The Engineering Society
For Advancing Mobility
Land Sea Air and Space®
INTERNATIONAL

400 COMMONWEALTH DRIVE, WARRENDALE, PA 15096-0001 U.S.A.

SAE Technical Paper Series

900035

The Introduction of a New Ultra-Lite Multipurpose Wankel Engine

DANKWART EIERMANN AND ROLAND NUBER
WANKEL R & D GmbH

MICHAEL SOIMAR
ROTEC MANUFACTURING AND ENGINEERING

International Congress
and Exposition
Detroit, Michigan
February 26 - March 2, 1990

The appearance of the ISSN code at the bottom of this page indicates SAE's consent that copies of the paper may be made for personal or internal use of specific clients. This consent is given on the condition, however, that the copier pay a $5.00 per article copy fee through the Copyright Clearance Center, Inc., Operations Center, 27 Congress St., Salem, MA 01970 for copying beyond that permitted by Sections 107 or 108 of the U.S. Copyright Law. This consent does not extend to other kinds of copying such as copying for general distribution, for advertising or promotional purposes, for creating new collective works, or for resale.

SAE routinely stocks printed papers for a period of three years following date of publication. Direct your orders to SAE Customer Service Department.

To obtain quantity reprint rates, permission to reprint a technical paper or permission to use copyrighted SAE publications in other works, contact the SAE Publications Group.



All SAE papers are abstracted and indexed in the SAE Global Mobility Database.

SAE GLOBAL MOBILITY DATABASE®

No part of this publication may be reproduced in any form, in an electronic retrieval system or otherwise, without the prior written permission of the publisher.

ISSN 0148-7191
Copyright 1990 Society of Automotive Engineers, Inc.

Positions and opinions advanced in this paper are those of the author(s) and not necessarily those of SAE. The author is solely responsible for the content of the paper. A process is available by which discussions will be printed with the paper if it is published in SAE Transactions. For permission to publish this paper in full or in part, contact the SAE Publications Division.

Persons wishing to submit papers to be considered for presentation or publication through SAE should send the manuscript or a 300 word abstract of a proposed manuscript to: Secretary, Engineering Activity Board, SAE.

Printed in USA

ABSTRACT

A new family of compact, light weight Wankel engines for multi-purpose applications was designed and is currently under an optimization test.

The engine short block with fewer parts reaches the pinnacle in the simplicity of the rotary combustion engine design concept.

New technological solutions have been employed in the design of the cooling, ignition and lubrication systems in order to lower the engine maintenance and operating costs.

The paper describes the primary components and systems of the engine and much of the design and development work that led to the validation of the new design.

The single rotor and two rotor engines cover a power range of 5-50Kw when naturally aspirated, with a weight to power ratio close to I lbs lhp. The design concept demonstrated a high potential for turbocharged applications. Unparalleled weight to power ratio are estimated for the fully developed turbocharged version of both engines. The new engines are suitable for diverse stationary and mobile applications in which weight, box volume and vibration are strict constraints.

INTRODUCTION

The technical "childhood diseases" of the Wankel type engines were the limited life of the apex seal, overheating of the rotor and rotor bearing, higher emissions and higher fuel consumption when compared with four cycle piston engine of comparable size.

The durability of the apex seal was considered the most critical of all improvement activities. Today, after better than 20 years of technological effort, it is no longer a limiting factor in rotary engine life.Technological progress in materials, heat treatment and surface coating (ceramics) have dramatically reduced the seal trochoid housing wear rate. Extensive endurance tests performed on current production rotary engines indicate the rates of these engine components low enough to enable 20,000 hours of engine operation at moderate load (1)*.

Dankwart Eiermann - Wankel R&D GmbH
Roland Nuber - Wankel R&D GmbH
Michael Soimar Rotec Mfg. & Eng. Corp.

Considerable improvements were made on engine emissions and fuel consumption to a level where now it is generally accepted that the rotary engine is more fuel efficient than a two stroke piston engine and can match the fuel consumption of small four stroke piston engines for stationary applications.

With respect to the rotor cooling, two methods were employed - Oil Cooled Rotor - OCR and Charge Cooled Rotor - CCR. See Figure 1. The best known practical realization are the Mazda and John Deere oil cooled rotor engines. The OCR solution is characterized by high power density while the CCR solution is associated with simplicity (2). Recently, a new concept in rotor cooling was developed at Wankel R & D GmbH using, as a starting point, a OCR type engine. The rotor and rotor bearing temperatures were controlled by an additional cooling circuit through a hollow eccentric shaft. The solution was designated as LCCR - Liquid and Charge Cooled Rotor.

Extremely low thermal loads and high durability were experienced for rotor and rotor bearing.

COOLING SYSTEM FOR ROTOR

Table 1 suggests a classification of the Wankel type engines from the point of view of the cooling system employed for rotor and rotor bearing

The best known concept to date is the oil cooled rotor (OCR) which is usually associated with a liquid cooling system of engine housings, i.e., rotor housing, front housing and rear housing. This was the original solution developed by NSU/Wankel, and was successfully applied in production type engines *by* Mazda, John Deere, and others (3-7). For these

TABLE 1 – The influence of the cooling system solution on engine performance

Bearing System	Cooling System			Classification	Shaft performance %
	Housing	Rotor	Eccentric Shaft		
Sleeve (Friction) Bearing	Liquid	Oil	No Cooling	OCR - Oil Cooled Rotor Current Wankel engine concept for heavy duty application; automotive, marine propulsion, etc.	100
	Air	Oil	No Cooling	OCR	80
Anti-Friction Bearing	Liquid	Charge Mixture	Charge Mixture	CCR - Charge Cooled Rotor Current Wankel engines for light duty applications	80
	Liquid	No Cooling	No Cooling	UCR - Uncooled Rotor (No practical application)	65
	Liquid	Charge Mixture	Liquid	LCCR - Liquid and Charge Cooled Rotor	95
	Air	Charge Mixture	Charge Mixture	CCR - light duty application, cost effective production type	65

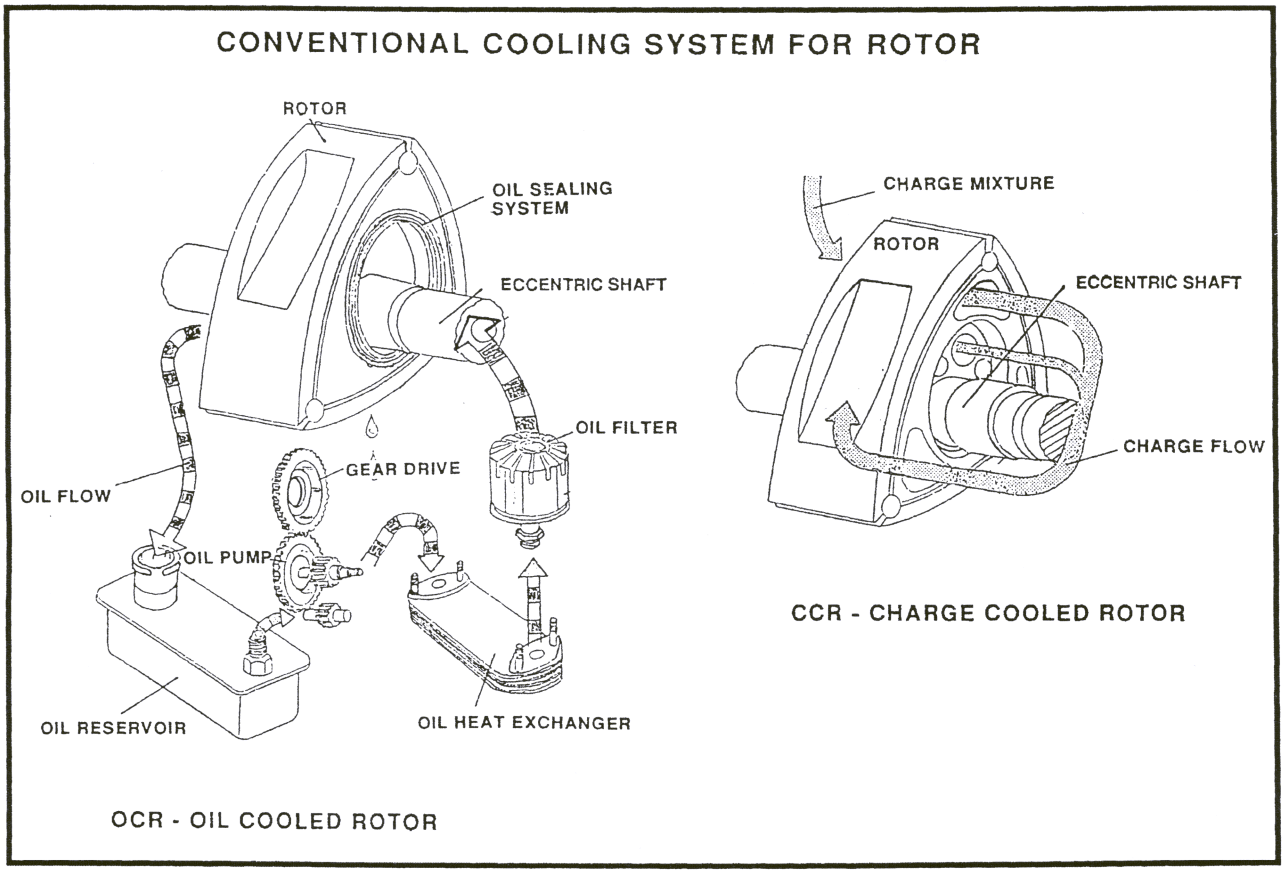


FIGURE 1 - VARIOUS ROTOR COOLING SOLUTIONS

reasons we considered this solution representing the current full potential of the Wankel engine and we credited it with 100% rank (see Table 1). For light duty applications, the charge cooled rotor (CCR) offers significant manufacturing cost reduction and added simplicity by eliminating the oil cooling system. Combined with a liquid cooling system for the engine housing, the CCR system offers only 80% of the maximum obtainable power when compared to the OCR system applied to the same basic engine design, e.g. volumetric displacement, engine rated speed, port arrangement, etc.

Poor performance of the CCR type engine is due to the higher temperature of the rotor, rotor bearing and eccentric shaft and to the diminished volumetric efficiency as a result of heat transfer from the above mentioned engine parts to the fresh charge mixture. The engine performance is even lower when the CCR solution is coupled with an air cooling system for the engine housings. Some CCR engines are using the fresh charge mixture to cool the eccentric shaft and rotor bearing. This method is usually employed when gasoline (mixed with oil) or natural gas are used as fuel. In the first case, the fuel evaporation helps the engine's internal cooling.

If the power of a basic CCR engine is increased by conventional means, such as higher shaft speed or tuned intake and exhaust systems, the engine durability is affected by the higher load. First in line to experience functional problems is the rotor bearing, especially when its lubrication is scarcely in order to control the engine oil consumption.

A dramatic improvement in the engine thermal distribution was obtained when a charge cooled rotor was combined with a liquid cooled rotor bearingthrough an additional liquid cooling circuit hosted by a hollow eccentric shaft. We designated the solution as LCCR - Liquid and Charge Cooled Rotor. While the patented cooling circuit is not directly cooling the rotor, t has a remarkable impact on its thermal load by keeping the eccentric shaft and rotor bearing temperature within close limit.

The LCCR solution solves a well known drawback of the CCR engine, namely, the increased thermal load imposed on the engine shaft by the blow-by gas escaping the side seal system. In both CCR and LCCR solutions, the charge mixture or intake air is drawn in an axial direction throught the rotor, so that all gas leakage eluding the side sealing system is mixed with the fresh charge and fed into the suction chamber through the chamber intake port. This is equivalent to a built-in ventilation system similar to the crankcase ventilation of reciprocating engines. This "in situ", internal ventilation system unfortunately has an unwanted side effect on shaft areas adjacent to the rotor. The blow-by gas escaping the side sealing system directly hits the shaft surface causing significant thermal loads on the shaft, rotor bearings and rotor gear. The shaft cooling system employed in the LCCR engines effectively compensates for this additional thermal load.

Numerous tests conducted on an early LCCR engine in its development period revealed the excellent potential of this solution.

Table 1 is far from being exhaustive. For example, the introduction of an intercooler for the charge mixture in association with the CCR solution opens another branch of the classification tree. Also, there are a few Wankel engines which are using the bleed air to cool the rotor and the rotor bearing. This

TABLE 2 – The influence of the cooling system solution on engine efficiency and manufacturing cost.

Design Solution	Cooling System Description	Shaft Performance %	Overall Efficiency Potential %	Production Cost %
1	OCR; Liquid Cooled Housing	100	100	100
2	OCR; Air Cooled Housing	80	90	100
3	CCR; Liquid Cooled Housing	80	100	70
4	UCR; Liquid Cooled Housing	65	90	65
5	LCCR; Liquid Cooled Housing Liquid Cooled Shaft	95	100	70
6	CCR; Air Cooled Housing	65	80	65

combination again extends the classification related to the rotor and rotor bearing cooling system.

The OCR and intercooler combination improves the engine volumetric efficiency and accordingly the power penalty of the basic CCR system can be easily compensated for (8). For instance, a 2 rotor racing engine with a total displacement of 588cc demonstrated over 135 hp at 9800 rpm and won the British Formula 1 championship for motorcycles. On the other hand, the intercooler solution increases the engine's overall weight and manufacturing cost.

Table 2 shows the influence of the rotor cooling design concept on estimated engine performance, total efficiency potential and production cost. The evaluation was limited to the basic design concept discounting the influence of engine accessories such as intercoolers, etc.

By eliminating the oil cooling system with an oil pump, a heat exchanger, an oil sump and especially the oil sealing system, a cost advantage of up to 30% can be achieved for a LCCR engine when compared with the OCR solution. The CCR solution offers an even better cost advantage but its concept is limited to the relatively small engines. To date, only CCR rotary engines up to 650cc have been developed and produced successfully (9).

The total efficiency of the CCR engines can equal that of the OCR engines due to the former's lower friction losses as long as the overheating phenomena can be controlled. Overheating is especially worrissom at part load conditions. in this respect, the LCCR engine demonstrates a decisive advantage by exactly controlling its internal temperatures.

BASIC RESEARCH

In order to assess the thermal load of the rotor, a single rotor research rig was instrumented with sliding contact brushes mounted in a slave side housing. The rotor was equipped with two corresponding sliding rails connected to thermocouples placed dose to the rotor flank surface. The instrumentation is shown in Figure 2.

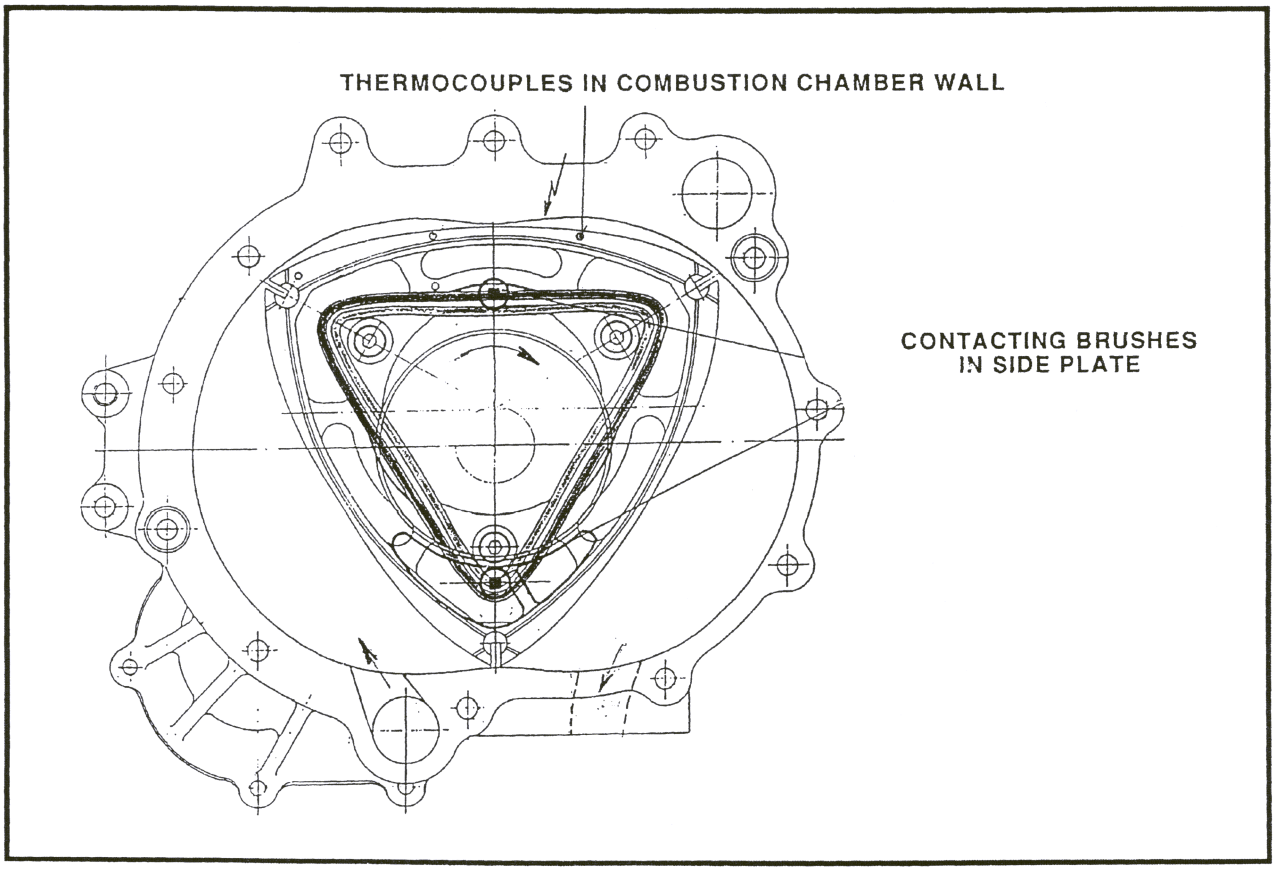


FIGURE 2 - ROTOR TEMPERATURE MEASURING METHOD

The rotor temperature variation, Figure 3, clearly demonstrates the dose dynamic correlation between rotor temperature, engine load and intake air temperature passing through the rotor in a charge cooled rotor arrangement Particularly in high load condidons, the rotor thermal load can top the thermo-hydrodynamic limits of bearing and lubrication. Therefore, in the case of a charge cooled rotary engine, it is essential to consider a careful layout of an effective bearing lubrication system and a special rotor bearing and shaft design.

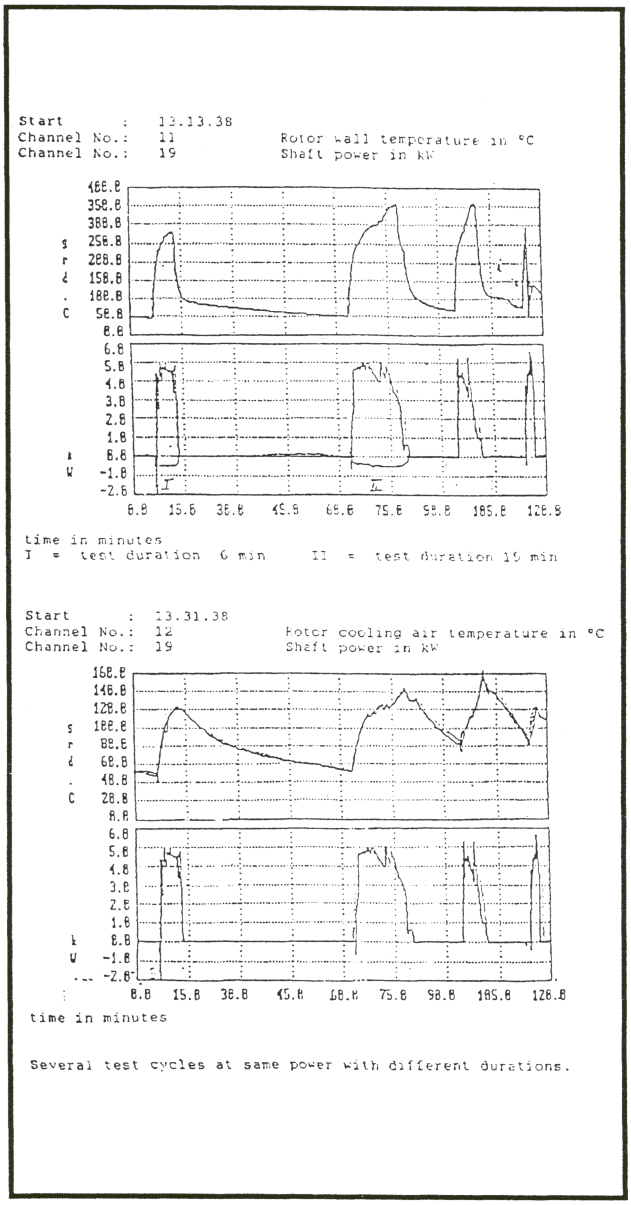


FIGURE 3 - ROTOR AND ROTOR COOLING AIR TEMPERATURES CYCLIC VARIATIONS

In comparative tests the influence of the water cooled shaft circuit on the rotor and shaft temperatures were evaluated. The engine was tested under part load and full load conditions in UCR, CCR and LCCR arrangements - see Table 1. The LCCR solution demonstrates a rotor thermal load reduction of about 30% when compared with the CCR solution and up to 60% reduction when compared with the UCR sloution.

To better evaluate the influence of the shaft internal cooling circuit on the rotor assembly thermal load, the rotor cooling by the fresh charge was interrupted. More simply stated, only the shaft cooling was employed as a means to control the rotor assembly temperature. The engine was fed by a direct peripheral intake port. Even at W.O.T. conditions, 8.5 bar BMEP at 6000 rpm, the rotor assembly thermal load did not exceed the critical limits.

When designing the rotor bearing concept, it is extremely important to keep the surface hardness of the bearing's inner race under special scrutiny since the cyclic load burdens the same area every revolution, while the mirror portion of the outer race moving with the rotor is loaded only every third rotation.

Therefore, any overheating situation coupled with poor lubrication will reduce the surface hardness dramatically in the critical area and finally will destroy the bearing system. An additional problem to be taken into account is the increased gas leakage from the combustion by rotor distortion. In addition to an effective gas sealing system design, the gas blow-by effect can be attenuated through efficient internal ventilation. This is achieved by the rotor charge cooling system. The thermal loads impact on the bearing system is further diminished in the LCCR arrangement by the shaft internal cooling system.

The LCCR cooling system arrangement is easy to follow when considering a longitudinal section of a twin rotor LCCR engine - Figure 4. The cooling solution facilitates a careful distribution of the coolant flow towards the engine's most heated parts. The water pump is mounted directly on the engine main shaft opposite the power take-off end - see Figure 4.

The first stage of the water pump rotor controls the entire circuit for the engine housings. The second stage of the rotor, comprised of four small blades, must supply enough coolant to the shaft where the coolant flows axially through a concentric pipe toward the critical areas of the hollow shaft and then back to the water pump inlet

A new manufacturing method has been devel-

oped for the hollow shaft structure - see Figure 5. A steel tube is formed in a corresponding pattern by hydraulic pressing (approx 6000 bar) in a cold fashioning process.

The critical stress areas of this special shaft design were identified during the development stage using a sophisticated computer program.

The program input is shaft speed, modulus of elasticity, shaft wall thickness, engine cycle pressure diagram and the dynamic load associated with the rotating parts. The program output display is the stress distribution in the shaft structure - see Figure 6.

An associated finite element program supplies decisive information on the critical stress areas and facilitates the development of an optimized lightweight shaft with maximum stability.

THE LCCR FAMILY OF WANKEL ENGINES

The LCCR family of engines is based on a modular concept in which the same carefully proportioned cross section module is used for the LCCR 400S(single rotor engine) and the LCCR 800T, (twin rotor engine) of the family. Figure 7 represents a cross section of the LCCR engine module. Details of a longitudinal section on the twin rotor engine were shown in Figure 4.

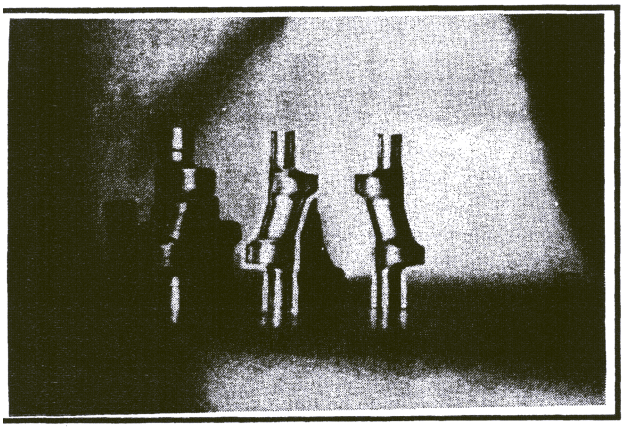


FIGURE 5 - HOLLOW SHAFT DESIGN OF THE LCCR 8OOT ENGINE

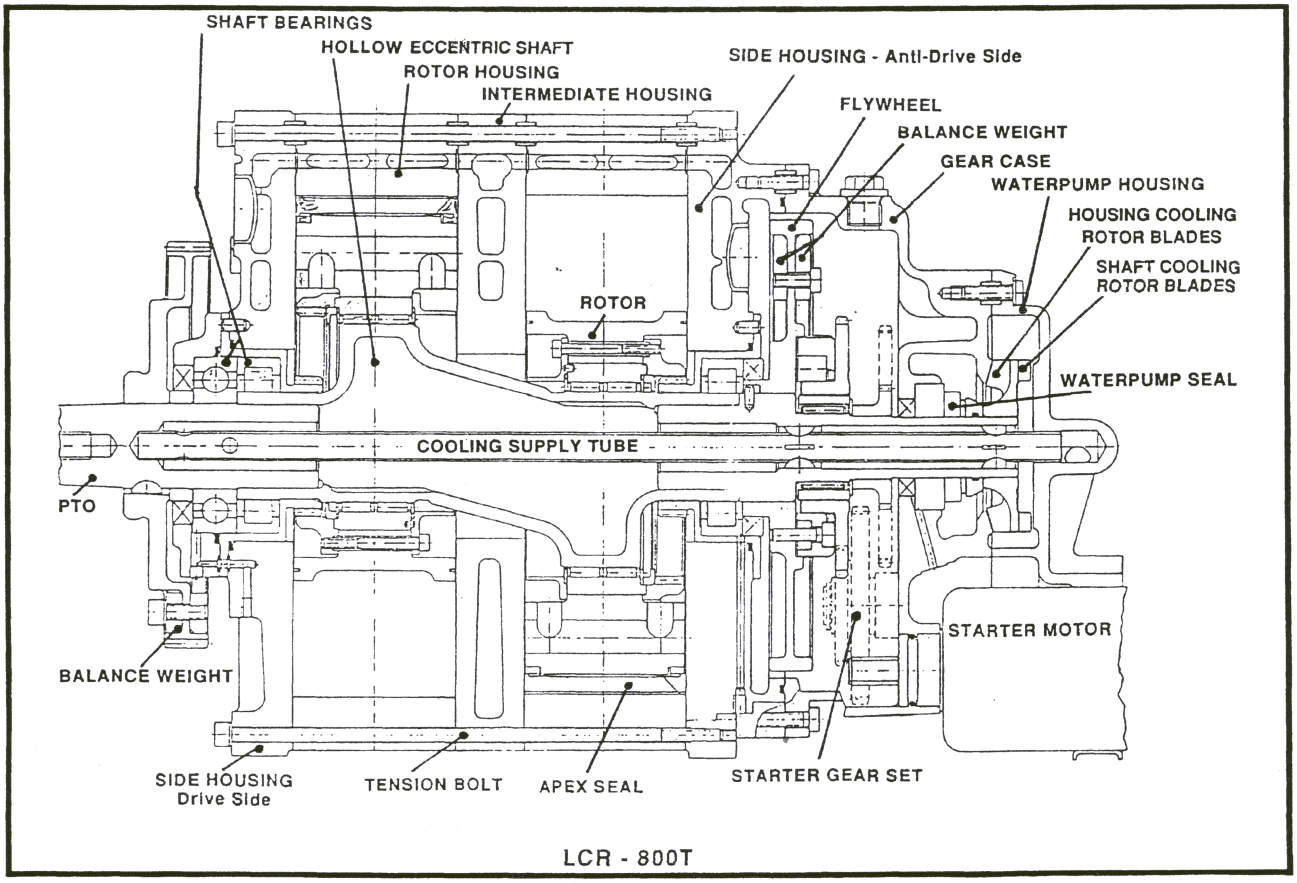


FIGURE 4 - LONGITUDINAL SECTION OF THE LCRR TWIN ROTOR ENGINE

TABLE 3 - Main features of the LCCR family of engines

ENGINE FEATURE	Single Rotor Engine LCCR 400S	Twin Rotor Engine LCCR 800T
Performance	26 kw / 6000 RPM	52 kw / 6000RPM
Displacement	407cc / Rev	816cc / Rev
Dry Weight	26 kg - 57 lbs	36 kg - 79 lbs
Dimensions: mm	400L x 268H x 303W	500L x 268H x 303W
inch	16L x 11H x 12W	20L x 11H x 12W
• Liquid Cooling System - Thermostat Control • Basic Version - Gasoline, carburated or low pressure injection system • Advanced Version - Turbine fuel and diesel fuel with high pressure injection system • Ignition System - Single or double spark plug system with electronic pick up sensor • Engine installation - Horizontal or vertical - any attitude • Lubrication system - Total loss system; Metering pump; no oil sump		

Capitalizing on the well known advantages of the rotary engine's design concept new members of the family can be subsequently created with minimal additional parts and developmental work.

Table 3 presents the main features of the LCCRengines. Figure 8 summarizes the layout dimensions of the single and twin rotor engines.

Figures 9 and 10 depict the LCCR 400S engine viewed from the spark plug side and respectively from intake and exhaust ports. A 200mm ruler helps in assessing the engine's

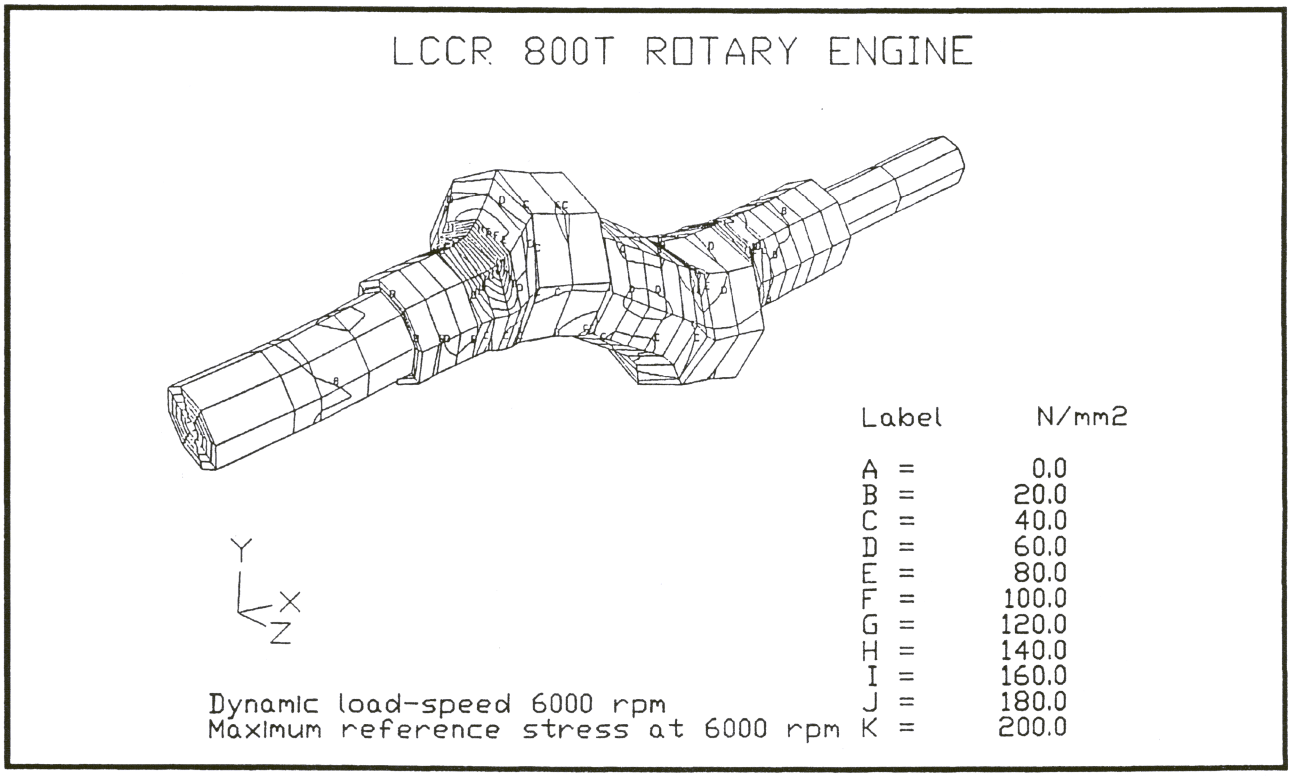


FIGURE 6 - THE ECCENTRIC SHAFT STRESS ANALYSIS

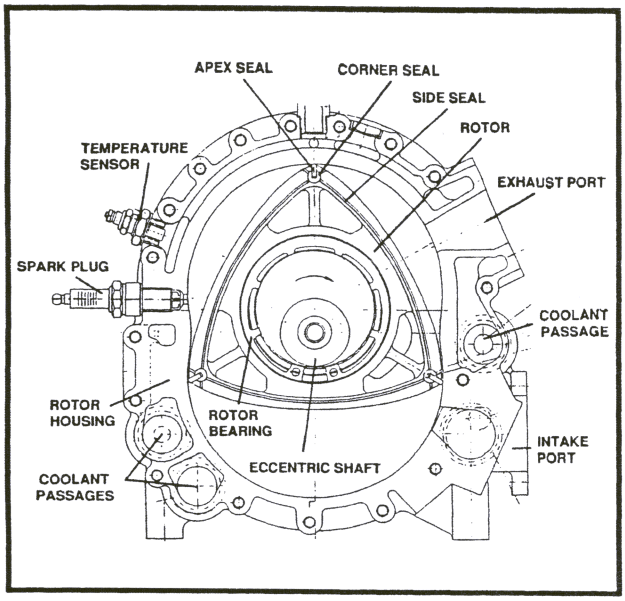


FIGURE 7 - CROSS SECTION OF THE LCCR SINGLE & TWIN ROTOR MODULE

overall proportions. Figures 11 and 12 represent similar views for the LCCR 800T engine. In the case of the twin rotor engine one single carburetor is mounted to the intermediate housing stippling the fresh charge alternatively to both combustion chambers.

The engine's main performance, power, torque and specific fuel consumption, for the gasoline version of both engines, are shown in Figure 13. These are baseline figures with no special effort directed to the performance optimization.

Figure 14 shows the gear case with all accessory drives, such as metering oil and starter motor gear. The gear case front side is closed by the water pump housing with the double stage pump and the water supply port for the hollow shaft at the rear side. Thermostat valve is located in the gear case beside the pump and controls coolant circuits for both housing and shaft. The side housings, front and rear and the rotor housing, common for both single and twin rotor engines, are shown in Figure 15. Each housing has one coolant supply port, one water outlet and a common axial water return passage, all sealed by rubber O-ring seals. The water discharge ports and cross passages are calibrated in order to closely control the necessary coolant flow for each housing. The coolant flow pattern is oriented in the circumferential direction in order to minimize coolant leakage, which in this case are much lower than those associated with an axial directed cooling system.

The cooling arrangement has proven high reliability and facilitates the easy assembly of the engine housings.

The aluminum rotor housing employs an electroplated ceramic coating for the apex seals sliding surface which requires an oscillating finish grinding process. The aluminum side housings are coated with wear-resistant materials in accordance with the engine application, associated surface load and lubrication conditions.

The surface ground housings are assembled by 17 tension bolts to keep the axial preload constant under all mechanical and thermal stress conditions.

The three housings for a single rotor module and the five housings for a twin rotor, twin module engine, are precisely interlocked by dowel pins.

The rotor shown in Figure 16 from both drive and antidrive sides, is cast from nodular iron. The design employs a special thin wall undercut casting using a ceramic core technique. The driving - synchronization gear is integrated in the rotor body and dimensioned in order to be broached in one step. The gas sealing system uses two piece apex seals. Depending on the application, a broad composition of materials can be used for apex, corner and side seals.

The engine uses a total loss lubrication system monitored by an oil metering pump which delivers small quantities of lubricant to all friction couples. No oil sump or oil filters are necessary and the engine can operate in any attitude. The oil consumption is equivalent to that of conventional four cycle piston engines.

Almost five years of development have resulted in a dramatic evolution towards design simplicity. The LCCR 400S engine has only 10 main parts of a total of 300 parts including the engine fastenings.

The number of LCCR engine main components is significantly low *when* compared with a piston engine of a comparable power range. Figure 17 compares an early version of the LCCR 400S engine with a four cylinder piston engine of the same class. The simplicity of the LCCR design concept is still evident when compared with an OCR single rotor type engine of the same displacement as shown in Figure 18.

The LCCR 400S and LCCR 800T engines are currently being optimized on gasoline, natural gas and heavy fuels.

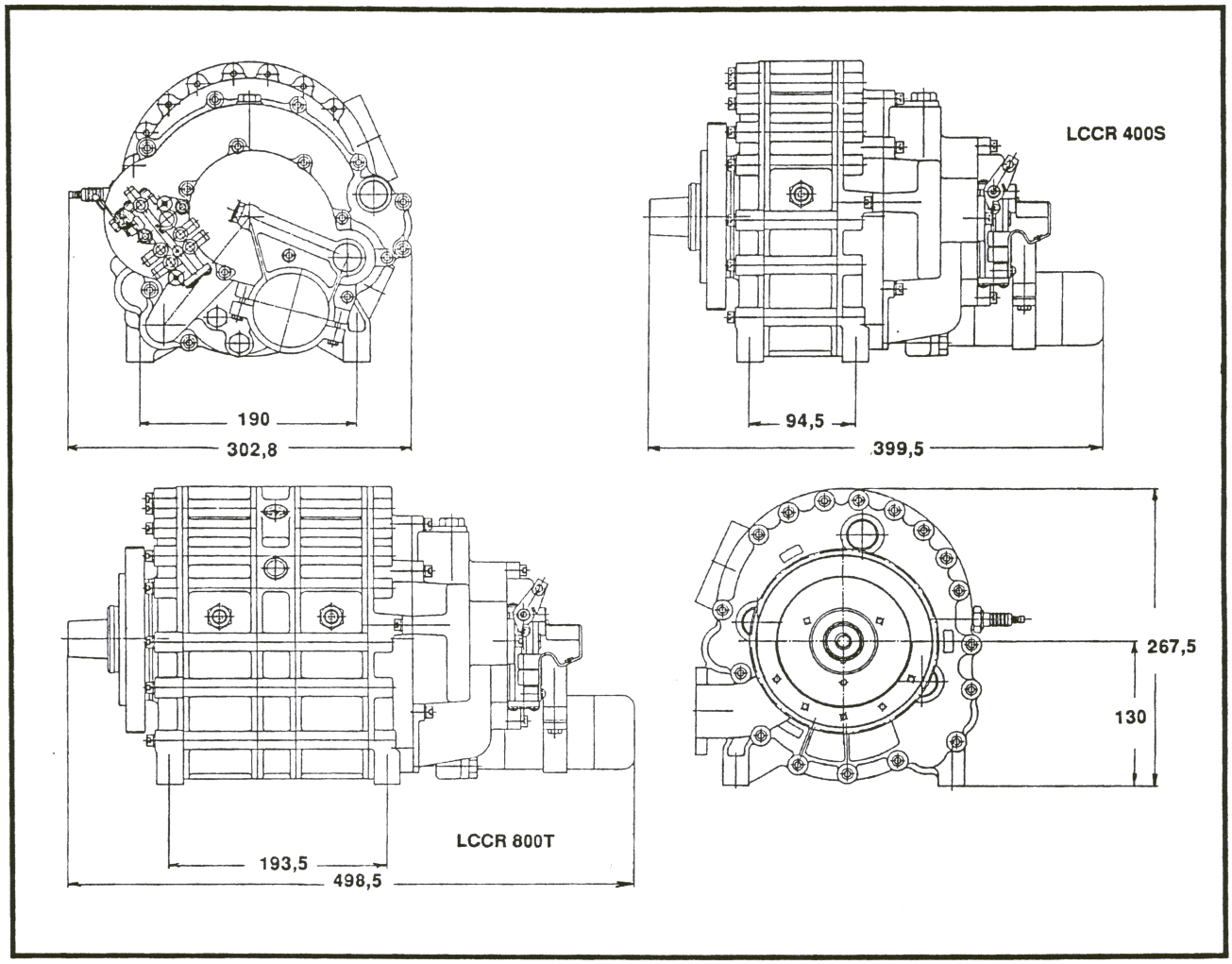


FIGURE 8 - LCCR 400S AND LCCR 800T ENGINE LAYOUT DIMENSIONS

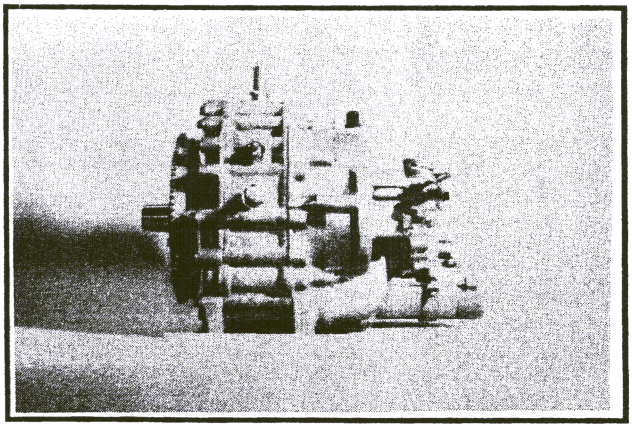


FIGURE 9 - LCCR 400S ENGINE
(Spark Plug Side View)

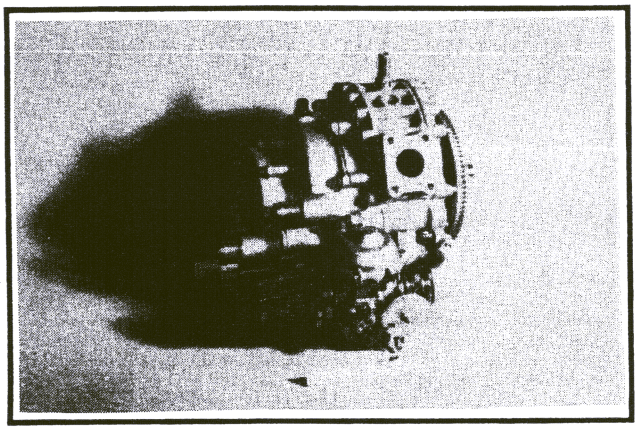


FIGURE 10 - LCCR 400S ENGINE
(Intake & Exhaust Port View)

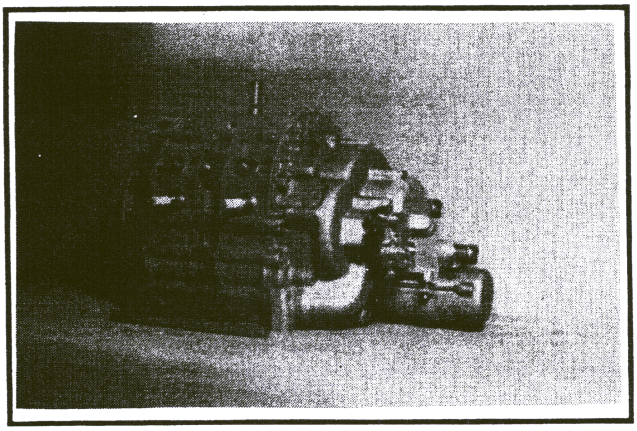


FIGURE 11 - LCCR 800T ENGINE
(Spark Plug Side View)

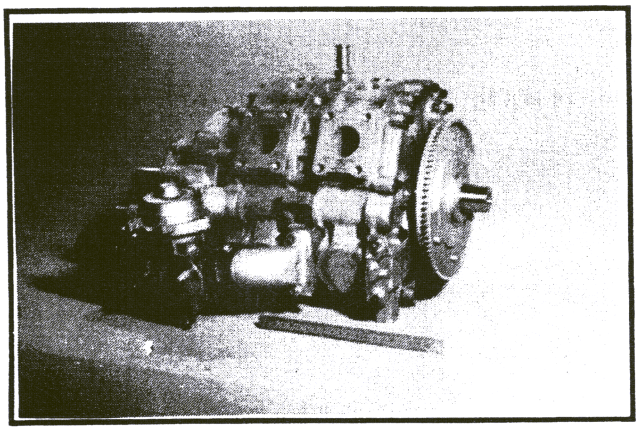


FIGURE 12 - LCCR 800T ENGINE
(Intake & Exhaust Port View)

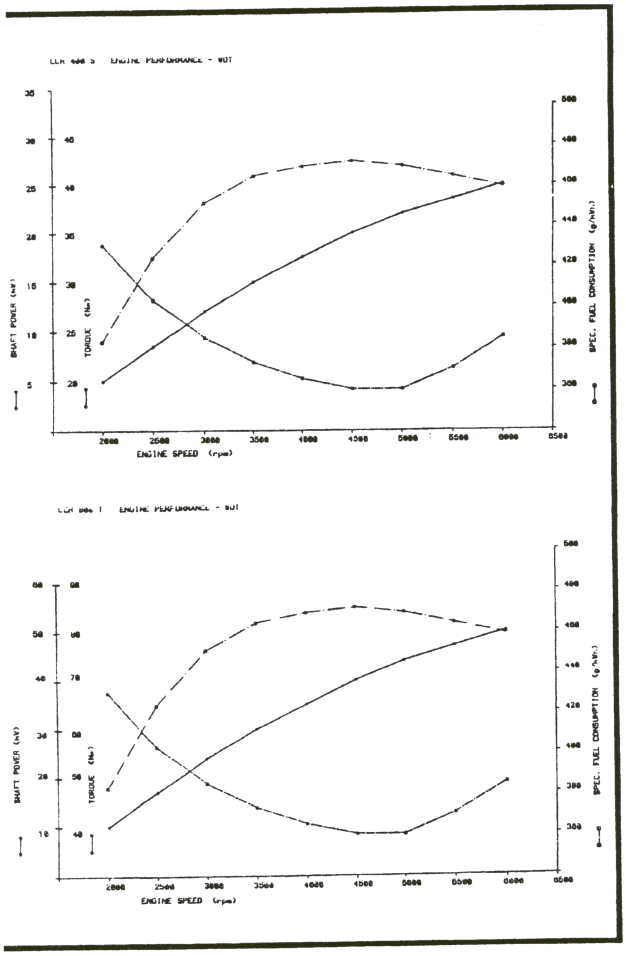


FIGURE 13
LCCR ENGINE MAIN PERFORMANCE

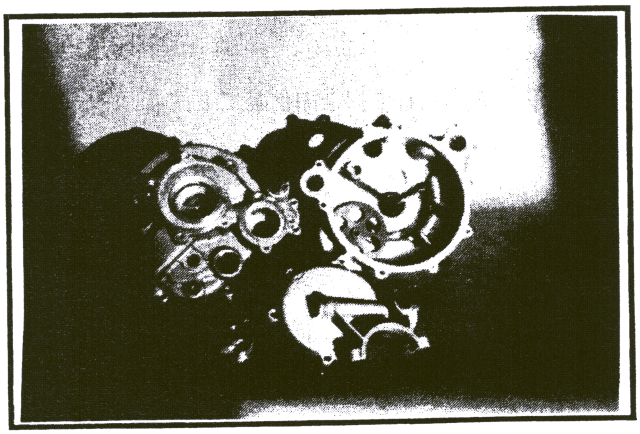


FIGURE 14 - LCCR ENGINE GEAR CASE



FIGURE 15 - LCCR ENGINE HOUSINGS

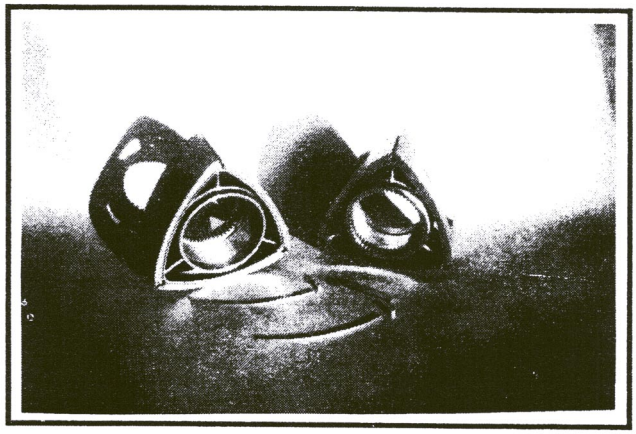


FIGURE 16 - LCCR ENGINE ROTOR

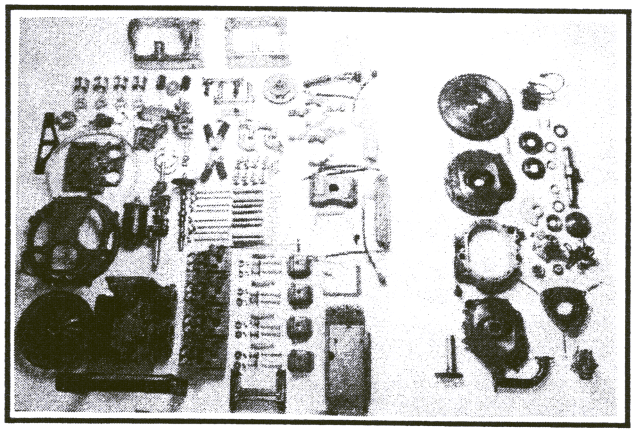


FIGURE 17 - LCCR ENGINE DESIGN CONCEPT COMPARED WITH A PISTON ENGINE

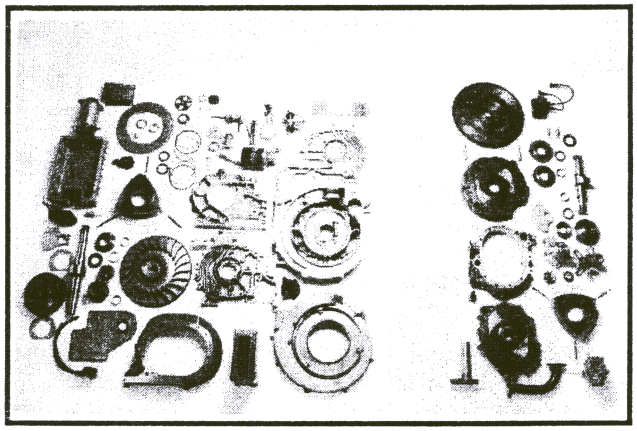


FIGURE 18 - LCCR ENGINE DESIGN CONCEPT COMPARED WITH AN OCR ENGINE

CONCLUSIONS

A new class of rotary combustion engines has been designed, developed and is being optimized on various fuels. The LCCR design concept conserves the prime advantages of the rotary engine while successfully addressing on of its few remaining drawbacks, the uneven heat rejection thru its rotating parts - rotor, rotor bearing, rotor gear and the eccentric shaft and the resulting overheating tendency of the CCR configuration. Employing a special cooling system in which the engine hollow shaft plays a central role, the thermal load of the rotor bearing is closely controlled. Extensive tests conducted during the engine development period revealed a high reliability of the rotor bearing and shaft assemblies.

REFERENCES

1. Steven R King
Durability of Natural Gas Fueled
Rotary Engine
SAE 870048

2. Dr. Kojino Yamaoka, Hiroshi Tado,
Yoshitsugo Hamada
Development of the Rotary Engine with a
Charge Cooled Rotor
MTZ No. 34 (1973) 6

3. Richard von Basshuysen,
Gottlieb Wilmers
An Update of the Development on the New
Audi NSU Rotary
SAE 780418

4. Wolf-Dieter Bensinger,
Rotationskolben-Verbrennun
smotoren
Springer verlag Berlin Heidelberg New
York
ISBN 3-540-05 886-9

5. Kenichi Yamamoto
Rotary Engine
Published by Sankaido Co., Ltd.,
Tokyo, 1981

6. Charles Jones
A New source of Lightweight compact
Multifuel Power for
Vehicular, Light Aircraft and
Auxiliary Applications -
The John Deere Score™ Engines The
American Society of Mech. Engineers
No. 88-GT-271

7. Shigeyasu Kamiya and Sada Shirasagi Suzuki
Production Rotary Engine, Model RE-5 for
Powering
Motorcycles
SAE No. 770190

8. D.W. Garside
Development of the Norton Rotary
Motorcycle Engine
SAE No. 821068

9. Harry M. *Ward,* Michael Griffith, George
E. Miller,
Donald K Stephenson
Outboard Marine Corp.'s Production Rotary
Combustion
Snowmobile Engine
SAE 730119

Positions and opinions advanced in this paper are those of the author(s) and not necessarily those of SAE. The author is solely responsible for the content of the paper. A process is available by which discussions will be printed with the paper if it is published in SAE Transactions. For permission to publish this paper in full or in part, contact the SAE Publications Division.

Persons wishing to submit papers to be considered for presentation or publication through SAE should send the manuscript or a 300 word abstract of a proposed manuscript to: Secretary, Engineering Activity Board, SAE.

Printed in U.S.A.