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ABSTRACT

The NASA Lewis Research Center (LeRC) as Project Manager of the Department of Energy's Automotive Heat Engine Program, is developing advanced gas turbine and Stirling engines for automobiles. To accomplish the program goals of improved fuel economy, reduced emissions, and broad alternative fuel capability major development programs have been undertaken for both engines. These programs are described along with the predicted characteristics of the engines under development and the key technology problems that must be resolved to achieve these objectives. NASA LeRC is also responsible for the development of the power conversion systems for the Parabolic Dish Solar Thermal Power Systems being developed for the Department of Energy by the NASA Jet Propulsion Laboratory. The requirements of this solar thermal application are reviewed and compared with the predicted characteristics of the automobile engines under development. A good match was found in terms of power level and efficiency when the automobile engines, designed for maximum powers of 65-100 kW (87 to 133 hp) were operated to the nominal 20-40 kW electric output requirement of the solar thermal application. At these reduced power levels it appears that the automotive gas turbine and Stirling engines have the potential to deliver the 40+ percent efficiency goal of the solar thermal program. However, in-depth studies are required to determine the extent of modifications required to adapt the engines for the solar application, and to fully assess the probable life, durability and resultant efficiency that can realistically be achieved in this application.

THE NASA JET PROPULSION LABORATORY (JPL), California Institute of Technology, is conducting a program for the U.S. Department of Energy to develop Parabolic Dish Solar Thermal Power Systems. In this effort the NASA Lewis Research Center (LeRC) is responsible for the selection and development of the Power Conversion Subsystem (PCS). The PCS converts thermal energy to electricity and normally includes an engine, an alternator, and associated auxiliaries.

Consideration is being given to adapting the automotive Stirling and gas turbine engines, currently in development under the Department of Energy's Automotive Heat Engine Program, to this use. The Lewis Research Center also has project management responsibility for the Heat Engine Program. In this program major development efforts are underway to develop improved gas turbine and Stirling engines which will provide at least a 30 percent improvement in fuel economy, broad alternative fuel capability, and reduced emissions. In this paper, these engine development efforts are briefly described, and the projected characteristics of the engines are evaluated against the requirements of the engines for the Power Conversion Systems in the solar thermal application.

BACKGROUND - AUTOMOTIVE HEAT ENGINE PROGRAM

The Automotive Heat Engine Program was begun by the Environmental Protection Agency (EPA) in 1971 and had the initial objective of developing alternative automotive heat engines with significantly reduced exhaust emissions. In 1973, the objectives of improved fuel economy and multifuel capability were added. In this program all known types of heat engines were evaluated and more detailed investigations of the more promising candidates were carried out. Today, the Heat Engine Program has converged on the two most promising alternative engine candidates, Gas Turbine and Stirling.

With the formation of the Energy Research and Development Agency (ERDA), the EPA automotive propulsion system activities were transferred to ERDA, and additional emphasis was placed on developing alternative propulsion systems with substantially improved fuel economy and adaptability to various fuels while at the same time meeting the legislated emission standards. In this revised program, project management responsibility for implementation of the Automotive Heat Engine Program was assigned to the NASA Lewis Research Center (LeRC). This relationship was continued when the transportation conservation activities of ERDA were transferred to the newly formed Department of Energy (DOE), and continues today.

In February 1978, the President signed into law Title III, P.L. 95-238 entitled, "Automotive Propulsion Research and Development Act of 1978." This law specifically directs the Department of Energy to "establish and conduct new projects and accelerate existing projects which may contribute to the development of advanced automobile propulsion systems and give priority attention to the development of advanced propulsion systems, with appropriate attention to these advanced propulsion systems which are flexible in the type of fuel used." Consistent with these and other directives of P.L. 95-238 and with specific guidelines provided by the DOE Office of Transportation Programs, the Advanced Automotive Heat Engine Program now has the following goal:

To develop and demonstrate in 1984-1985 advanced gas turbine and Stirling automobile propulsion systems that meet the following objectives:

- At least 30 percent improvement in fuel economy (mpg) over a 1984 production vehicle of the same class and performance, powered by conventional spark ignition engines (based on equal BTU content of fuel used).

- Emissions levels that meet or exceed the most stringent Federal research standards; 0.4/3.4/0.4 g/mi, $HC/CO/NO_x$ - (particulate levels will be added when defined).

- Ability to use a broad range of liquid fuels derived from crude oil as well as synthetic fuels from coal, oil shale, and other sources.

- Suitability for cost competitive mass production.

Current development efforts for both the gas turbine and Stirling engines are being carried out in accordance with the Program Schedule Chart, Fig. 1. As shown, development efforts for both engines include two engine generations and will conclude with verification testing by EPA of the MOD 2 engines in vehicles.

TECHNOLOGY HISTORY - AUTOMOTIVE STIRLING ENGINE (ASE) - The Stirling engine is a relatively undeveloped engine with no current base of production engine experience for any application. Further, the technology base for the Stirling engine resides primarily in Europe with N. V. Philips, United Stirling of Sweden, and Maschinenfabriek Augsberg Nuremberg (M.A.N.). General Motors Corporation conducted an extensive Stirling engine effort from 1958 to 1970 under a license agreement with N. V. Philips. They performed substantial development work on the Stirling engine during this period (1)*, but apparently never seriously pursued its application to the conventional automobile. The Ford Motor Company established a licensing agreement and undertook a joint effort with N. V. Philips in 1971. Under this agreement Ford set out to specifically assess the Stirling engine for the automobile. As part of this effort N. V. Philips designed and built the four cylinder, 120 hp, swashplate drive, 4-215 Stirling engine (Fig. 2) for installation and test by Ford in a 1975 Torino vehicle. Results of these tests, published in Ref. 2, yielded fuel economies from 10 to 20 percent below the baseline spark ignition powered Torino vehicle, and 13 to 23 percent below predicted values. In spite of these relatively poor initial results, it was believed that the Stirling engine did have significant fuel economy improvement potential. This view was supported by the Automobile Power Systems Evaluation Study (3), completed by the Jet Propulsion Laboratory in 1975.

In September 1977 the Ford Motor Company initiated work on a seven year, cost shared Stirling Engine Development contract funded by DOE and managed by NASA. The first year of this effort was an intensive fuel economy assessment effort aimed at firmly establishing the fuel economy potential of the Stirling engine in the automobile.

This activity utilized the Ford 4-215 Stirling engine as a date base and estimated fuel economy improvement potential of a pro-

*Numbers in parentheses designate References at end of paper.

jected fourth generation (1984) engine based on both analytical and experimental evaluations of potential improvements. The results indicated an excellent fuel economy potential of from 38 to 81 percent beyond that of the baseline spark ignition engine vehicle of the same class and performance. In spite of these results, Ford Motor Company chose to terminate their Stirling engine activities due to their need to devote available resources to more near term problems.

The primary engine development effort in the Stirling Engine Program is now being conducted by a team consisting of Mechanical Technology Inc. (MTI), United Stirling of Sweden (U.S.S.), and AM General (AMG) - a wholly-owned subsidiary of American Motors Corporation. This DOE funded, NASA contracted effort was initiated on March 22, 1978. This effort is directed to the development of an advanced experimental Stirling engine for automotive application which will meet the program goal and achieve the transfer of Stirling engine technology to the United States. MTI is responsible for overall program management, development of component and subsystem technology, and transfer of Stirling engine technology to U.S. manufacturers. USS is primarily responsible for engine development. AMG is responsible for engine-vehicle integration, testing, and evaluation. In addition, it is intended to add to the project team during the course of development an American engine manufacturer who will be licensed to produce the Stirling automotive engine.

TECHNOLOGY HISTORY - AUTOMOTIVE GAS TURBINE (AGT) - In contrast to the Stirling engine, gas turbine engines have a long history of development and production for a wide variety of military and commercial applications. The Lewis Research Center has been involved to various extents in the evolution of the gas turbine engine for automotive application for approximately 20 years. Initially, LeRC was consulted by the Chrysler Corporation in the area of turbomachinery aerodynamic design for their early generations of experimental automotive gas turbine engines. To our knowledge, this was the first consideration of aircraft or advanced technology to this type of engine. The performance and features of the last of these engines, the 6th generation Chrysler engine, is shown as item e, Fig. 3 and Table 1.

Direct Government involvement in the development of the gas turbine engine as an approach to reducing automotive emissions came in 1972 with the award of a contract to Chrysler. Under this contract, durability tests of the 6th generation engine for 3500 hours of automotive type operation were successfully performed. The engine was also down-sized and upgraded with components embodying early 1970's technology. This included an air bearing, a ceramic regenerator, an electronic control system, a low-emissions combustor system and LeRC-designed compressor and turbine aerodynamics. The results of this effort, the Upgraded Engine project, item d, Fig. 3 and Table 1, showed that the application of the improved technology could improve the thermodynamic efficiency of the engine, particularly at part-powers where the engine operated over most of its automotive duty cycle.

Part of this increase in thermodynamic performance was due to a 24° C (75° F) increase in the allowable turbine-inlet-temperature (TIT) made possible by the use of more advanced metal alloys in the turbines. However, these materials were considered too costly and strategic for widespread automotive use, and while the steady state fuel economy approximated that of the spark ignition engine, it fell far short of the newly established Automotive Heat Engine Program objectives. To meet these new objectives, in-depth LeRC-directed and DOE-funded studies were conducted by automotive and aerospace contractors (4-7) to generate automotive gas turbine designs that would meet or exceed the program objectives. Considered were regenerative and recuperative engines having one, two, or three shafts with ceramic and, in some cases, metal turbines, and with a level of technology which was felt to be achievable by no later than the early-to-mid 1980's. The results of the studies (4-7) were threefold. They indicated that (1) structural ceramic materials could be developed as a replacement for the metal alloys in the combustors and turbines; that (2) as a result, the TIT could be increased by as much as 333° C (600° F); and hence, (3) thermodynamic efficiency could be improved by a factor of approximately two, making the gas turbine engine capable of meeting the fuel economy objectives of the Automotive Heat Engine Program.

Currently, two major AGT development efforts are underway. The first, pursuing a single shaft AGT, is being carried out by AiResearch Manufacturing Company (AiR) with Ford Motor Company providing the vehicle integration and some ceramic component development activities. The second effort, a two-shaft AGT, is being conducted by Detroit Diesel Allison Division of General Motors (DDA) with the Pontiac Division providing vehicle integration activities. A third contract effort with Chrysler Corporation with support from Williams Research Corporation (WRC) is being considered pending availability of funds.

SOLAR THERMAL PCS REQUIREMENTS

A description of the complete solar thermal power system and a detailed discussion of the power conversion subsystem requirements is contained in a companion paper, "Heat Engine Requirements for Advanced Solar Thermal Power Systems" by H. G. Pham and L. P. Taffe, Jet Propulsion Laboratory, California Institute of Technology, being prepared for this same 1981 SAE Congress. The following is a summary of key preliminary PCS system requirements and constraints which were assumed as the basis against which the applicability of automotive heat engines are assessed in this paper.

OPERATION - The PCS with the solar receiver subsystem (SRS) must be able to operate with solar input only, fuel fired heat input only, or with a combination of solar input and fuel fired heat. Since the power system must track the sun, the PCS must be capable of operation from 0 to 90° from the horizontal.

POWER AND PERFORMANCE - Rated net electrical output of 60 Hertz power is anticipated to be between 20 and 40 kW, with the final value dependent on mirror size, and the efficiencies of the various subsystems. The PCS efficiency at rated power shall be 40 percent or greater (including the alternator unit and any auxiliary losses), and shall be 37 percent or greater at 50 percent rated power. Average output power is estimated to be in the order of 80-100 percent of rated power.

RELIABILITY AND MAINTENANCE - Time between major overhauls should be at least 100,000 hours of operation in the solar-only mode. Minor maintenance should not exceed four times per year nor require more than one man-hour each time.

COMPARISON WITH AUTOMOBILE APPLICATION - In contrast to the above, the automobile has a life requirement of about 3500 hours without major overhaul, a maximum power requirement in the order of 65-100 kW (87 to 133 hp), and an average power of about 10-20 percent of maximum power. Further, the automobile engine experiences frequent rapid speed and power changes, particularly in urban driving. These solar thermal and automobile requirements are compared briefly in Table 2.

AGT APPLICATION TO THE SOLAR THERMAL PCS

This section discusses the potential application of the three AGT engines evolved from the studies of Refs. 4 to 7, and now in development, to the solar thermal application.

PERFORMANCE EVALUATION - The predicted performance and design features of the three AGT engines are shown as items a, b, and c in Figs. 3 and 4 and Table 1. The efficiency curves of Fig. 3 are for a variable speed mode of operation. The variable compressor inlet guide vanes (VIGV's) incorporated in these engines are fixed in the position to provide maximum power and high efficiency at all speeds. All three designs deliver near their maximum efficiencies in the power range required for the PCS application. Differences in efficiency levels between the engines reflect differences in turbine inlet temperatures and engine configuration since all three engines incorporate appoximately the same level of component technology. Applying an assumed efficiency of 94 percent for the alternator unit to each of the designs at a nominal 30 kW power level yields "base" PCS efficiencies of 44.1, 38.2, and 36.7 percent for the AiR, DDA, and Chrsyler designs, respectively. However, actual application of any of the three engines must consider the unique features of each, and the potential effects of necessary modifications and system integration on the installed performance of the PCS. The following discussion addresses areas of potential performance impact as well as considerations for durability.

MODIFICATIONS FOR RECEIVER - Because the PCS must be capable of hybrid operation (operation on solar energy, fossil fuel, or both), the AGT engine must retain its own combustor system, or it must be incorporated with the solar receiver. In either case, addition of external flow ducting is required to stage the airflow through both the solar receiver and the combustor. An example of these structural changes and ducting additions required for the AiResearch/Ford-AGT, Fig. 4(a), is shown in Fig. 6. These changes increase the system pressure loss, leakage and heat loss, and requires physical modifications to the combustor and engine housing and will require detailed evaluation.

MODIFICATIONS FOR ALTERNATOR - Integration of the alternator unit into the PCS presents a number of technical questions and design options. These start with the very high turbine output shaft speeds ranging from 48,000 to 87,000 rpm, in Fig. 5 and the need to vary speed to modulate power. Potential design solutions include direct drive high speed alternators, the use of gearboxes, variable speed drives, and a variety of electrical conversion arrangements, including dc to ac conversions as well as ac to ac frequency conversions.

In order to simplify the requirements for the alternator unit, a constant-speed mode of throttling the engine may be desirable. This mode of operation is illustrated in Fig. 7 on the performance map for the AiR-AGT engine. The engines' variable inlet guide vanes (VIGV) would be utilized to vary the power at constant speed. Throttling line (a) on the figure shows that this mode would decrease engine efficiencies somewhat from those shown in Fig. 3 (throttling lines b and c on Fig. 7). However, the possible benefits of this mode of operation would have to be evaluated against the potential impact on engine reliability and durability, part-power operating range, and the efficiency and operation of the alternator unit to determine its suitability for the PCS.

MODIFICATION FOR DURABILITY - The AGT engine must operate at from three to five times the average power level and for thirty times the number of hours in the PCS application as compared to an automobile application (Table 2). However, the number of equivalent start-stop cycles and acceleration-deceleration cycles may be somewhat reduced. The rotative speed information in Fig. 5 indicates that the engines in the solar application would operate at shaft speeds of 62-87 percent of their maximum automotive design speed (gasifier speed in the case of the DDA-AGT 2-shaft engine). Finally, Fig. 8 which is a plot of the operating temperatures for the AGT's, indicates that the AiResearch engine would operate at generally less than its maximum design turbine inlet temperature (TIT) but at its maximum regenerator inlet temperature (RIT), over the rated power range for the PCS, while just the reverse would be true for the DDA engine. For the automotive application, the average rotative speed for the AGT's range from approximately 55 to 60 percent of maximum speed, the average TIT's are from 90° to 150° C (160° and 270° F) below their maximum value, and the RIT is at its maximum value. The total amount of engine time spent at 100 percent rotative speed and maximum TIT to satisfy the requirements for the automotive application is approximately 100 hours.

Evaluation of the combined effect of these differences on engine life and required modifications is beyond the scope of this paper. However, several areas are apparent as follows:

The regenerator cores and seals will not have adequate life to meet the requirements for the PCS. Two to four man-hours are required to replace the regenerator seals in the Chyrsler Upgraded engine compared to the desire to limit the down-time for periodic maintenance on the PCS to one man-hour. This, combined with the adverse effect that seal leakage has on efficiency, suggests the desirability to develop a recuperator to replace the regenerator system. Balanced against this would be an extensive modification to the engine's flow path and housing to change to a recuperative system. Also, the technology and experience in ceramic recuperator design is not as advanced as regenerators.

The B-1 life for the rolling contact bearings used on both shafts of the DDA-AGT, and the cold-end of the shaft for the AiResearch and Chrysler AGT's will be roughly twice the 3500-hour life required for the engines when operating over their normal automotive duty-cycle. Those bearings would require replacement with probably air-journal-bearings and air-thrust-bearings, for the PCS application. This would require a bearing development and engine modification effort. The life of the contact shaft seals would also be inadequate, and would require either periodic replacement, which would require engine teardown, or replacement with noncontacting labyrinth type shaft seals, which would probably increase engine air leakage and performance losses.

The inherent buildup of oxide films on the surface of ceramic parts may present problems for the PCS application. Mating parts in sliding contact with each other, such as the variable-geometry parts of the AGT combustor, or various housing parts, may stick or fuse together. This is because of their exposure to higher operating temperatures for longer periods of time between changes in engine speed and operating temperature, and over a much longer life than in the AGT. The moving sections of the combustor are exposed to approximately 260° to 320° C (470° to 575° F) higher air temperatures in the PCS when operating in the solar-thermal mode than in the fuel-only mode. However, elimination of the variable-geometry feature may be feasible without increasing emissions if the operating range for the combustor in the PCS application is less than the AGT. Other modifications to the combustor may also be required to prevent fuel coking, or auto-ignition during hybrid operation.

ASE APPLICATION TO THE SOLAR-THERMAL PCS

A schematic drewing of the ASE design, currently being developed, is shown in Fig. 9. Its potential for application to the solar thermal requirements is discussed in this section.

The projected performance map of the ASE, based on information supplied by MTI and U.S.S., is shown in Fig. 10. The top performance curve is a plot of net shaft power versus engine speed for a charge pressure of 15 MPa (2175 psia) and heater tube temperature of 820° C (1508° F). An overlay plot of constant net efficiency is also shown. Net efficiency is defined as net shaft power divided by the Q of the fuel. Note that at 1800 rpm a net shaft power of 39 kW (52.3 hp) can be developed at an engine efficiency between 42 and 42.5 percent. At 1200 rpm, a net shaft power of 27 kW (36.2 hp) can be developed at an efficiency better than 43 percent.

Varying engine pressure and selecting either 1200 or 1800 rpm allows the engine efficiency to be kept at approximately 42 percent or higher over an engine power range of 17-39 kW (23-52 hp). It also allows constant speed operation for fixed 60 Hertz frequency with a direct drive alternator. If we assume that the ASE engine heater head can be used in the solar application ith the same void volume and heater tube heat distribution characteristics as the automotive application, and that heat is rejected by a natural convection heat exchanger, the engine and PCS system can be expected to perform as shown in Table 3. In this analysis, Helium has been substituted for Hydrogen as the working fluid. Auxiliaries for the solar application include an oil pump, water pump, and helium compressor. This analysis indicates a maximum PCS output power of 35.1 kW (47 hp) at 1800 rpm assuming a 94 percent efficient alternator unit. A full 40 kW (53.6 hp) PCS output power could be achieved by increasing engine speed to approximately 2100 rpm. However, additional efficiency penalties would be encountered, including about one point in engine efficiency and either gearbox losses or electrical frequency conversion losses encountered in providing the 60 Hertz output. The resulting reduced efficiency and increased complexity should provide considerable incentive in final system sizing trade-offs for limiting PCS output power to 35 kW (47 hp) or less.

MODIFICATION FOR PERFORMANCE - When a Stirling engine is integrated with a solar receiver as a power conversion system the heat exchanger tubes that intercept the solar radiation may connect directly to the engine cylinder heads which contain the working fluid. In some designs, a heat pipe heat transport system may couple the solar insolation to the engine heater tubes. Since the Stirling engine heater tube volume is "dead" volume that decreases the cylic power output of the engine, an attempt should be made during engine design to minimize heater head dead volume without compromising the heat transfer properties of the heater head. Design of the Stirling engine heater head for a solar application will depend upon the type of solar receiver that is attached to the engine. For example, a solar receiver that uses a sodium heat pipe heat transport system, between the solar heated evaporator end of the heat pipes and the engine heater tubes, will require less heat exchanger surface area (less dead volume) than a combustor or direct solar radiation heated heater head. Such a heat transport system offers very uniform heating of the heater tubes thus permitting engine operation at higher average heater tube temperatures for the same limiting maximum heater tube temperature. This should yield a net improvement in engine efficiency.

The efficiency predictions of Table 3 were based on Helium working fluid. The utilization of hydrogen as the working fluid, as in the ASE, would yield approximately a two point efficiency improvement and should be carefully evaluated against the considerations for hydrogen handling, hydrogen permeability, and materials strength and compatability (see below).

MODIFICATION FOR DURABILITY - The operating lifetime goal for the solar PCS is 100,000 hours. Critical components of the ASE engine that must be considered relative to such a lifetime goal are the engine hot section parts consisting of the heater tubes, cylinder housings, and regenerator housings.

There are several design approaches that may be taken to extend the lifetime of these critical ASE engine components beyond the present 3500 hours. A significant increase in creep rupture lifetime will occur if engine hot section temperature is decreased from near 800° C (1472° F) toward 700° C (1292° F). Decreasing engine gas pressure also results in a substantial increase in creep rupture lifetime, especially at the lower temperature near 700° C (1292° F). Of course, reducing temperatures and pressures will also reduce engine efficiencies.

Stirling engines in the past have achieved reasonable engine lifetime by using cobalt based alloys for the hot section components. N-155 alloy (20 percent cobalt) has been used for the heater tubes, and HS31 (54 percent cobalt) for the cylinder and regenerator housings. N. V. Philips company has tested an engine with heater tubes made of N-155 alloy for more than 10,000 hours without any sign of degradation of the material (8). However, because cobalt is a rare and costly metal, a mass production engine could not economically or strategically contain this amount of cobalt.

Iron based alloys are being pursued as the primary candidates for use in the ASE engine in the automotive application because nickel-based alloys are generally unsatisfactory for use with the hydrogen working fluid. Typical alloys are 19-9DL for the heater tubes and XF818 for the cylinder and regenerator housings. Since helium is planned as the working fluid for the solar engine application, nickel-based alloys may also be used. The creep properties of Inconel 617 and 625 are attractive for heater head fabrication. Nickel-chromium 713LC alloy is an excellent cylinder and regenerator housing material. It has good castability and could be cast in the same mold that is used to cast the automobile ASE engine housings.

It is customary in cylinder and regenerator designs to define allowable creep lifetime of these components in terms of percent deformation. Typically, this failure criterion is 1 percent creep deformation. During design modifications of the ASE engine for solar application, a study should first be performed to determine the extent of cylinder creep deformation that could be allowed in the design, short of rupture, without degrading the ASE engine performance below an acceptable level.

For this application, piston rod and piston ring seals may have to be considered as maintenance replacement elements. Operation of the ASE engine at the lower (1200 rpm) speed should extend the lifetime of these seals beyond the current 3500 hour objective. However, achieving 100,000 hours without seal replacement would appear very unlikely. The rod seal that is used in the ASE engine is a proprietary Pumping Leningrader seal that is under development by United Stirling Corporation. Engine testing of the seal has exceeding 3000 hours duration at a speed of 2000 rpm. The seal has been tested in engine and seal rigs for a total of more than 8000 hours (9).

Another type of seal that could be considered as an alternate rod seal is the Philips rollsock seal. This seal has been successfully tested in a Philip's I-98 engine for 10,000 hours at a speed of 3000 rpm (10). Philips is also developing a dual pumping ring seal as an alternate to the rollsock seal. This seal has accumulated more than 7000 hours of testing in a seal test rig. In consideration of the extremely long life requirement and the susceptability of the engine to degradation from oil contamination, some form of positive rod seal such as the rollsock, a diaphragm, or bellows should be given strong consideration for this application.

Based on the above reported seal testing work, it is reasonable to assume that by the year 1985 a reliable seal with a lifetime of at least 10,000 hours can be developed, provided that an intensive seal development effort is undertaken. Further design modifications may be required to facilitate the desired short seal replacement times.

SUMMARY AND CONCLUSIONS

This preliminary evaluation indicates that both the AGT and ASE engines have the potential for meeting the efficiency objectives of the solar thermal program. However, in both cases there is significant question about the potential for achieving the life and durability goals of the program. Some reduction in efficiency may result during the actual process of adapting the engines to the application and incorporating the necessary modifications in design and/or operating conditions to meet the life and durability requirements. In both cases, in-depth design studies are required to fully assess the probable efficiency, life, and durability that can be achieved and the amount of modification required to adapt these automotive engines to the solar thermal application. Assuming that much of the existing basic engine designs could be retained, substantial development cost savings should be realized with this approach. However, it would be desirable to evaluate the efficiency, life, durability, production cost, and life cycle cost differences between this approach and that of "clean sheet" gas turbine and Stirling engines designed specifically for the solar thermal application, before entering into an active program to adapt one of these engines to the solar thermal application.

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Table 1. - Design Characteristics of Automotive Gas Turbine Engines

Engine designation	Max. TIT, °C (°F)	Max. RIT, °C (°F)	Max. power, kW (hp)	No. of shafts	Max. shaft gasifier, rpm	Speed power, rpm	Remarks
(a) AiResearch/Ford AGT	1371 (2500)	1094 (2000)	97.5* (130)	1	100,000	100,000	Ceramic regenerator, burner, turbine
(b) DDA/Pontiac AGT	1288 (2350)	1055 (1930)	64.5 (86)	2	86,200	68,000	Ceramic regenerator, burner, turbines
(c) Chrysler/WRC AGT	1260 (2300)	983 (1800)	65.3 (87)	1	99,500	99,500	Ceramic regenerators, burner, turbine
(d) Chrysler Upgraded	1052 (1925)	748 (1378)	78 (140)	2	58,500	50,000	Ceramic regenerator, advanced controls, compressor, turbines, and bearing technology
(e) Chrysler 6th generation	1010 (1850)	727 (1340)	113 (150)	2	44,600	44,500	Demonstrated 3500 hr. endurance under EPA part of program

*Gearbox limited to 75 kW (100 hp).

Table 2. - Requirements Comparison

Solar Thermal PCS vs. Automobile

	Solar thermal PCS	Automobile
Life, hours	100,000	3500
Maximum power, kW	20-40	65-100
Average power, percent of max.	80-100	10-20
Transient operation	Infrequent	Frequent

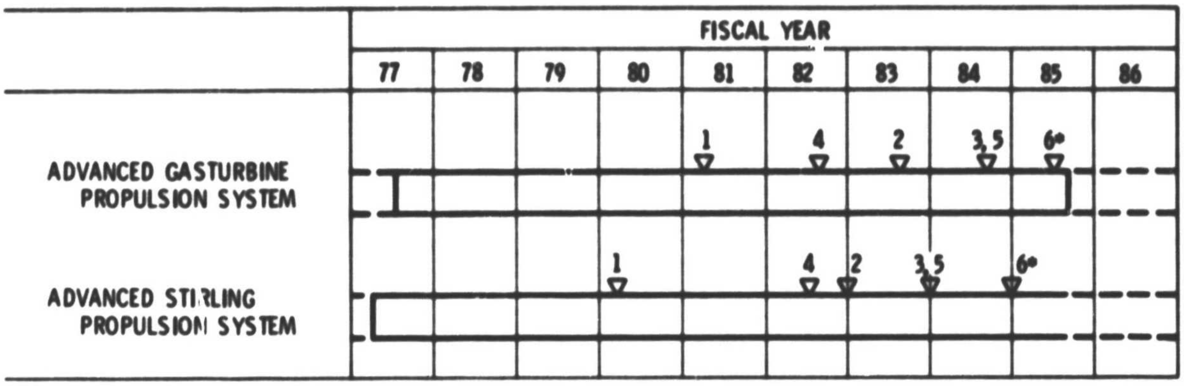
Table 3. - Solar ASE/Alternator PCS

[Natural convection heat rejection, helium working fluid]

	1200 rpm Power output*		1800 rpm Power output*	
	Full	Half	Full	Half
Engine speed, rpm	1200	1200	1800	1800
Heater head temp., °C (°F)	820 (1508)	820 (1508)	820 (1508)	820 (1508)
Charge pressure, MPa (psia)	15 (2175)	**	15 (2175)	**
Brake power, kW (hp)	26.2 (35.1)	13.1 (17.6)	37.3 (50.0)	18.7 (25.1)
Brake efficiency, percent	45.0	42.7	43.5	41.7
PCS efficiency, percent (alternator eff. = 94 percent	42.3	40.1	40.9	39.2
PCS output power, kW (hp)	24.6 (33.0)	12.3 (16.5)	35.1 (47.1)	17.6 (23.6)

*Based on computed ASE performance curve (Fig. 10), but using estimated power consumption values of auxiliaries that are required for solar stationary application.

**Pressure reduced sufficiently to produce half output power for same engine speed and heater head temperature conditions.



CODE

1. 1ST GENERATION (MOD I) POWERTRAIN DESIGN REVIEW
2. MOD I POWERTRAIN CHARACTERIZATION COMPLETE
3. MOD I POWERTRAIN IN VEHICLE
4. MOD II POWERTRAIN DESIGN REVIEW
5. MOD II POWERTRAIN CHARACTERIZATION
6. MOD II POWERTRAIN IN VEHICLE

*EPA TEST

Figure 1. - Automotive heat engine program schedule.

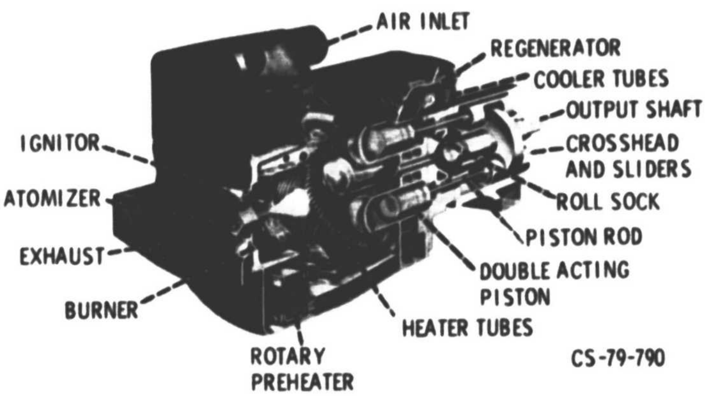


Figure 2. - Ford/Philips stirling engine.

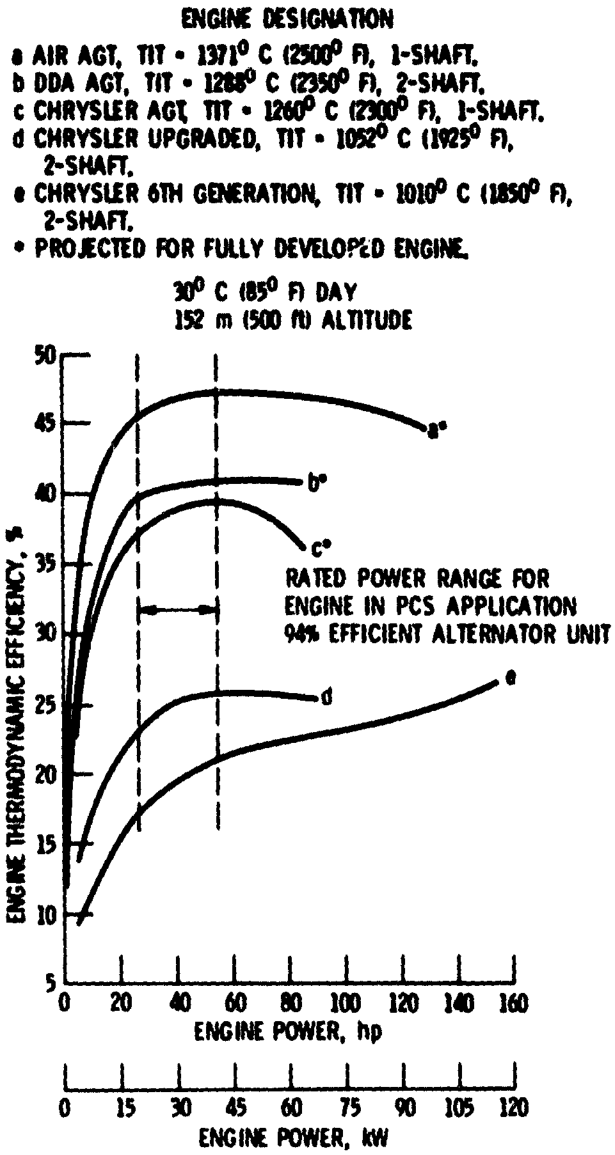
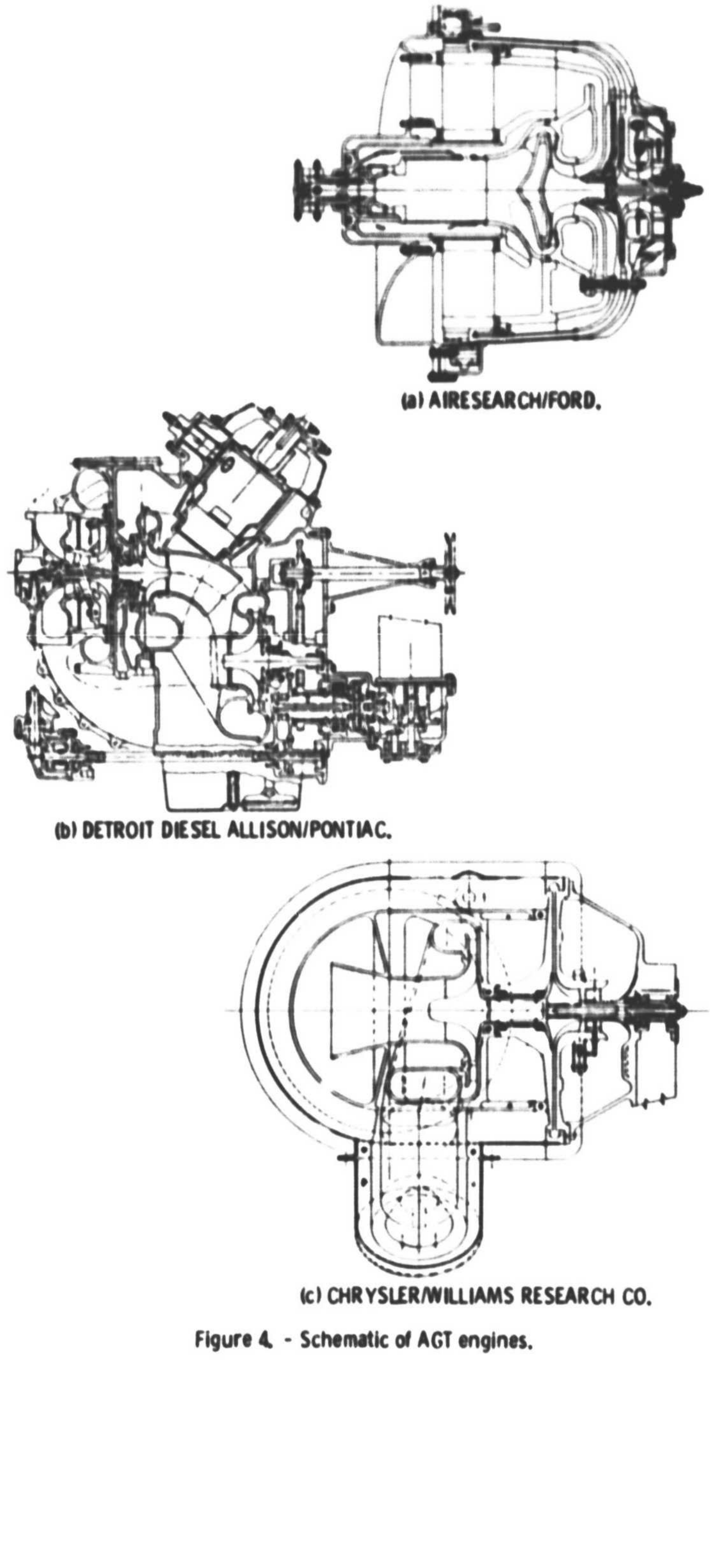


Figure 3. - Engine performance characteristics for variable speed mode of operation.



(a) AIRESEARCH/FORD.

(b) DETROIT DIESEL ALLISON/PONTIAC.

(c) CHRYSLER/WILLIAMS RESEARCH CO.

Figure 4. - Schematic of AGT engines.

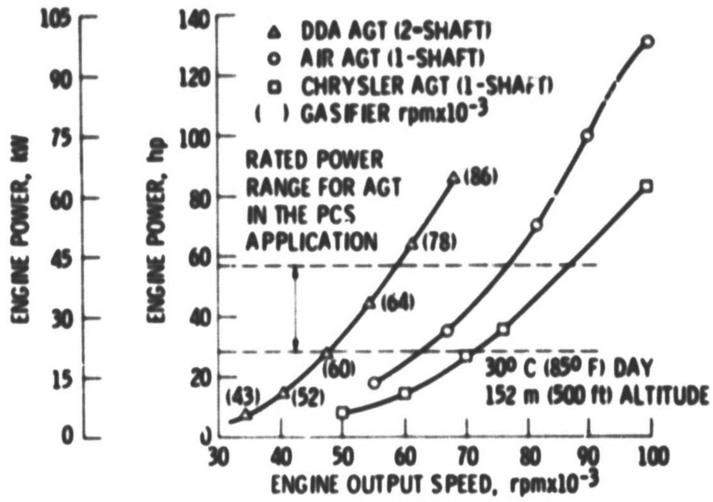


Figure 5. - AGT operating speeds for variable speed mode of engine operation.

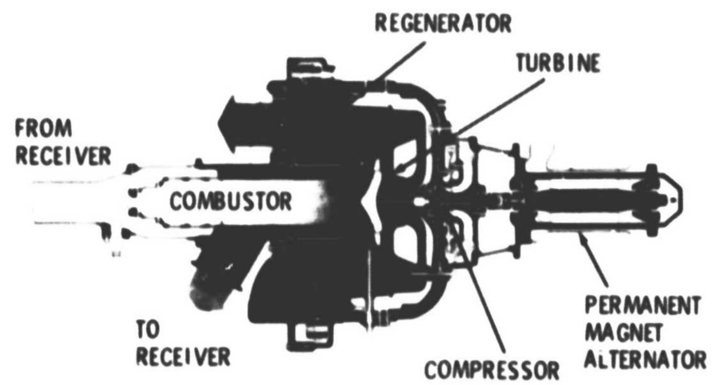


Figure 6. - Sketch of example modifications to AIR-AGT for PCS application.

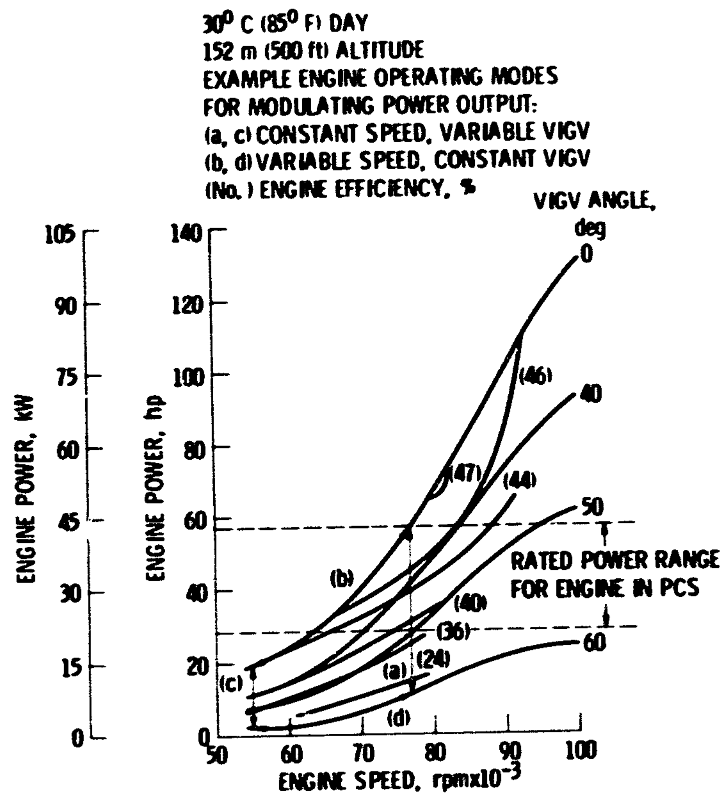


Figure 7. - Performance map for AIR-AGT engine.

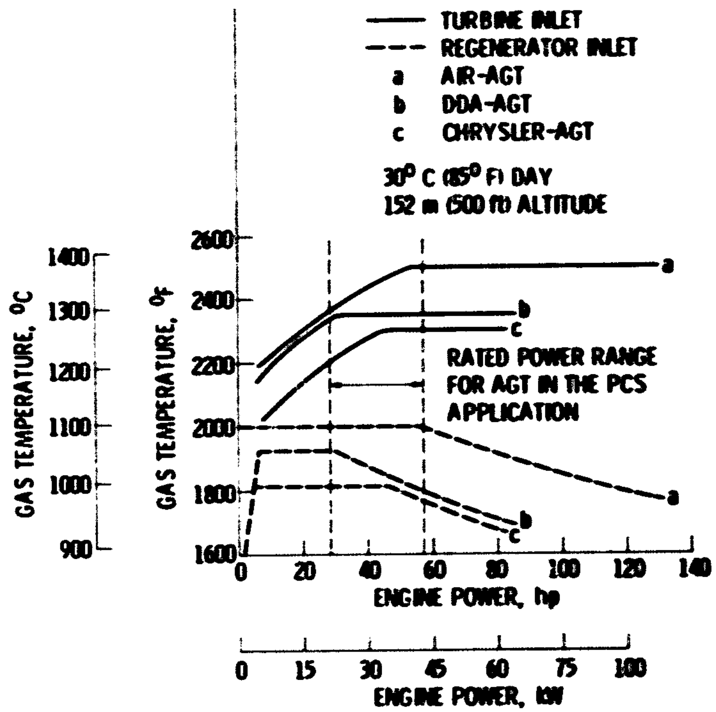


Figure 8. - AGT operating temperatures for variable speed mode of engine operation.

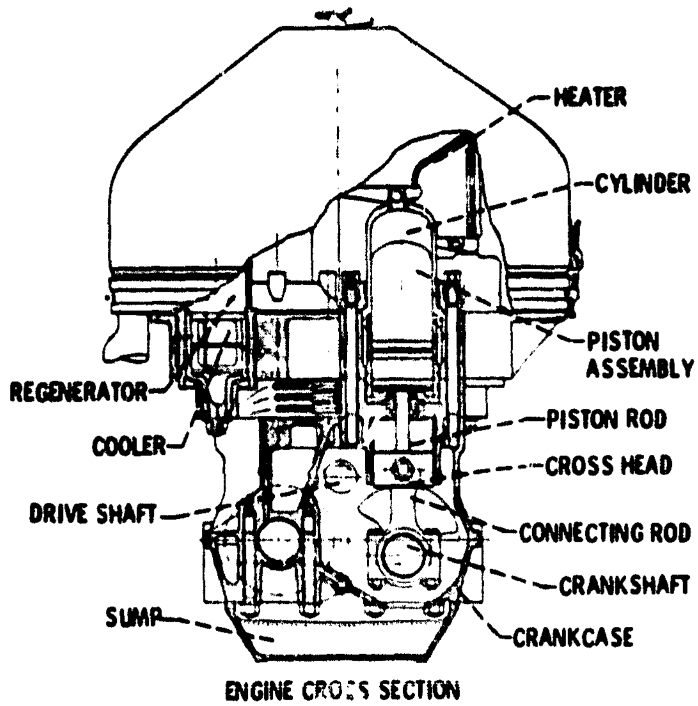


Figure 9. - ASE engine schematic.

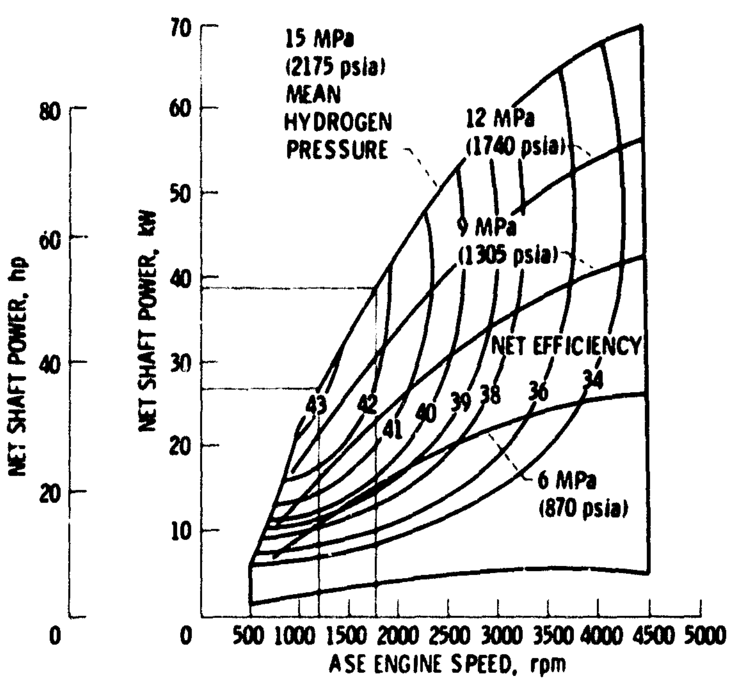


Figure 10. - Performance map of ASE engine.