be accomplished by removing the reduction gearbox which had been needed for a propeller drive; deleting the variable-speed transmission, which had been needed for turbomachinery and diesel speed matching, and instead incorporating a free turbine stage for power extraction; reducing the number of turbomachinery stages substantially from the original Nomad design; and then by utilizing modern materials and structural analysis techniques.

Until recently, few major advances have occurred in reciprocating engines. In 1977, however, a joint Defense Advanced Research Project Agency (DARPA), Air Force, and Garrett program, reference 7, investigated a highly turbocharged, power compounded turbofan/diesel engine for a cruise missile application. Power densities greater than seven times that of the best current production diesels were demonstrated in a single cylinder rig. A mission redirection terminated that effort, however, that program formed the basis for the present activity.

COMPOUND CYCLE ENGINE PROGRAM

The long term goal of the compound cycle engine program is a 30 to 40 percent reduction in mission fuel weight with a resultant 50 percent improvement in payload-range product for a light helicopter. In the near term, the specific objective is to attack the high risk, barrier technologies in preparation for a multicylinder core demonstrator program in the early 1990's. Toward this end, three parallel phased contractual efforts with the Garrett Turbine Engine Company are underway. In the first phase, a feasibility study was conducted to determine the merit of using a compound cycle engine in a light helicopter. In the second phase, component research is being conducted on a single cylinder test rig. Lubricant and material research is being conducted in phase three.

Phase I: Light Rotorcraft Feasibility Study

Figure 2 depicts the numerous options which were considered in the engine feasibility study. It should be noted that the engine looks very similar to a normal turboshaft configuration, but with the combustor replaced by a power producing diesel core. The turbomachinery maps were essentially lifted from existing turbine engines, with the study effort primarily revolving around the diesel core configuration.

The study options include: 2-stroke versus 4-stroke cycle, compressor discharge aftercooling, scavenging method (loop versus uniflow versus 4-stroke), turbocompounding versus turbocharging, method of compounding, and cylinder geometry. The engine design point conditions were also considered options. Figure 3 presents a summary plot of BSFC and weight trends as they were affected by scavenging option, and by turbocompounding versus turbocharging option. Turbocompounding was chosen due to its substantially lower engine weight and fuel burned. The 2-stroke cycle, with two times as many power strokes as a 4-stroke, provide a lighter power plant than the 4-stroke cycle. To achieve the lowest possible predicted weight, a uniflow scavenged design was chosen. Finally, for more stable off-design operation, a one-and-one-half spool turbocompounding scheme was selected. The half spool refers to the use of a mechanically disconnected, or free, power turbine.

The decision on aftercooling was driven by life considerations. A two point SFC penalty was predicted with aftercooling, due to pressure losses and power extracted for a blower. However, an effectiveness of 0.4 produced a reduction in cylinder inlet temperature of 300 °F at maximum power, which should result in a significant improvement in life. The weight added due to the aftercooler was balanced by a cylinder size and weight reduction, since the cooler, more dense intake air charge now required less displaced volume for the same mass flow.

The trends which led to the final design are shown in figure 4. These plots assumed that for the life goal of the helicopter CCE, a mean piston speed of 3000 ft/min should not be exceeded. Having previously selected a uniflow scavenged cylinder, a minimum bore size of 3.0 in. was required to allow room for exhaust valves and an injector, and this drove the design to six cylinders. The six cylinder configuration accepted a small weight penalty compared to eight or ten cylinders, however, the weight was somewhat reduced by selecting an over-square bore to stroke ratio of 1.05 to reduce cylinder height. As life and wear are the major concerns in this engine, the selection of the six cylinder design did allow a substantially lower engine speed than either the eight or the ten. SFC was nearly independent of both bore to stroke ratio and numbers of cylinders, and although the maximum firing pressure is independent of the number of cylinders, the pressure was slightly reduced by choosing the 1.05 bore to stroke ratio. Thus, the final design configuration, presented in table I, is seen to be a trade among life, performance, and weight considerations. A schematic of the final design is presented in figure 5.

A simple analysis, using figures 6 to 8, may be performed to examine the benefits of a compound cycle. In figure 6, a composite mission profile is presented for comparison purposes. It can be seen that 80 percent of the mission is spent at 50 percent power or less. Using the performance shown in figure 7, an advanced technology 1000 hp turboshaft engine would weigh about 240 lb and operate at an SFC of 0.55 lb/hp-hr at the 50 percent power condition. A compound cycle engine, under the same conditions, weighs about 430 lb and has an SFC of 0.36 lb/hp-hr. Looking now at the fan plot of figure 8, it is obvious that the SFC difference of 0.19 lb/hp-hr begins to outweigh the CCE weight deficit of 190 lb in less than an hour. The fan plot is a simple representation of the dependence of breakeven time on the differences in specific weight and in fuel consumption between two engines, and includes an allowance for tankage. The advanced technology turboshaft engine used in the comparison represented T800 technology, but at 1000 hp. The performance levels presented are, therefore, representative of what might be expected in the near term.

The mission used in the preliminary design, which was shown in figure 6, was 2 hr, with a 30-min fuel reserve. The engine was designed to produce 1000 hp from sea level on a standard day to 4000 ft on a 95 °F, hot day. This flat rating of the CCE is achieved by upspeeding the compressor by 4 percent while increasing the trapped equivalence ratio from 0.68 to 0.80. The gas turbine, however, when designed to produce 1000 hp at the 4000 ft/95 °F condition, is actually in the 1400 hp range at sea level/standard day, and the aircraft must be designed to carry this heavier engine. In addition, the performance of the gas turbine is penalized in that at 50 percent of rated power, 1000 hp, it actually uses less than 40 percent of the maximum available power, and thus the gas turbine cruises at an even lower efficiency.

It should be pointed out that considerable effort in the study phase of this program was directed at formulating a weight prediction method. This method is discussed in some detail in reference 2. Based on this prediction, the CCE will weigh 0.432 lb/hp. This was nearly 30 percent lower than the initial weight prediction which was based on the CCTE of reference 7. The trend from the CCTE design, to the present CCE all-metal design, to a highly advanced design incorporating new technologies such as advanced materials and improved energy recovery methods, should continue as shown in figure 9. An example of such design improvements would be the development of lubricants which can be operated at high enough temperatures to permit the removal of the aftercooler. As indicated above, this could result in essentially no weight change but should subtract two points from the SFC.

Phase II: Component Technology Development

This phase of the CCE program began by using hardware from the DARPA-Air Force CCTE program which had already been run at more than seven times the power density of the best current production diesels, reaching 7.2 hp/cu-in. This hardware, while loop scavenged, provided an early opportunity to concentrated on thermal characterization and piston ring/liner wear while operating at the specific power level of the CCE. The thermal characterization work was directed toward measuring cylinder and piston temperatures to validate analytical, thermal models. The piston ring/liner wear activity dealt mainly with the development of a method for making in-situ measurement of wear. These measurements make use of a SPIRE-WEAR radionuclides measurement system which has evolved to a point of utility for the CCE program, reference 8. The results were used to establish baseline wear rate measurements. Typical trends are shown in figure 10. It should be noted that during the single cylinder engine tests, power densities of nearly 5 hp/cu-in were consistently run in over 100 hr of testing.

Development of the wear measurement system required identification of an appropriate material/isotope combination to provide a reasonable energy level and half life to accomplish wear rate test objectives. Location of the radiation detector for optimum data acquisition, and maintenance of a constant detector temperature were key to achieving consistent results. Software activities included changing the energy integration technique to an area integration scheme over a wider bandwidth than originally proposed. This allowed faster, more accurate acquisition of data. As a results, the SPIRE-WEAR system and test setup is now ready to be applied on the next test sequence, which will employ a uniflow scavenged engine.

Since the preliminary CCE design had uniflow scavenged cylinders, a uniflow, single cylinder test rig activity has been undertaken. Detroit Diesel Allison has provided GTEC, under a subcontract, modified series 53 hardware which is being operated as a single cylinder engine test bed. The DDA hardware support is three phased. An initial set of hardware is being installed to begin baseline uniflow testing, producing 50 hp (about 1 hp/cu-in) in its single 53 cu-in cylinder, while operating at 2500 rpm and a BMEP of 140 psia. A second set of upgraded hardware, will permit 100 hp (about 2 hp/cu-in) by operating at 3500 rpm and a BMEP of 213 psia. The third phase, an upgrade of the second set of hardware will allow 150 hp (nearly 3 hp/cu-in) by operating at 4000 rpm and a BMEP of 280 psia.

The predicted operating conditions for the three rig builds are shown in table II. As indicated above, the main factors in achieving the higher power densities are increased manifold pressure, to more closely simulate CCE levels of boosting, and increased engine speed. The maximum piston speed is 3000 ft/min. This single cylinder test rig will thus provide the capability to systematically make wear measurements in a uniflow scavenged configuration, while operating at conditions which approach those of the CCE.

Phase III: Lubricant and Materials R&D

The lubricant and material research and development activities have centered around two efforts; the first is a lubricant specification for compound cycle engines, and the second is a Hohman wear rig. A draft of the CCE lubricant specification has been written and was circulated to government, industry, and university experts for comment. The Hohman wear rig, is being used to screen lubricant/additive combinations and lubricant/material couples for the CCE program. In conjunction with this activity, industry sources have been providing lubricant and additive samples for evaluation. Figure 11 shows a schematic of the Hohman wear rig and preliminary test results. The Stauffer STL plus 10 percent TAP is the baseline, or control, lubricant for this activity. The Montsanto MCS 2189 with its 85 percent reduction in wear and its 30 percent lower friction coefficient has produced the most promising bench test results to date. Combining the baseline single cylinder wear data with the improvements believed possible using Montsanto 2189, life for the CCE should be near 1400 hr. While life and wear continue to be the major barriers to the development of a CCE, the potential of 1400 hr of life at such an early stage in this program is significant progress toward breaking down those barriers.

OTHER ACTIVITIES RELATED TO ACCOMPLISHING CCE LONG TERM GOALS

Beyond the CCE contractual efforts, there are several other related activities. Because the highest risk technologies of this program are life and wear, most of the related activity is in the area of tribology. A significant technology advancement is hoped for through a recently initiated consolidation of efforts in the government's diesel research community. The goal of this consolidation, in which the efforts of all participants are being coordinated, is to attack common problems and allign parallel efforts. The US Army AVSCOM at the Propulsion Directorate, the Tank-Automotive Command, and the Belvoir Research and Development Center; Southwest Research Institute; the National Aeronautics and Space Administration; and the Department of Energy are contributing their individual inputs into a combined program plan, a significant accomplishment for an activity of this magnitude.

Another related activity is an effort to allign the research activities in the university community more directly with the needs of the Compound Cycle Engine Program. We are working with the Army Research Office and also with the European Research Office to target more research toward our program needs.

Beyond these basic research thrusts, we have been advocating the CCE program throughout the engine industry. There has been an ongoing effort to spark the interest of industry in our program, and also to explore and extend their interest in attacking several other barrier technologies, such as high speed, high pressure combustion; breathing and scavenging; high pressure fuel injection; as well as the technologies affecting engine life.

SUMMARY OF RESULTS

The CCE program goals are to prepare the way for a 1990's core engine demonstration of the compound cycle by attacking the barrier technologies. A major contracted activity is being conducted by the Garrett Turbine Engine Company. Other related efforts are being conducted within the government, within industry, and in universities. Collectively, these activities will put the Aviation Systems Command in the best position possible to successfully accomplish the CCE demonstrator program.

The implementation of a compound cycle engine in a light helicopter can result in a 30 to 40 percent reduction of mission fuel weight as compared to a conventional advanced technology gas turbine. In addition, an increase in range-payload product of about 50 percent is predicted. These enormous savings, on one of its most difficult applications, presents a promising future propulsion system alternative, not only for Army aviation systems, but also for numerous other applications.

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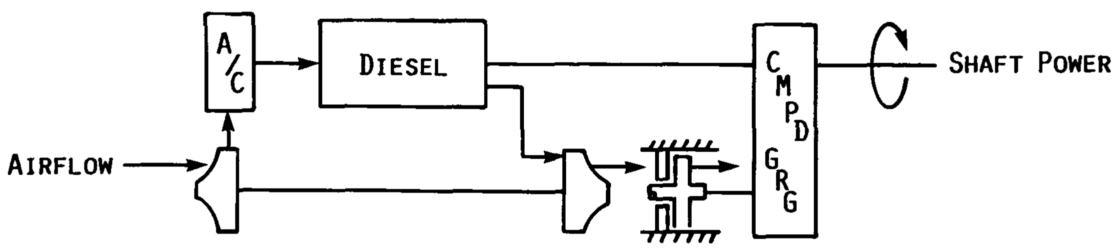
TABLE I. - FINAL DESIGN CONFIGURATION - 1000 HP ENGINE
1-1/2 SPOOL TURBOCOMPOUNDED



	Diesel		Turbomachinery
Configuration	V-6		Radial/Axial
Power output, percent	76		24
Speed, rpm	6100		66 000/19 000
BSFC, overall lb/hp-hr		[a]0.33	
BMEP, psi	390		-------------
Compression/pressure ratio	7.5		10.6
Airflow, lb/sec		2.44	
Specific power, hp/cu-in	5.7		-------------
Specific weight, lb/hp (Wet installed)		0.43	
Aftercooler Effectiveness		0.4	

[a]Includes 5 percent oil cooler/aftercooler fan power penalty, but not accessories.

TABLE II. - UNIFLOW SINGLE CYLINDER RIG OPERATING CONDITIONS

	Build		
	1	2	3
Horsepower	50	100	150
Speed, rpm	2500	3250-3500	4000
Inlet air temp, °F	200	300	300
Manifold press, psia	36	60	90
Coolant temp, °F	200	200	200
Bulk oil temp, °F	200	200	200
BMEP, psi	140	213	280
Max pressure, psi	1550	2300	3000
Equivalence ratio	.5	.5	.5
Compression ratio	14	12-10	10-8

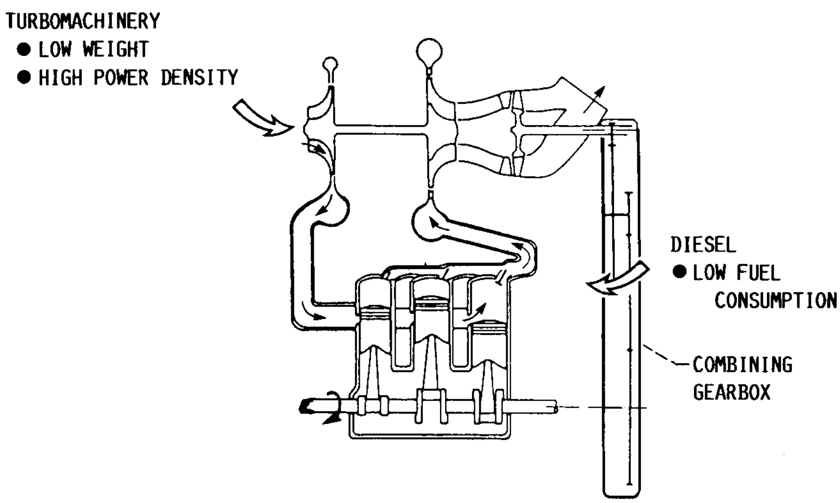


FIGURE 1.- SCHEMATIC OF COMPOUND CYCLE ENGINE.

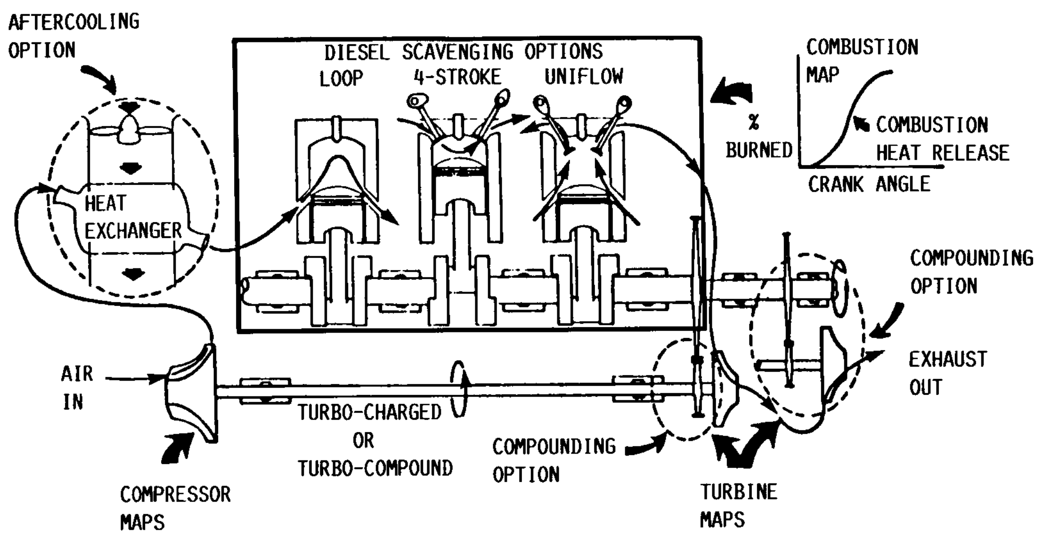


FIGURE 2.- FEASIBILITY STUDY OPTIONS.

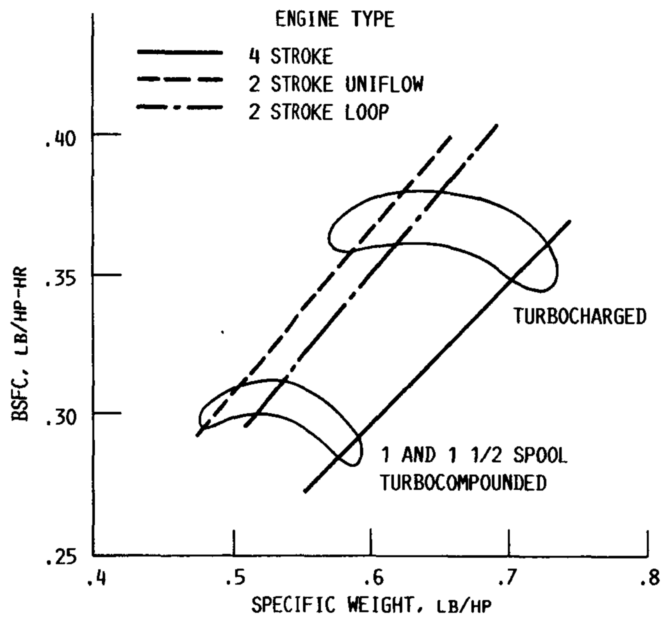


FIGURE 3.- VARIATION OF BRAKE SPECIFIC FUEL CONSUMPTION (BSFC) WITH SPECIFIC WEIGHT FOR VARIOUS SCAVENGING AND COMPOUNDING OPTIONS.

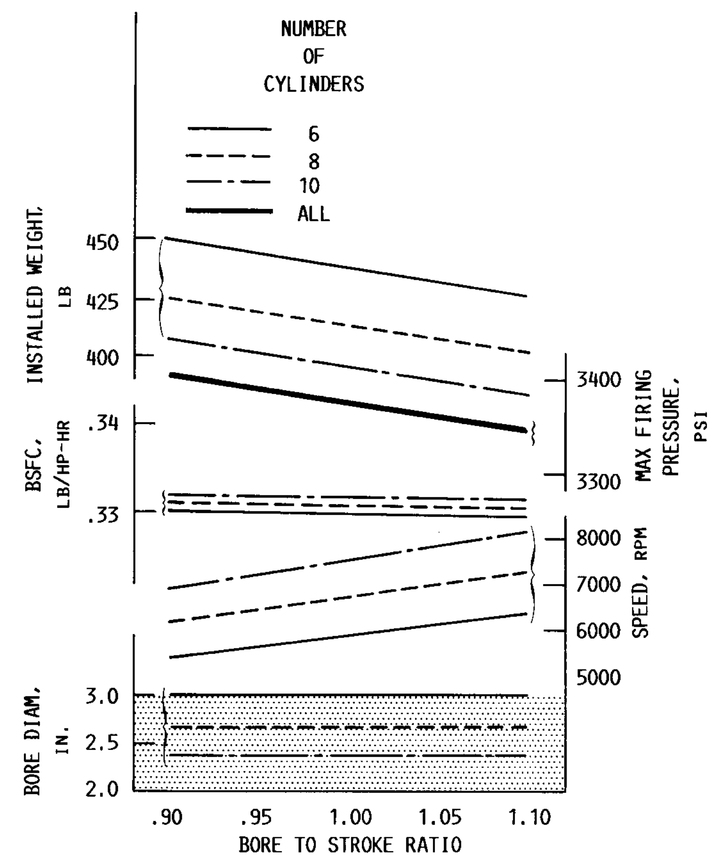


FIGURE 4.- TRENDS LEADING TO FINAL CCE DESIGN CONFIGURATION.

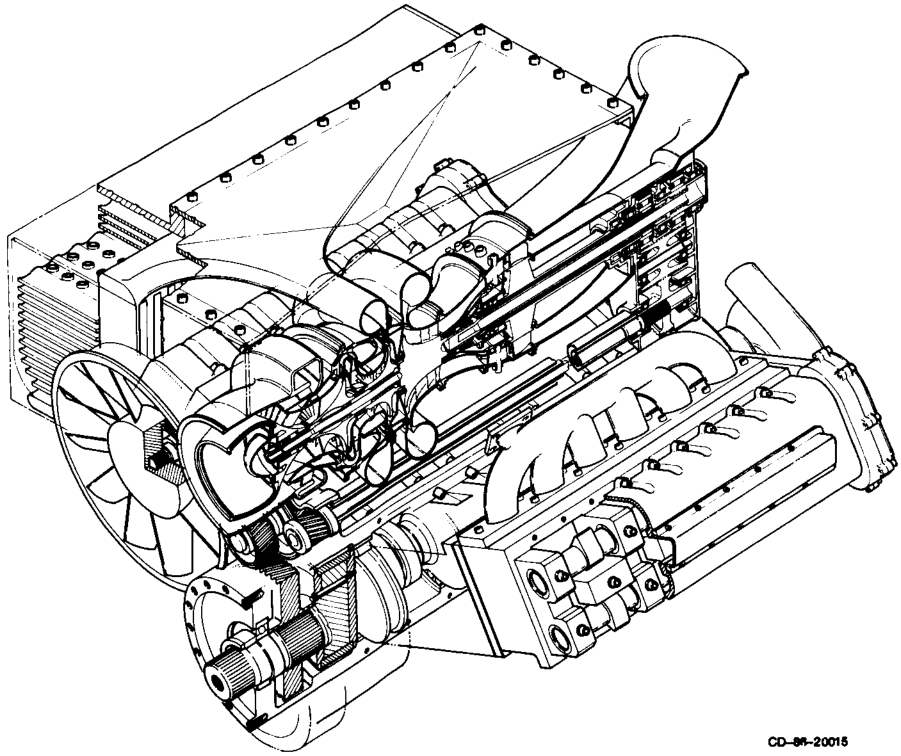


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FIGURE 5.- COMPOUND CYCLE ENGINE-CUTAWAY DRAWING OF FINAL DESIGN.

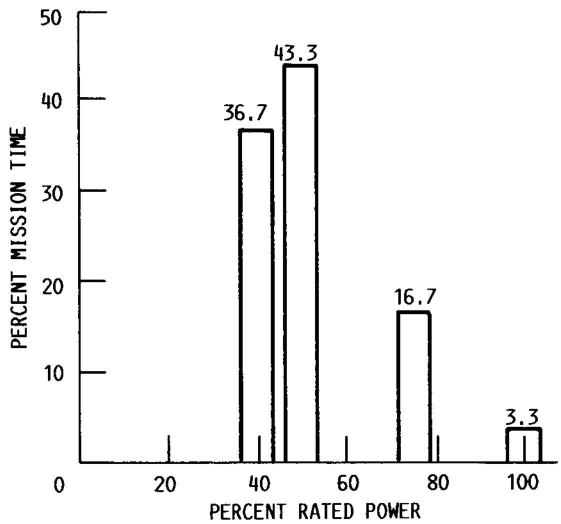


FIGURE 6.- COMPOSITE PROFILE OF TYPICAL LIGHT HELICOPTER MISSION (2 HOUR + 30 MINUTE FUEL RESERVE).

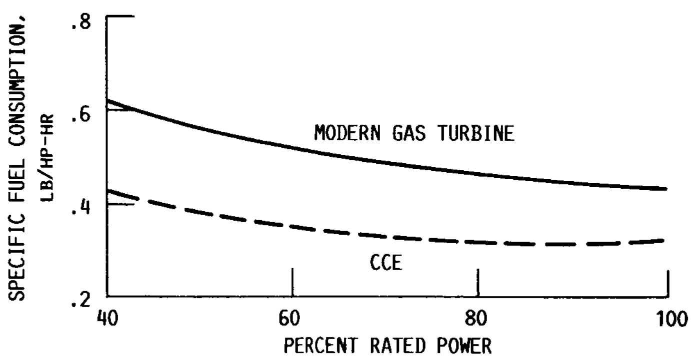
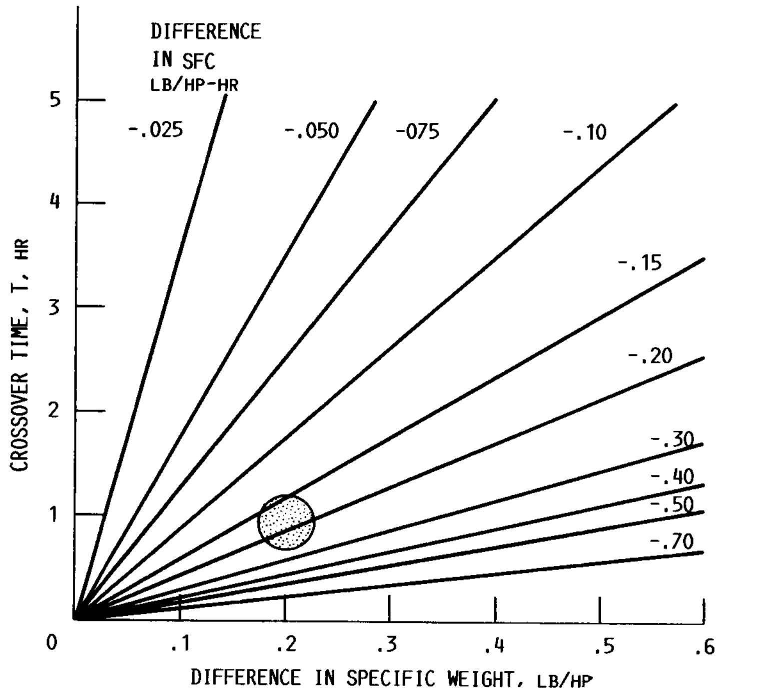


FIGURE 7.- SPECIFIC FUEL CONSUMPTION VARIATION WITH PERCENT RATED POWER FOR 1000 HP ENGINES.



SPECIFIC WEIGHT DIFFERENCE

$SW_{CCE} - SW_{GT} = .19$ LB/HP

SPECIFIC FUEL CONSUMPTION DIFFERENCE

$SFC_{GT} - SFC_{CCE} = .19$ LB/HP-HR

$$T = \frac{SW_{CCE} - SW_{GT}}{1.15\ (SFC_{GT} - SFC_{CCE})}$$

FIGURE 8.- CROSSOVER TIME AS A FUNCTION OF DIFFERENCES IN ENGINE SPECIFIC WEIGHT AND SPECIFIC FUEL CONSUMPTION.

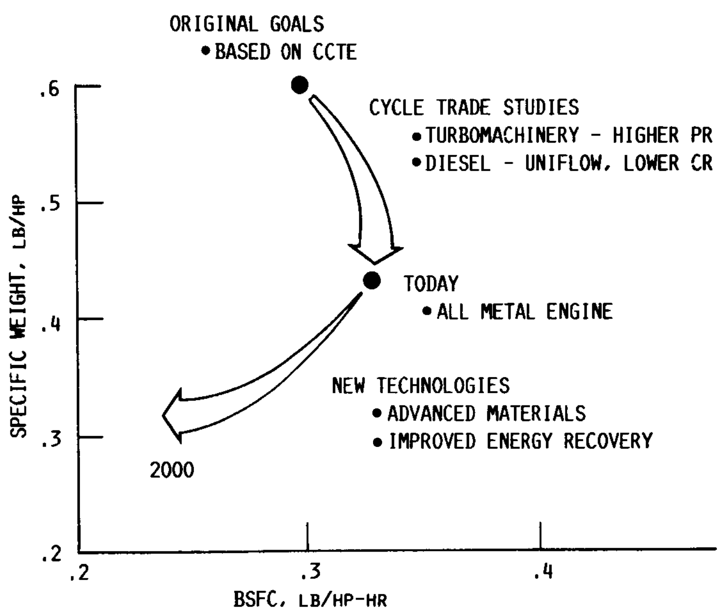


FIGURE 9.- COMPOUND CYCLE ENGINE - PERFORMANCE TRENDS.

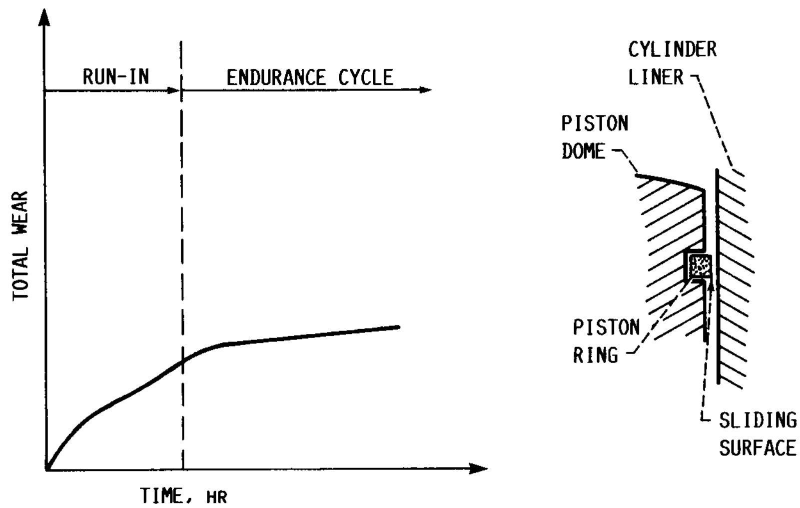


FIGURE 10.- TYPICAL RING WEAR TRENDS BASED ON RADIONUCLIDES MEASUREMENT SYSTEM.

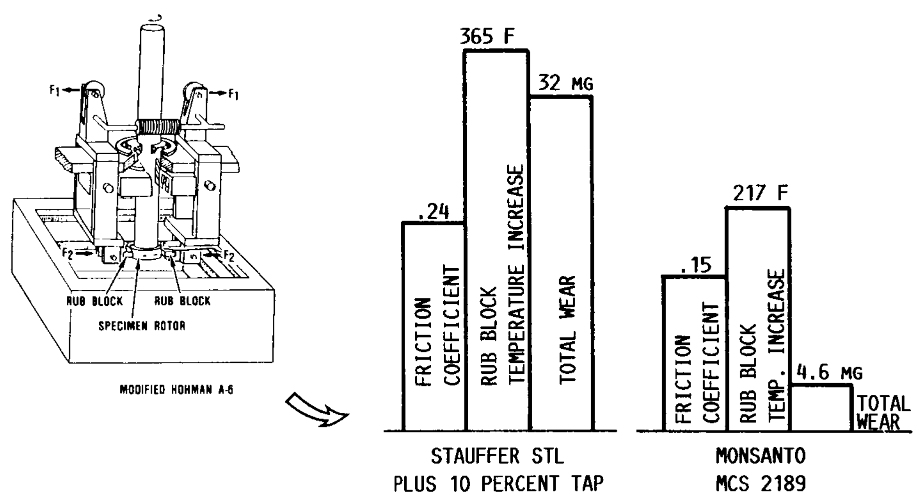


FIGURE 11.- LUBRICANT AND MATERIALS R AND D RESULTS.

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16. Abstract

The Compound Cycle Engine (CCE) is a highly turbocharged, power compounded power plant which combines the lightweight pressure rise capability of a gas turbine with the high efficiency of a diesel. When optimized for a rotorcraft, the CCE will reduce fuel burned for a typical 2 hr (plus 30 min reserve) mission by 30 to 40 percent when compared to a conventional advanced technology gas turbine. The CCE can provide a 50 percent increase in range-payload product on this mission. A program to establish the technology base for a Compound Cycle Engine is presented. The goal of this program is to research and develop those technologies which are barriers to demonstrating a multicylinder diesel core in the early 1990's. The major activity underway is a three-phased contract with the Garrett Turbine Engine Company to perform: (1) a light helicopter feasibility study, (2) component technology development, and (3) lubricant and material research and development. Other related activities are also presented.

17. Key Words (Suggested by Author(s))
Compound Cycle Engine; Diesel; Turbine/diesel; High performance diesel; Lightweight diesel; Helicopter engine

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