THE STRATIFIED CHARGE ROTARY ENGINE

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ABSTRACT

A brief history of the Rotary engine leading up to the development of the turbocharged stratified charge rotary engine is presented. The dual nozzle stratified charge concept is discussed as are some of the design and development techniques used to expedite the design, analysis and optimization of the engine. Various market segments for the application of the rotary engine to power generation and propulsion uses for ground vehicles, aircraft and marine are discussed.

INTRODUCTION

The emphasis on recent developments in Internal Combustion Engines has been toward compact fuel efficient engines. The major thrust for this push had its focus in the energy shortage of the 70's and the subsequent push for improved fuel consumption for the automobile.

Smaller, lighter cars and smaller engines were the initial primary result of this push. In the mid eighties, we have seen the retention of the smaller engines, but there continues to be a significant demand on the part of the customer for increased performance from the engines. The increased power density from the engines is an inevitable result of this customer pressure. The technical publications contain much information on how the engine industry has responded to the above stimulus.

The Stratified Charged Rotary Engine represents a power plant that responds to the customer's desire for increased power, while retaining the desired small package size, light weight, and improved fuel efficiency. In addition the SCORE design engine has a significant plus in its ability to burn a wide variety of fuels. John Deere's Rotary Engine trademark is SCORE' Stratified Charged Omnivorous Rotary Engine.

This presentation will deal with some of the history toward the development of the Stratified Charged Omnivorous Rotary Engine, some of our more recent development information, and a discussion of some market developments to date.

HISTORY

A number of very good books have been written which discuss the invention, introduction and development of the 'Wankel' based rotary engine configurations (1)(2)(3)(4). The basic concept involves a rotating, triangular shaped rotor inside a trochoid shaped housing.

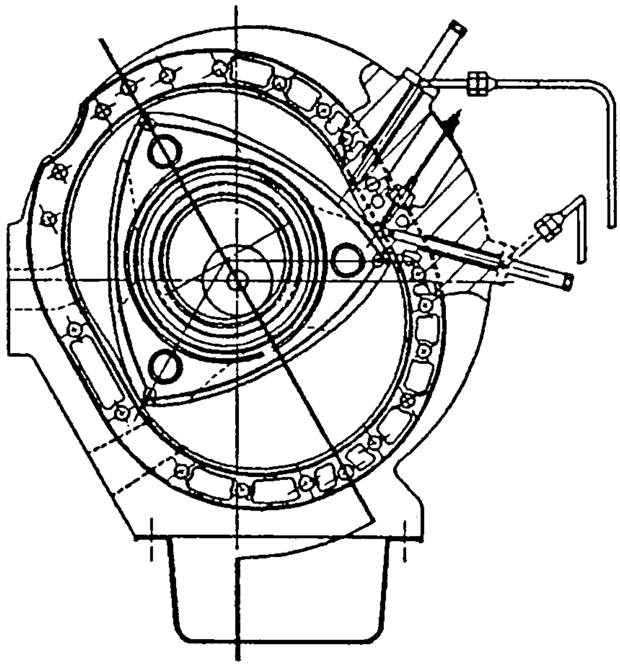

Fig. 1 Cross section of Rotary engine showing trochoid shaped rotor housing and triangular shaped rotor.

In the first engines which Felix Wankel ran, the shaft was stationary, and the rotor and trochoid housing rotated.

A number of development difficulties (getting ignition to moving spark plugs, engine idling characteristics, dynamics of the moving housing, and power extractions, etc.) resulted in subsequent designs evolving to the basic configuration of today's Rotary engine.

A number of engine prototypes were made by the various organizations to whom Wankel sold specific 'rights'. Various prototype applications, include; autos, motorcycles, boats, snowmobiles, airplanes, trucks, lawnmowers and numerous others. The early enthusiasm for this new engine concept was one of the factors in sometimes rushing into production designs which had not had sufficient development effort to work out the various design bugs.

Early problems include; rough idling characteristics, high oil consumption, excessive leakage past the combustion gas seals, and excessive wear of apex seals.

Most of these early engines were precharged (carbureted) and spark ignited, although there was some development done on a compression ignition version of the engine. (7) The carbureted engines tended to have higher fuel consumption than their reciprocating counter parts, in part due to the high surface to volume characteristics of the combustion chamber. This high surface to volume ratio, also meant that there was potential for more of the partially burned fuel/air mixture at the boundary layer surfaces to show up in the exhaust as unburned hydrocarbons.

The rotary engine as applied to automobiles in today's Mazda cars, and its popularity indicates that these early engine problems have been satisfactorily solved, and applied to production versions of the engine.

THE STRATIFIED CHARGE COMBUSTION CONCEPT

As development of the engine proceeded at Curtiss-Wright, it was felt that if the engine could operate unthrottled as does the diesel engine, and if the fuel could be injected directly into the compressed air charge at or near 'TDC', rather than introduced as a fuel air mixture, engine fuel consumption could be improved and emissions decreased. The improved fuel consumption would come from a combination of the unthrottled intake system, and the introduction of fuel only as required rather than trying to 'fill the entire combustion chamber' with an ignitable fuel/air mixture.

Furthermore, if the fuel which was introduced could be ignited by an ignition source, rather than relying on the self ignition characteristics of the fuel (as in diesel-compression ignition) then the engine would have a wider tolerance to fuel characteristics. Successful development of such a combustion system would potentially enable the engine to operate as a true "multi-fuel" engine.

Early efforts at Curtiss-Wright to develop the stratified combustion concept involved the use of a multihole nozzle with one of its sprays directed toward the spark plug. This engine, as did most efforts to stratify reciprocating "diesel" engines resulted in engines that ran well under rather narrow operating conditions of speed and load. (The primary difficulty was one of maintaining the correct fuel/air ratio in the vicinity of the spark plug. Under specific operating conditions, the 'fuzz' from the injector spray would be 'just right', and the engine ran fine, having the smoothness, and fuel economy desired. Once the spray penetration characteristics changed as the amount of fuel injected either increased or decreased, the optimum conditions for ignition of the fuel spray that existed by the spark plug changed, resulting in poorer combustion characteristics.)

Various schemes of the single nozzle stratified charged combustion concept were evaluated with varying degrees of success. (6) (See fig. 2&3)

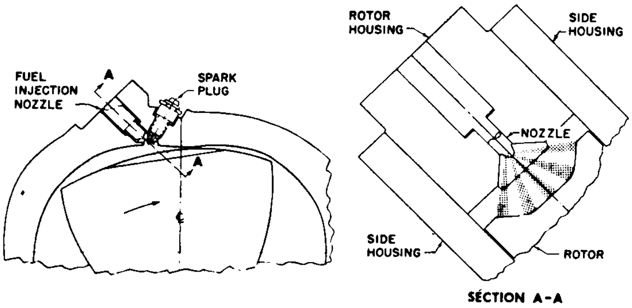

Fig. 2 Co-planar single nozzle SC design.

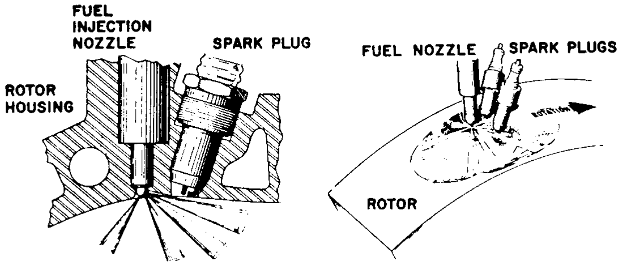

Fig. 3 shower head sc nozzle design.

As the Curtiss-Wright engineers worked with the combustion system, they developed the two nozzle stratified charged concept. See Figure (4).

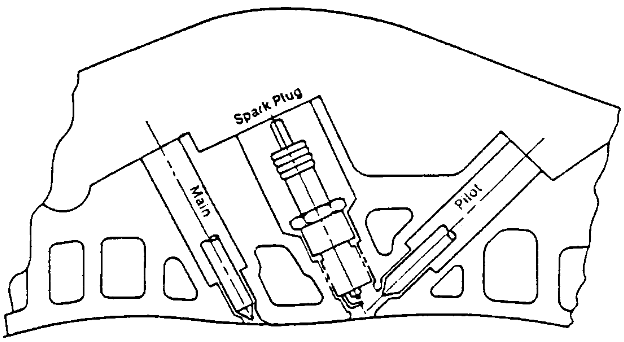

Fig. 4 dual nozzle stratified charged configuration.

This concept involves a single orifice 'pilot' nozzle which essentially injects a constant quantity of fuel optimized for producing an ignitable mixture in the vicinity of the spark plug. A second nozzle which incorporates multiple orifices, serves as the main fuel source for the combustion process, and is designed to inject fuel as it is required for controlled combustion.

The quantity of fuel injected is determined by the load requirements on the engine.

This dual nozzle stratified combustion system has lived up to its expectations. It has successfully demonstrated its ability to run on gasoline, methanol, diesel fuel, and jet fuel without any engine adjustments. Further details of the performance results obtained during the development program on the Stratified Charged Combustion System are presented in reference (6).

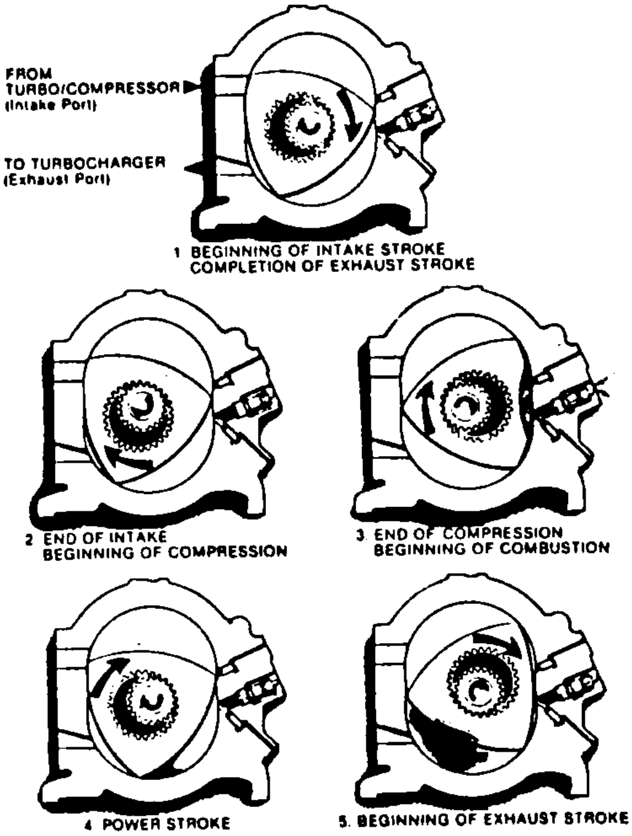

Fig. 5 basic geometry and operation cycle stratified charge rotary engine.

The turbocharged rotary engine uses a rotor with three combustion laces. These laces (which are equivalent to pistons in a reciprocating engine) provide for a power impulse (stroke) during each crank revolution. The rotor Ills closely around the crank eccentric, but turns al 'I, of Its speed. Producing rotary motion directly eliminates all those parts needed In a reciprocating engine to convert the up and down motion to rotary motion.

The cutaway drawings (shown at right) demonstrate a typical rotary cycle. (For this explanation, we will follow only one of the three rotor laces.)

1. The operation begins when the APEX seal uncovers the Intake port and unthrottled air from the turbocharger compressor enters into the combustion chamber.

2. Air continues to enter the chamber until the trailing APEX seal closes the port. Air is compressed as the rotor continues Its rotation.

3. As the air is compressed to its minimum volume the pilot fuel charge Is Ignited.

4. Combustion is stratified. This is controlled by the main injector and air motion resulting from a specially designed rotor pocket. The power stroke is completed when the exhaust port is uncovered.

5. High temperature gases then exit through the exhaust port. The exhaust turns the turbocharger turbine, which In turn powers the turbocharger compressor

TURBOCHARGING

One of the distinct advantages of the rotary engine, is the elimination of the intake and exhaust valves required of the typical reciprocating engine. The elimination of the valves and their accompanying flow restrictions and dynamics limitations, as in the Rotary engine, expands the engine maximum speed potential, and increases the exhaust energy available.

Turbocharging to use this available exhaust energy is a logical and viable step in the evolution of the Rotary engine, and especially the Stratified Charged Rotary engine. (Since the fuel is injected as required rather than precharged, the engine can be boosted to a higher level with out concern for preignition.)

Some turbocharging performance was done on the Stratified Charged Rotary Engine in the early 80's.(7) Much of this work was done on the engine designed primarily to run as a naturally aspirated engine.

As the result of an extensive study funded by NASA, which pinpointed the Advanced Turbocharged Stratified Charged Rotary Engine as being the most promising small aircraft power plant of the future. A Technology Enablement Program was funded by NASA to conduct tests on a 40 cubic inch (0.7 Liters) single chamber Stratified Charged Rotary research engine.

Early results of these tests are reported in (12). The engine which has been built and run by John Deere was designed to withstand the higher operating pressures resulting from turbocharging and the higher power outputs.

Fig. 6 score tm 70 single rotor research rig engine.

This single rotor engine has successfully run at over 75 kW (100 hp) and up to 8000 rpm. Fuel injection system limitations precluded running at higher power levels.

As a result of our initial running of the NASA research rig engine, we have embarked upon the second phase of the program. This phase includes evaluation of an advanced injection system capable of delivering controlled fuel injections over the speed and load range capabilities of the engine. A electronically controlled, hydraulically actuated unit injector fuel injection system has demonstrated its capabilities to satisfactorily inject and control fuel quantities up to 100 cubic millimeters per injection at speeds in excess of 10,000 injections per minute. This system is scheduled for engine testing starting in August 1986.

We have used this research rig engine to evaluate the benefits of various engine porting arrangements, nozzle configurations, turbocharger trims, and intercooler conditions.

Additional turbocharging performance has been conducted on the SCORE ™ 580 engine (a 5.8 liters per rotor engine being currently run in a single rotor research configuration, and a two rotor demonstration engine) to in part verify our Finite Element predictions and to evaluate some of the design changes required to modify the basic naturally aspirated version of the engine.

Extensive finite element analysis of the major structural components led to significant design changes as compared to the engine as designed for naturally aspirated operation. (See figures 7 & 8)

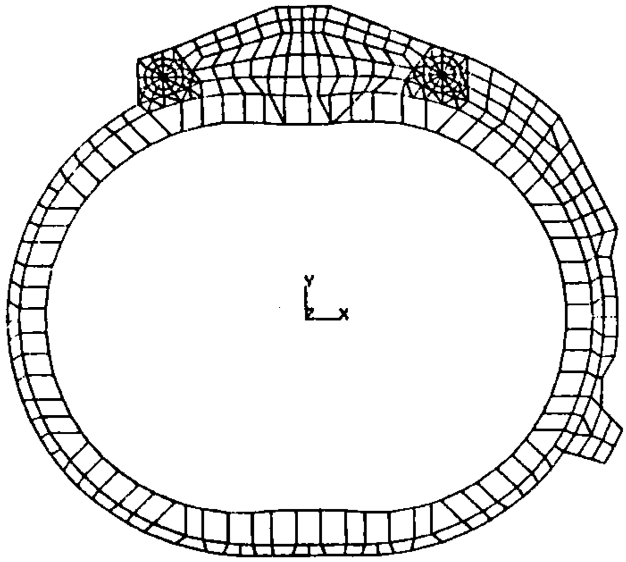

Fig. 7 naturally aspirated version of rotor housing.

In order to accommodate the higher firing pressures due to turbocharged operation, the rotor was beefed up by incorporating additional support ribs. The rotor housing has been modified to change the bolt locations, and to provide extra support in the combustion chamber portion of the housing.

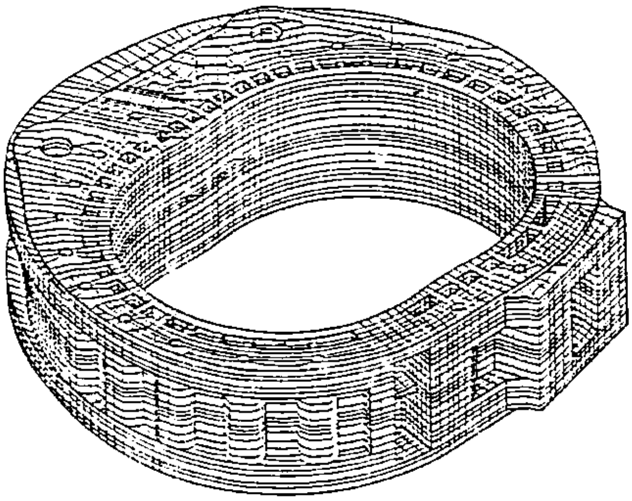

Fig. 8 FEM of rotor housing modified for turbocharging.

In addition to rotor housing modifications, a center main bearing was added to the two rotor version of the engine.

Additional factors which needed to be considered as the result of turbocharging to obtain additional engine output, were housing vibration levels, excitation forces on the apex seal, crankshaft configuration, rotor and housing surface temperatures.

Based upon the results of preliminary turbocharger testing, turbochargers were selected for our engines operating at a rated power of 280 kW (375 hp) per rotor at 3600 rpm.

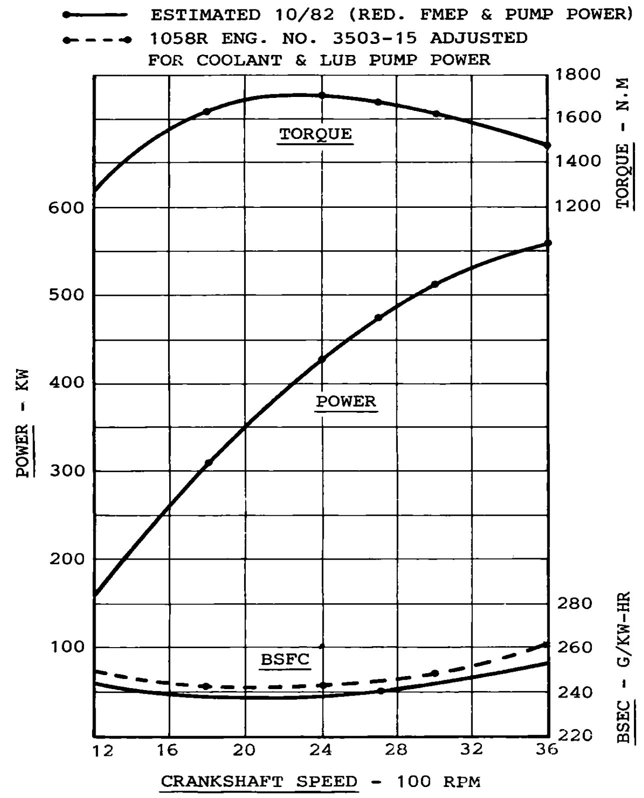

Fig. 9 curve showing some performance results from turbocharged 580 two rotor engine.

The engine as designed has significant power growth potential. As we gain experience at the current rating, and verify the validity of the redesigns (based upon FEM studies) we will expect to increase the output per rotor to 375 kW (500 hp) or more.

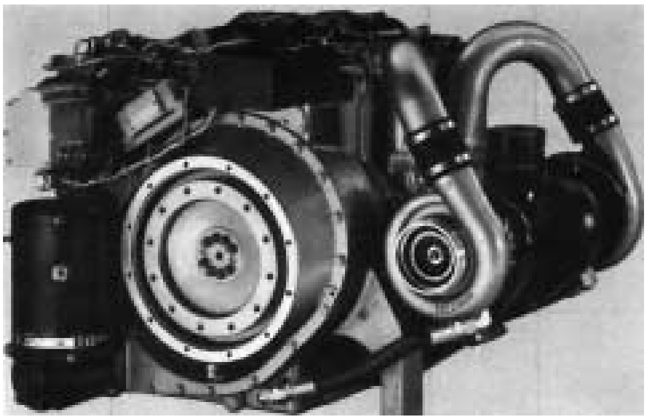

Fig. 10 score 580 early configuration

VALUE CONCEPTS STUDY

There has been significant market interest in the Stratified Charged Rotary engine, primarily because of the power density and fuel savings advantages to its potential users. In order to determine if this engine concept could cost effectively compete in the market, John Deere conducted an extensive Value Concepts study early in the SCORE TM design program.

The purpose of such a study was to get input from experts of various pertinent disciplines to assess such factors as, optimum design and function of engine subsystems, manufacturability, potential target markets and market size, and production costs. Input was also obtained on where we should put emphasis for our Engineering Development and Research programs.

The results of this study indicated, the market areas on which we should concentrate for initial production units. In addition the cost data indicated that the engine could be produced to compete effectively with the light, medium and heavy duty diesel market, as well as the small gas turbine market. While much of the data generated must necessarily be considered proprietary, the technique used for the Value Concepts study are discussed in reference (10).

The system approach to value analysis not only provided direction on potential significant cost savings, but provided information where we should apply extra effort to assure the appropriate level of reliability and durability.

Fig. 11 mock-up of engine configuration resulting from value concepts study.

MARKET DEVELOPMENT

The high level of power output per unit volume available in the Stratified Charge Rotary Engine is of particular interest in commercial and military applications where space claim is critical. Automotive applications are advanced small, aerodynamically clean automobiles, a variety of tracked and wheeled military vehicles. Other applications are high mobility military generator sets, shipboard generator systems and airborne auxiliary power units. The engines small size and weight, combined with the ability to burn jet fuel also makes the engine attractive for propulsion, in fixed wing and rotary wing aircraft, both commercial and military.

To address these market demands, John Deere has planned late 1980's, early 1990's production of three families of engines, covering a wide power range from 60 to 1680 kw (80 to 2250 bhp), Figure 12.

The three famlies are identified as:

- SCORE 70 – 0.67 litres/rotor or 40 cu. in./rotor
- SCORE 170 – 1.72 litres/rotor or 105 cu. in./rotor
- SCORE 580 – 5.8 litres/rotor or 350 cu. in./rotor

Within the three families of engines, current activities involve a variety of end applications.

SCORE FAMILIES OF ENGINES
BASIC PERFORMANCE AND BRIEF SPECIFICATIONS

SCORE 70 SERIES

Model	No. of Rotors	Power kW(bhp)	Displace-ment l(in^3)	Height mm(in)	Width mm(in)	Length mmlin)	Weight kg(lbs)
1007R	1	60 (80)	.7 (40)	505 (20)	530 (21)	560 (22)	90 (198)
2013R	2	120 (160)	1.3 (80)	505 (20)	530 (21)	685 (27)	115 (253)
30208	3	180 (240)	2.0 (120)	505 (20)	530 (21)	840 (33)	166 (366)
4026R	4	240 (320)	2.6 (160)	505 (20)	530 (21)	965 (38)	195 (430)

SCORE 170 SERIES

Model	No. of Rotors	Power kW(bhp)	Displace-ment l(in^3)	Height =(in)	Width mm(in)	Length mm(in)	Weight kg(lbs)
1017R	1	150 (200)	1.7 (105)	508 (20)	661 (29)	585 (23)	147 (325)
2034R	2	300 (400)	3.4 (210)	508 (20)	661 (29)	745 (29)	223 (490)
3051R	3	450 (600)	5.1 (315)	508 (20)	661 (29)	880 (35)	291 (640)
4068R	4	600 (800)	6.8 (420)	508 (20)	66] (29)	1020 (40)	364 (800)
6102R	6	900 (1200)	10.2 (630)	508 (20)	661 (29)	1460 (57)	514 (1130)

SCORE 580 SERIES

Model	No. of Rotors	Power kW(bhp)	Displace ment l(in^3)	Height mm(in)	Width mm(in)	Length mm(in)	Weight kg(lbs)
1058R	1	280 (375)	5.8 (350)	760 (30)	990 (39)	610 (24)	385 (848)
2116R	2	560 (750)	11.6 (700)	760 (30)	990 (39)	1118 (44)	615 (1354)
3174R	3	840 (1125)	17.4 (1050)	760 (30)	990 (39)	1320 (52)	815 (1795
4231R	4	1120 (1500)	23.1 (1400)	760 (30)	990 (39)	1525 (60)	1020 (2246)
6347R	6	1680 (2250)	34.7 (2100)	760 (30)	990 (39)	2185 (86)	1450 (3190)

NOTE: BASIC DIMENSIONS AND PERFORMANCE CAN VARY IN PACKAGING FOR SPECIFIC APPLICATIONS.

Fig. 12 SCORE family specs

SCORE 70 SERIES

An envelope drawing for a single rotor, SCORE 70, for advanced automotive application is shown in Figure 13. The engine height of 16.6 inches is very attractive from a vehicle packaging standpoint in advanced design, smaller and lighter cars. The engine performance is shown in Figures 14 & 15, reflecting a relatively low level of specific fuel consumption over a wide speed and load range and a reasonable torque curve.

A two rotor version of the SCORE 70 series engine, designated 2013R, is currently in the design phase at John Deere with prototypes scheduled for mid 1987. This engine, with 150-200 HP range for the near term is applicable to light trucks and minivans (in the automotive field). It is also of interest in high mobility military generator sets, airborne auxiliary power units and other military airborne applications, Figure 16. A four rotor, uprated version at 550 HP has been defined for studies toward automotive vehicular application in the military's Small Integrated Propulsion Systems (SIPS).

SCORE 170 SERIES

A license agreement is in place between John Deere Technologies International, Inc. and AVCO Lycoming, Williamsport Division for development of a two rotor, SCORE 170 engine for general aviation.

The joint development program was initiated in July 1985. The purpose of the joint program is to obtain FAA Certification and prepare for production in early 1990 of a 300 kw (400 HP) twin rotor general aviation engine. A basic preliminary specification for the engine is presented in Figure 17. The designation L2A-400-AI is AVCO's designation for 2 rotors of 3.4 liters total displacement (210 cu. in.), 400 BHP and accessory arrangement designation AI.

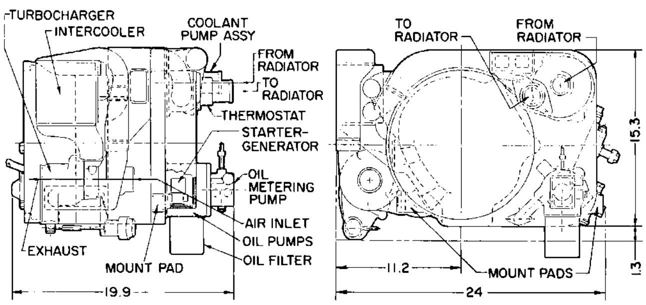

Fig. 13 1007R score 70 engine-automotive application 100 hp.

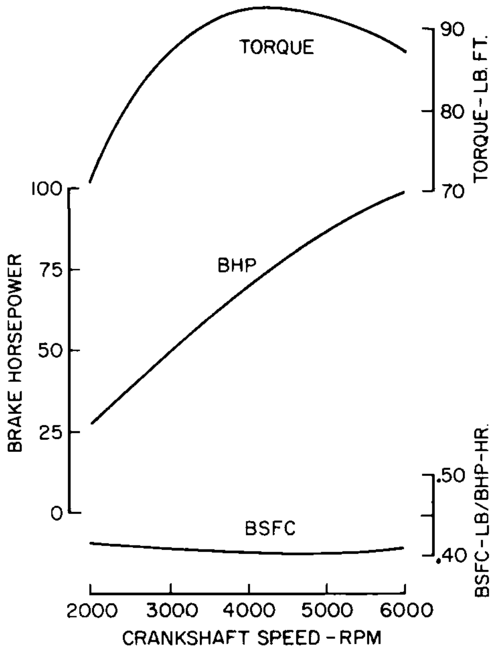

Fig. 14 SCORE 70 series 1007R estimated full load performance.

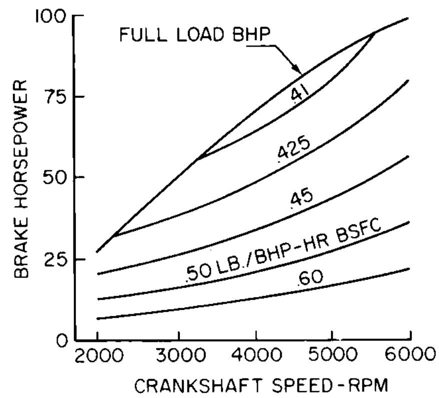

Fig. 15 SCORE 70 series 1007R estimated part load performance.

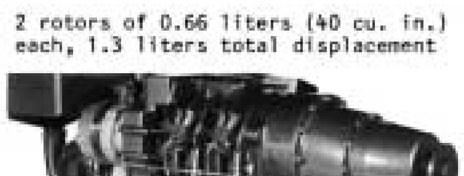

Fig. 16 2013R general aviation preliminary arrangement.

L2A-400-A1 ENGINE

FUEL INJECTED, TURBOCHARGED, LIQUID COOLED, GEARED, INTERCOOLED, WITH CABIN BLEED AIR PROVISIONS

Take-off Power	350kW (400hp)
Take-off Crankshaft Speed	5800 RPM
Take-off Altitude Capability	Sea level to 6000m (20,000 Ft.)
Cruise Power (75% Cruise)	225kW (300HP)
Cruise Crankshaft Speed	4350 RPM
Cruise Altitude Capability	To 7500m (25,000 Ft.)
Engine Weight Goal	228kg (506 Lbs.)
BSFC at Take-off	243-255kg/kW-Hr. (.40-.42 Lbs/BHP-Hr.)
BSFC at 75% Cruise	231-249kg/kW-Hr. (.38-.41 Lbs./BHP-Hr.)
TBO	2,000 Hours
Fuel, Aviation Grade	Jet-A
Oil Consumption (Based on 75% Cruise)	.27kg/Hr. (0.6 Lbs./Hr.)
Production Target	Early 1990

Fig. 17 preliminary engine specification.

JDTI, is performing the primary design for the core power section. AVCO is performing the primary design for the accessory drive gear box, prop shaft and reduction gear and the integration of the package. Coordination with airframe manufacturers toward general requirements and flight test activities is in progress by AVCO. Also, FAA involvement has been initiated.

Automotive versions have been defined for the SCORE 170 family for consideration in the anticipated U.S. Army Armored Family of Vehicles (AFV) as shown in Figure 18. Ratings for 1989 and growth ratings for 1994 are listed. Figure 19 outlines general arrangement and installation features for a three rotor version of the SCORE 170 series, designated 3051R, rated at 600 HP in 1989 and 750 in 1994. Full load performance for the engine is shown in Figure 20.

SCORE 170 SERIES FAMILY FOR AFV

MODEL NO.	NO. OF ROTORS	RATED BHP (1989)	GROWTH BHP (1994)	LxWxH, INCHES	WT., LBS.
1017R	1	200	250	23 x 29 x 20	325
2034R	2	400	500	29 x 29 x 20	490
3051R	3	600	750	35 x 29 x 20	640
4068R	4	800	1000	40 x 29 x 20	800
6102R	6	1200	1500	57 x 29 x 20	1,130

FUEL CONSUMPTION (LB./BHP-HR.)

	RATED POWER	651 POWER
1989	0.42	0.40
1994	0.39	0.37
1994 w/TURBOCOMPOUNDING	0.35	0.34

Fig. 18

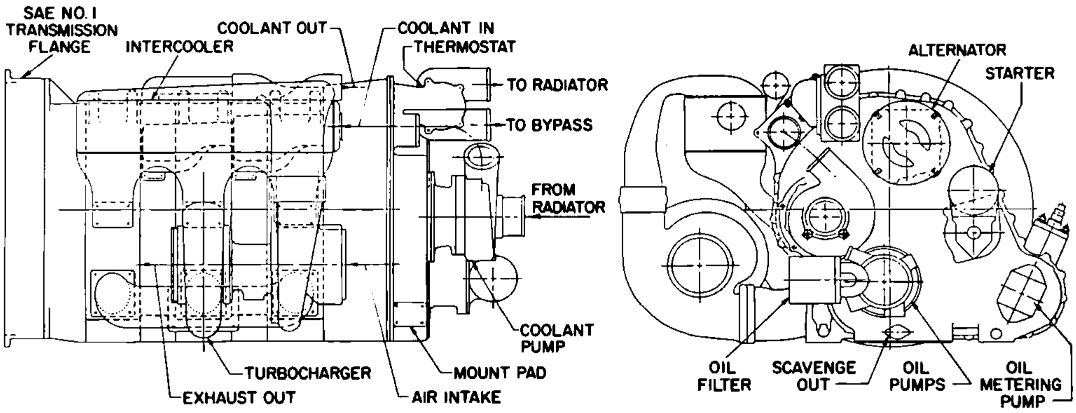

Fig. 19 3051R SCORE 170 series

SCORE 580 SERIES

Contractural efforts with the USMC are in progress for the Demonstration and Validation of a two rotor, 5.8 liters/rotor, 2116R engine rated at 750 BHP/3600 RPM for amphibious, tracked vehicle application. Higher output engines, using a modular approach of coupling of two rotor or three rotor sections, are under consideration for a variety of automotive vehicle applications and ship electrical service generators.

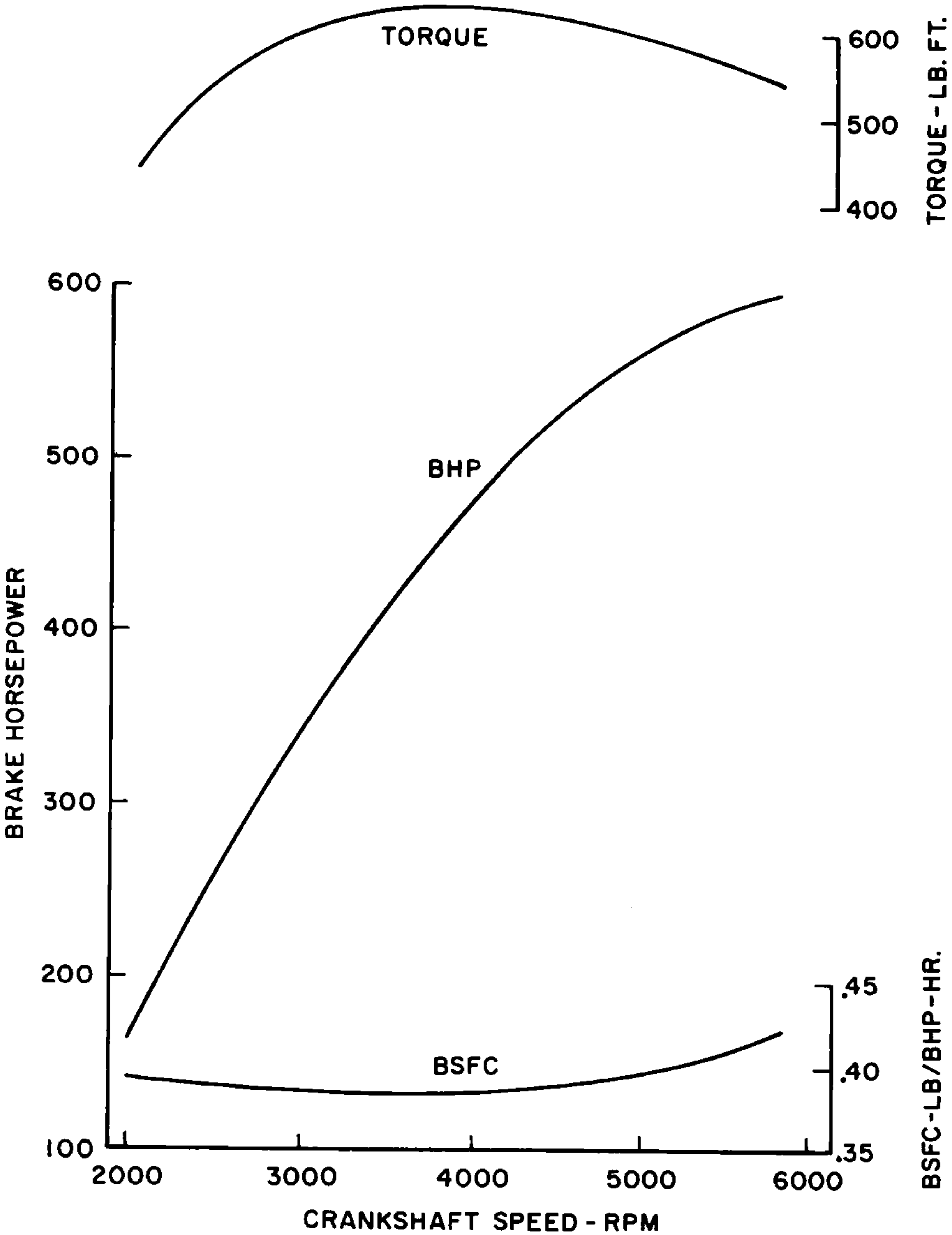

Fig. 20 SCORE 170 series 3051R estimated full load performance.

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