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SOLAR BRAYTON ENGINE/ALTERNATOR SET

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ABSTRACT

Garrett's work on the Mod 0 solar Brayton engine/alternator set is being redirected to utilize solarized components of the automotive advanced gas turbine (AGT) being developed by Ford and Garrett under contract to NASA. The new configuration is referred to as the Mod I. Commercialization of solar Brayton engines thus should be enhanced not only by relating the design to an engine expected to reach the high quantity, low cost production rates associated with the automotive market, but also by the potential the AGT components provide for growth of efficiency and power rating. This growth would be achieved through use of ceramics in later versions making operation possible at temperatures up to 2500°F. The longer program duration and higher cost of the Mod I is considered compatible with the extended schedule of the application and the system test program for which the Brayton engine/alternator set is first intended. Subject to funding availability, the initial solarized AGT should be under test by Nov 1981, and a complete Mod I engine/alternator set deliverable approximately one year later.

The Mod I will operate at 1500°F turbine inlet temperature (TIT) and produce 23 kw shaft output power at about 32 percent shaft efficiency. Growth versions incorporating ceramic parts will be capable of operation at 2100 to 2500°F TIT and should develop 51 to 71 kw shaft power at efficiencies from 40 to 48 percent.

INTRODUCTION

This paper will report the status of the design, procurement and test effort by Garrett under NASA/DOE Contract DEN3-181. The purpose of this effort is to provide Brayton engine/alternator set hardware for demonstration of parabolic dish solar electric power modules.

When commercialized, the solar power modules will be the building blocks of dispersed solar power plants ranging in size from a few kilowatts to systems up to 10 megawatts. The concept of a dispersed power plant consists of combining the electrical output from the required number of identical solar power modules. The modules would be controlled from a conveniently located substation where any final power conditioning also would be performed. Each module would comprise a concentrator, a receiver, and an engine/alternator (E/A) set sometimes referred to as a power conversion subsystem (PCS). The E/A set hardware being procured under Contract DEN3-181 is expected to be evaluated at JPL's Parabolic Dish Test Site at Edwards Air Force Base, California. The E/A set will be part of an experimental solar power module that also includes a test bed concentrator and a Garrett solar receiver.

During the period from February to July of 1980 the analysis and design of the Mod 0 engine/alternator set was essentially completed. The resulting configuration which is shown in Figure 1 reflected the initial guidelines, a low risk approach with minimum program cost and schedule. The Mod 0 design was based on use of the turbocompressor from the GTP36-51, a high performance state-of-the-art gas turbine recently designed for production rates up to 1000 per year as an Army generator set, two GT601 truck gas turbine production configuration recuperator cores, and an off-the-shelf Bendix 400 Hz alternator. At the 1500°F TIT limitation, set by the intended use with a metallic solar receiver, the estimated Mod 0 shaft efficiency was 30 percent.

Redirection of the contract effort to a Mod I design was initiated in July 1980 to replace the Mod 0 components with more advanced components designed with lower cost higher production rates in mind. The Mod I design selected by JPL includes solarized versions of the turbocompressor and regenerator from the automotive advanced gas turbine (AGT) under development by Ford and Garrett on NASA Contract DEN3-167 and a new permanent magnet alternator (PMA). This selection was made on the basis that these components would reduce the overall cost and schedule for achieving a commercialized Brayton engine for the solar power market in the 1990's.

This Mod I engine/alternator set (see Figure 1) will operate at 1500°F and produce 23 kw of shaftpower at about 32 percent shaft efficiency in the initial metallic version. When ceramic AGT housings become available from the automotive program, the solarized version with a ceramic receiver should be capable of operation to 2100 to 2500°F where the shaft output power and efficiency should be 51 to 71 kw and 40 to 48 percent respectively.

MOD I COMPONENTS

Figure 2 illustrates the key design changes made to improve the commercialization potential of the Brayton engine generator set. The solarized GTP36-51 turbocompressor and GT601 truck recuperator cores were replaced by the solarized AGT turbocompressor and regenerator. A comparison of some of the design features is made in Table 1.

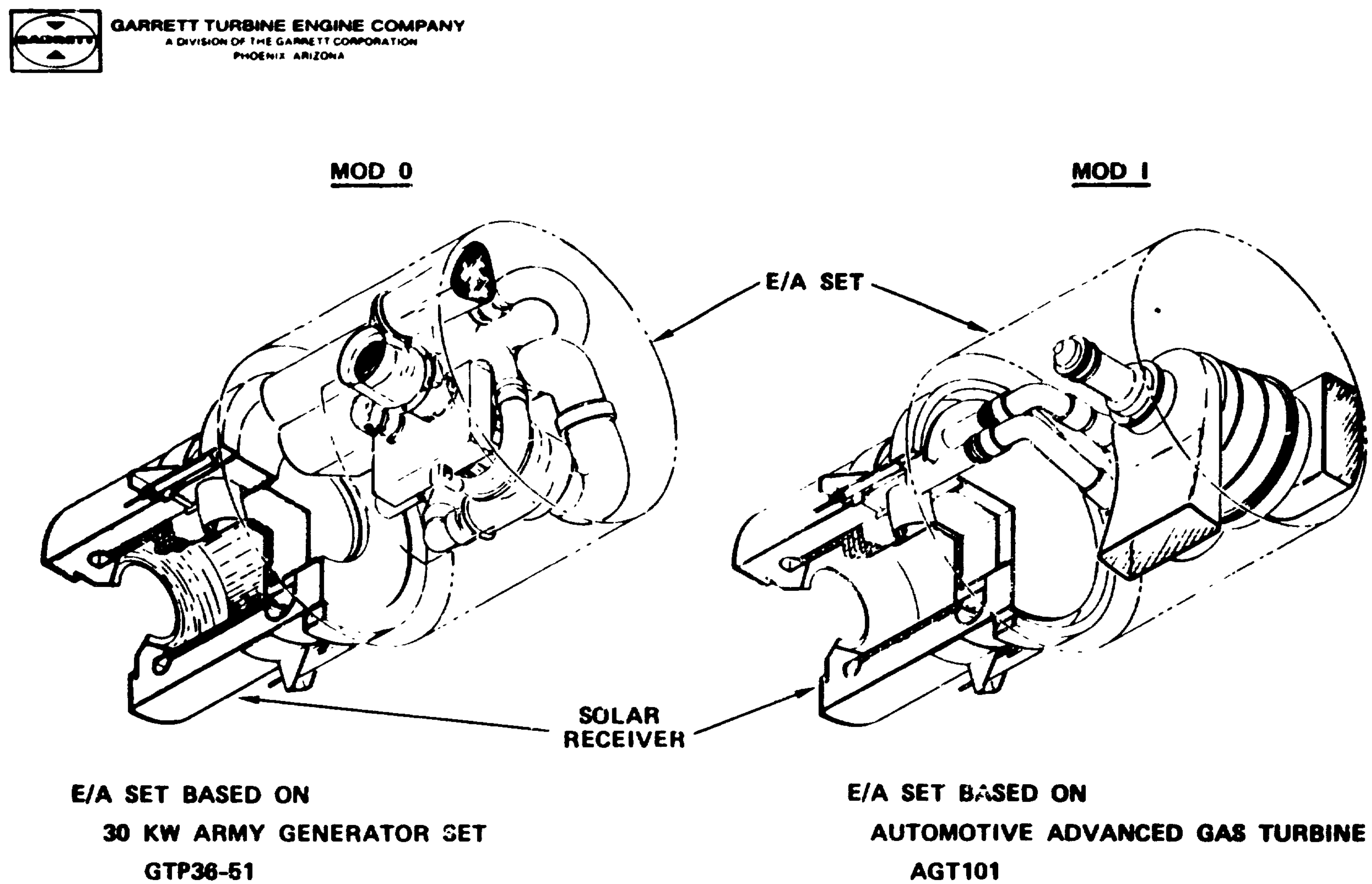

Figure 1. Brayton Engine/Alternator Set and Receiver.

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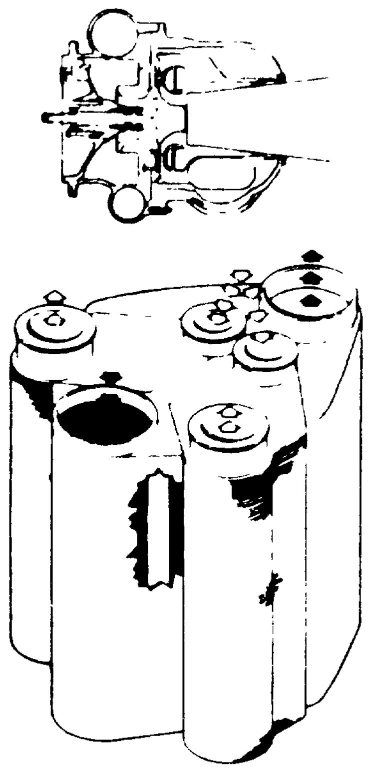
MOD O

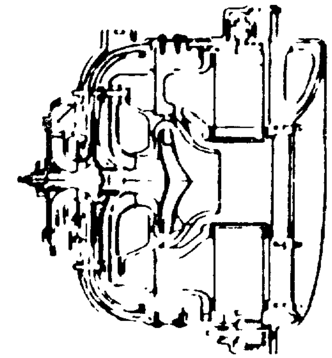
(SOLARIZED
GTP36-51)



- TURBO COMPRESSOR
  EXISTING GTP36-51 GENERATOR S'.T
  ALL METALLIC DESIGN
- RECUPERATOR
  EXISTING GT601 TRUCK CORF

MOD I

(SOLARIZED
AGT)



- TURBO COMPRESSOR
  DESIGNED FOR AUTOMOTIVE APPLICATIONS
  ADVANCED PERFORMANCE
  CERAMIC HOUSINGS IN FUTURE UNITS
- REGENERATOR
  CERAMIC AUTOMOTIVE DESIGN

Figure 2. Engine and Recuperator/Generator.

TABLE 1. SOURCE ENGINE COMPARISON

	GTP36-51 ARMY GENERATOR SET AND GT601 TRUCK RECUPERATOR	AGT101 AUTOMOTIVE ENGINE
• MAX OPERATING TEMPERATURE – TURBINE WITH METALLIC TURBOCOMPRESSOR °F WITH CERAMIC TURBOCOMPRESSOR HOUSINGS °F WITH CERAMIC ROTOR AND HOUSINGS °F	1675	1600 2100 2500
• MAX OPERATING TEMPERATURE – RECUPERATOR WITH METALLIC RECUPERATURE °F WITH CERAMIC REGENERATOR °F	1300	1800-2000
• BEARINGS	2 BALL BEARINGS	1 BALL BEARING AND 1 FOIL BEARING
• MAX DESIGN SPEED, RPM	80,000	100,000
• COMPRESSOR DIAMETER, IN MATERIAL	4.86 15-5 PH	4.3 2219-T6
• TURBINE DIAMETER, IN MATERIAL	5.156 IN738	5.2 ASTROLOY
• DATE OF FIRST OPERATION	4/75	7/81

Figure 3 illustrates other changes that were incorporated to upgrade the Mod I concept to more closely represent a commercialized configuration. The slab gearbox and off-the-shelf 400 Hz Bendix alternator were replaced with a direct driven permanent magnet alternator to be developed specifically for this solar application. The PMA will be designed to also perform as a synchronous starter motor when supplied with suitable power from a dual converter. The dual converter is so named because it also serves as the output power conditioning element, controlling and converting the alternator high frequency output to 60 Hz ac during periods of power generation. This alternator start capability will eliminate the need for a separate starter such as the hydraulic starter, included for reasons of expediency, in the Mod 0.

MOD I PERFORMANCE

The range of possible maximum power design points for the Mod I engine is plotted on Figure 4 with two illustrative choices "A" and "B" identified. When ceramic housings and a 17-meter dish become available, the maximum rated shaft power can be 51 kw with the engine operating at 2100°F and 90,600 rpm, (Point "B"). At this design point, the use of a gearbox will probably be required since the power delivered at engine shaft speed is too great for present day direct drive permanent magnet alternator technology. Initially, for use with the existing 1500°F metallic solar receiver and the 11- to 12-meter dishes, the engine design point (Point "A") will be 23 kw and 80,200 rpm. For reference, the Mod 0 design point (Point C) also is shown on the figure.

The 80°F sea level design speed for Point "B" was chosen to allow adequate margin for operation at other ambient conditions. For instance, if the same engine/alternator set were installed at 5000 feet and operated on a clear hot day, the engine speed must increase to absorb the concentrator heat output from 90,600 rpm to approximately 100,000 rpm, which is the AGT turbocompressor design limit.

Part-load characteristics of the Mod I engine corresponding to the two previously identified design Points "A" and "B" are shown on Figure 5. Currently, the part load control strategy is to hold the variable inlet guide vane (IGV) angle constant at about 20 degrees from full open for a 1500°F rating and reduce engine speed to match reduced thermal outputs from the solar concentrator and receiver. Note that this control strategy results in much higher part load efficiency than does holding the speed constant. From Figure 5, it is apparent that the efficiency is essentially constant over the 100 to 50 percent part-load power range.

Figure 3 illustrates other changes that were incorporated to upgrade the Mod I concept to more closely represent a commercialized configuration. The slab gearbox and off-the-shelf 400 Hz Bendix alternator were replaced with a direct driven permanent magnet alternator to be developed specifically for this solar application. The PMA will be designed to also perform as a synchronous starter motor when supplied with suitable power from a dual converter. The dual converter is so named because it also serves as the output power conditioning element, controlling and converting the alternator high frequency output to 60 Hz ac during periods of power generation. This alternator start capability will eliminate the need for a separate starter such as the hydraulic starter, included for reasons of expediency, in the Mod 0.

MOD I PERFORMANCE

The range of possible maximum power design points for the Mod I engine is plotted on Figure 4 with two most probable choices "A" and "B" identified. When ceramic housings and a 17-meter dish become available, the maximum rated shaft power will be 51 kw with the engine operating at 2100°F and 90,600 rpm, (Point "B"). At this design point, the use of a gearbox will probably be required since the power delivered at engine shaft speed is too great for present day direct drive permanent magnet alternator technology. Initially, for use with the existing 1500°F metallic solar receiver and the 11- to 12-meter dishes, the engine design point (Point "A") will be 23 kw and 80,200 rpm. For reference, the Mod 0 design point (Point C) also is shown on the figure.

Point "B", the 80°F sea level design point for 2100°F, was chosen to allow adequate margin for operation at other ambient conditions. For instance, if the same engine/alternator set were installed at 5000 feet and operated on a clear hot day, the engine speed must increase to absorb the concentrator heat output from 90,600 rpm to approximately 100,000 rpm, which is the AGT turbocompressor design limit.

Part-load characteristics of the Mod I engine corresponding to the two previously selected design Points "A" and "B" are shown on Figure 5. Currently, the part load control strategy for the Mod I is to hold the variable inlet guide vane (IGV) angle constant at about 20 degrees from full open and reduce engine speed to match reduced thermal outputs from the solar concentrator and receiver. Note that this control strategy results in much higher part load efficiency than does holding the speed constant. From Figure 5, it is apparent that the efficiency is constant over the 100 to 50 percent power range.

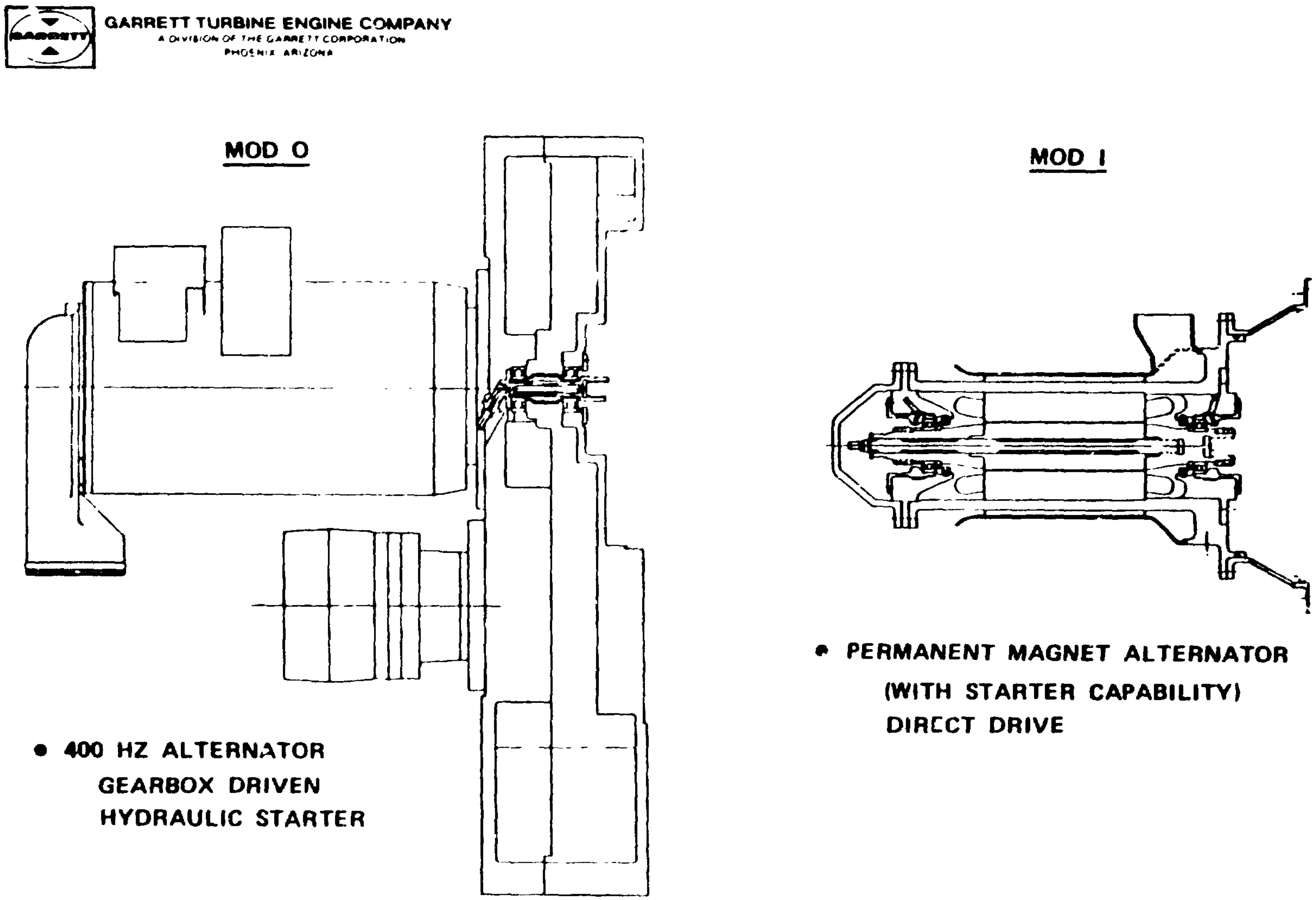


Figure 3. Alternator (Plus Gearbox) and Starter.

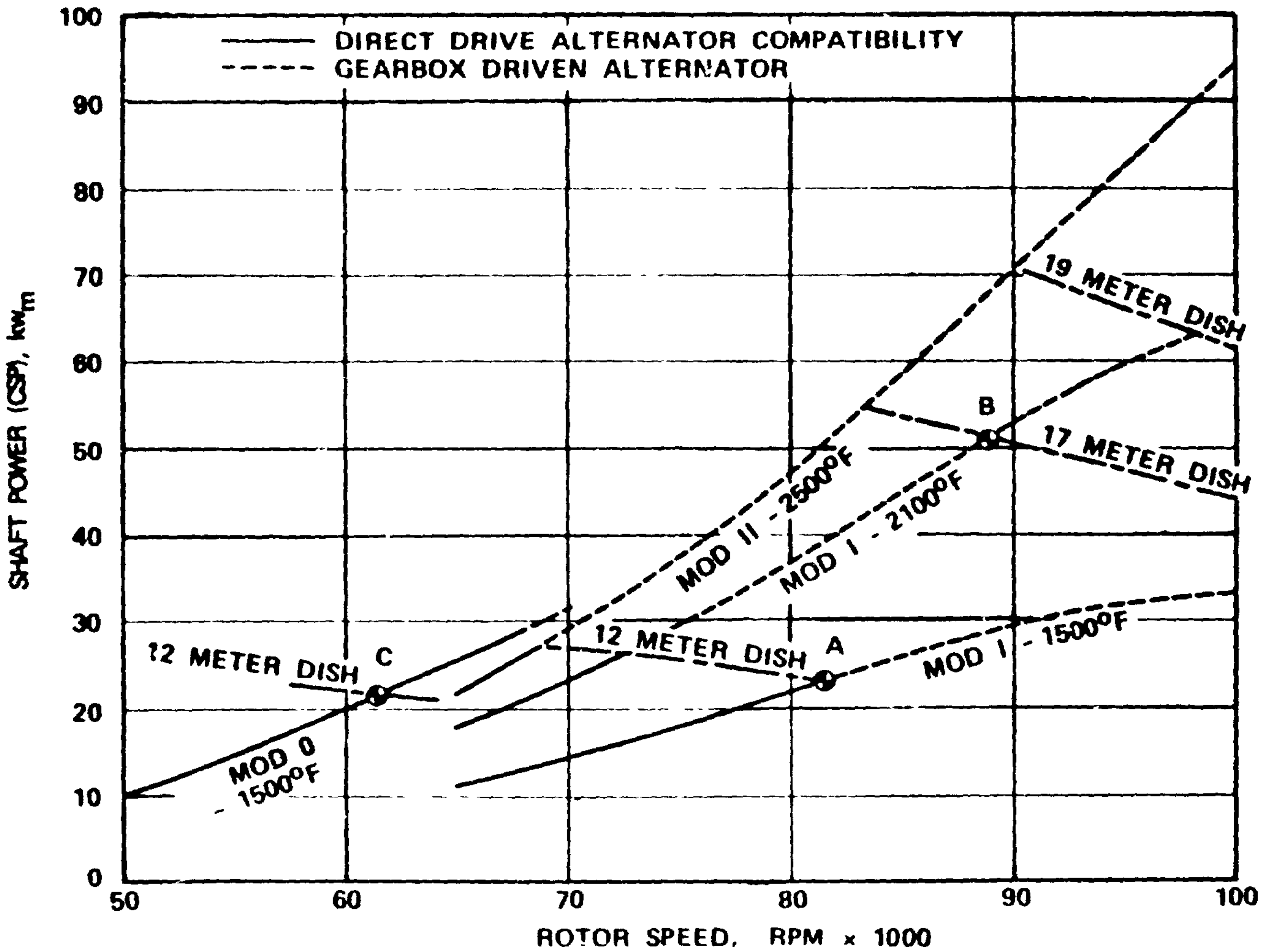


Figure 4. Design Point Performance

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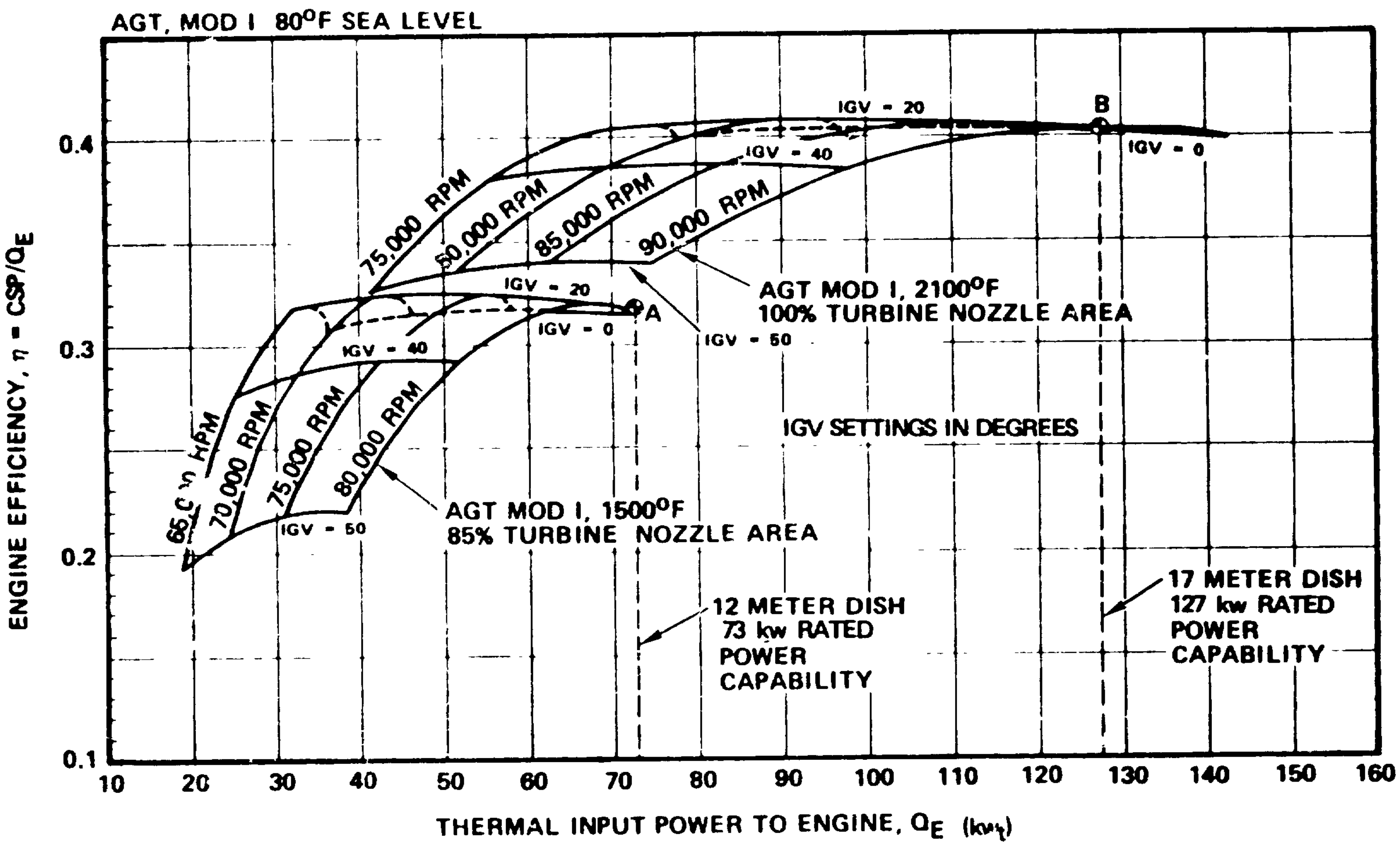

Figure 5. Part-Load Performance.

PROGRAM APPROACH AND SCHEDULE

As shown on Table 2, the Mod I program has been structured to accommodate vagaries of funds availability. Subject to go ahead in January, 1981 funds remaining on the contract will be used to design the solarized metallic AGT. As additional funds become available the solarized AGT will be fabricated and operated in the Garrett test laboratory, thus completing the first column of Table 2. Further funding will allow the balance of the Mod I engine/alternator set to be designed, fabricated and tested preparatory to shipment for evaluation at JPL's Parabolic Dish Test Site at Edwards Air Force Base. This activity is defined in the second column of Table 2. Depending on the requirements of future programs such as the EE-2a and the MX-RES, the design will be modified as indicated in the third column of Table 2 with required quantities fabricated and delivered.

SUMMARY

In mid-year of CY 1980, requirements for the Brayton engine/alternator set hardware appeared to be slipping, and additional development funds appeared to be forthcoming. Therefore, redirection of the Mod 0 program was initiated by JPL. The object of the redirection was to utilize the added time and funds to upgrade the Mod 0 design to a Mod I configuration, allowing incorporation of design features that would enhance the ultimate commercialization of Brayton engine/alternator sets. The more important of these Mod I design features are summarized as follows:

- A low cost, high production rate automotive design
- A potential for growth to 40-48 percent shaft efficiency
- A potential for growth to 51-71 kw shaft power

The Mod I program has been restructured to provide for achievement of meaningful milestones consistent with the expected incremental nature of future funding. Two major milestones are now defined as follows:

First test, solarized AGT - November 1981

Delivery, first Mod I E/A Set - March 1983

These milestones should be periodically reviewed to evaluate whether they are adequate and timely for requirements such as the EE-2a and MX-RES.

PROGRAM APPROACH AND SCHEDULE

As shown on Table 2, the Mod I program has been structured to accommodate vagaries of funds availability. Subject to go ahead in January, 1981 funds remaining on the contract will be used to design the metallic AGT solarization. As additional funds become available the solarized AGT will be fabricated and operated in the Garrett test laboratory, thus completing the first column of Table 2. Further funding will allow the balance of the Mod I engine/alternator set to be designed, fabricated and tested preparatory to shipment in March 1983 for evaluation at JPL's Parabolic Dish Test Site at Edwards Air Force Base. This activity is defined in the second column of Table 2. Depending on the requirements of future programs such as the EE-2a and the MX-RES, the design will be modified as indicated in the third column of Table 2 with required quantities fabricated and delivered. As a first step toward design and building the third column units, additional analysis will be required to confirm the design or define the additional design modifications required in areas such as:

- Durability for solar duty cycle

  Regenerator core and seals
  Ceramic housings
  Bearing life

- Maintenance cost and selling price

- Power rating and concentrator size for the 2100°F engine/alternator set

- Type of alternator and power conditioning equipment for higher power rating

SUMMARY

Toward the end of FY 1980, predicated schedule requirements for the Brayton engine/alternator set slipped, and additional development funds appeared to be forthcoming. Therefore, redirection of the Mod 0 program was initiated by JPL. The object of the redirection was to utilize the time and expenditures necessary in upgrading the Mod 0 design to a Mod I configuration, and incorporating design features that will enhance the ultimate commercialization of Brayton engine/alternator sets. The more important of these Mod I design features are summarized as follows:

- A low cost, high production rate automotive design

- A potential for growth to 40-48 percent shaft efficiency

- A potential for growth to 51-71 kw shaft power

TABLE 2

PROGRAM APPROACH - MOD I

	FIRST TEST HARDWARE (DEN3-181)		SUBSEQUENT HARDWARE
APPLICATION	NEAR TERM SAGT ENGINE LABORATORY DEMONSTRATION	COMPLETE MOD I E/A SET FOR PDTS	COMPLETE E/A SETS FOR EE-2A OR MX-RES
RATING, ^{o}F TIT/KW_S	1500/23	1500/23	1500/23 OR 2100/27 OR 2100/54
COMPONENTS			
TURBOCOMPRESSOR	METALLIC AGT	METALLIC AGT	METALLIC OR CERAMIC AGT
REGENERATOR/ RECUPERATOR	AGT CERAMIC REGENERATOR	AGT CERAMIC REGENERATOR	AGT CERAMIC REGENERATOR
REMOTE COMBUSTOR	UNMODIFIED	MODIFIED	MODIFIED
POWER EXTRACTION	LABORATORY GEARBOX AND BRAKE	PMA	TBD
POWER CONDITIONING	NONE	DUAL CONVERTER, AC OUTPUT AND STARTING	TBD
CONTROLS	LAB CONTROLS	DEVELOPED CONTROLS	DEVELOPED CONTROLS
FUEL AND LUBE SYSTEMS	LABORATORY SYSTEMS	DEVELOPED SYSTEMS	DEVELOPED SYSTEMS
INSULATION, FILTER, STRUCTURE AND ENCLOSURE	NONE	DEVELOPED EQUIPMENT	DEVELOPED EQUIPMENT
SCHEDULE			
FIRST ENGINE TEST	NOV. 1981(1)	NOV. 1981(1)	TBD
FIRST ENGINE/ ALTERNATOR	N.A.	DEC. 1982(1)	TBD