PRESENT STATUS AND FUTURE VIEW OF ROTARY ENGINES

Akihito Nagao, Hiroshi Ohzeki, and Yoshinori Niura

Mazda Motor Corp.
Hiroshima, Japan

INTRODUCTION

The fundamental mechanism of the rotary engine (RE) was invented by Dr. Felix Wankel who had carried out thorough investigations into the smoothness of centroid motions of moving parts. The RE has no reciprocating piston and valvetrain which are the sources of vibration and the obstructions to increased engine speed. The RE aspirates a larger amount of air per unit volume of engine package than the reciprocating piston engine does, because the charge flows continuously from an intake stroke chamber through an exhaust stroke chamber. Hence, the inherent features of RE are less vibration, compactness, light weight and high performance.

It has been 25 years since Mazda started to develop the RE. Mazda has produced more than 1,500,000 automotive REs taking advantage of the features mentioned above. Considering the actual production, it can be said that the RE is playing an important role as an automotive engine. At present, a number of companies and institutes are carrying out research and development on advanced and multi-fueled REs for wide use in various fields, such as in aerospace[1], marine, and industrial use[2], in addition to automotive use.

When we review the process of development of the RE for practical use, the subjects may be classified into three technical areas. The first is the development of gas seals and a sliding surface lubrication system, which is necessary to reduce the friction and wear of seals and housings. The second area is the development of combustion and emission control technologies to improve fuel economy under emission standards. The third area is the development of high performance technologies to intensify the inherent features of the RE.

This paper concerns the automotive rotary engine and explains its existing and future technologies. The main emphasis is placed on the techniques essential to the RE: lubrication, gas seals, combustion, and supercharging.

DEVELOPMENT OF RE TECHNOLOGY

The development of automotive RE technologies which Mazda introduced for practical use is shown in Table 1[3,4]. During the second half of the 1970's, extensive research was made on the Lean-burn RE to obtain better fuel economy under the stringent exhaust emission standards that appeared after the oil crises. In the 1980's, the development of a higher performance RE began. This work is bringing out many other potentials inherent in the RE.

LEAN BURN RE

In the early period, a thermal reactor system[5] was used as an emission control system, because it was fit for the emission characteristics of the RE, such as less NOx, more HC and comparatively higher gas temperatures in the exhaust than those of the reciprocating engine, and because it had good applicability for leaded fuel. To obtain an improved, leaner reaction, a secondary air pre-heating system and a heat insulator of exhaust port were adopted. However, it turned out that making the mixture lean tended to limit the effectiveness of the thermal reactor system.

Generally, a catalyst system is advantageous for improving fuel economy because it maintains a high conversion efficiency under low exhaust gas temperature due to a leaner mixture combustion.

Accordingly, the Lean Burn RE[5] with a catalyst system was introduced for practical use at the beginning of this decade. Two main problems had to be overcome to adopt the catalyst, the reduction of HC upstream to the catalyst to prevent heat deterioration, and the development of a high efficiency catalytic converter system. These subjects were solved as follows.

Reduction of raw HC;

1. Improved gas seals with elastic sealing material
2. High energy ignition system with 4-electrode wide gap spark plug
3. Shutter valve type deceleration control system

Development of exhaust system with higher conversion efficiency;

1. Reactive exhaust manifold for better warm-up
2. 1-converter with 2-bed type catalyst
3. Secondary air switching system for effective emission control under various driving conditions

Table 1. Development of Rotary Engine at Mazda

Year	'75	'80	'85
Car	RX-3	RX-7	NewRX-7
Emission sys.	Thermal Reactor	3way Catalyst	
Fuel sys.	Carburetor		EGI
Charging sys.	573cc×2 12A	6 Port Induction	
		12A	TC
		654cc×2 13B	Super Injection
			13B SI with TC

By introducing these technologies, the Lean-Burn RE with catalyst system realized a fuel economy improvement of about 20% under the LA-4 mode and 30% at idling.

HIGH PERFORMANCE RE

At the first stage of making a high performance engine, a 6-Port Induction system[6], which is a kind of variable port timing mechanism, was installed in the Lean Burn RE. This system made it possible to overcome the problems of fuel economy at low speed and output performance at high speed.

At the next stage, the carburetor was replaced by an EGI (Electric Gasoline Injection) and a turbocharger[6] was introduced. Since the RE has no exhaust valve, high exhaust gas energy tau drive the impact turbine effectively. To further improve the response and the torque characteristics over a wide range of speeds, the twin-scroll type turbocharger[7] was developed.

Together with a magnification of the displacement volume from 573 cc x 2 (Type 12A) to 654 cc x 2 (Type 13B), a new dynamic effect intake system[8], named Super Injection, has been developed.

In the process of developing the abovementioned high performance RE, several kinds of techniques to improve gas sealing, lubrication, and combustion have been put to practical use. The fundamental techniques for the RE are explained in the following chapters.

EXISTING TECHNIQUES FOR RE

ANALYSIS OF MECHANICAL FRICTION

Fig. 1[9] shows the friction loss of the RE compared with those of the reciprocating gasoline engine (CE) and the diesel engine (DE) having nearly the same displacement volume. The friction factors were analyzed by means of the strip down method while motoring. The friction loss of the RE is less than those of the reciprocating engines, especially in the high speed range. The RE has such a small friction in total because it has less friction in the rotor than reciprocating engines do in the piston, and it has no valve train friction. These results indicate that the RE is suitable for high speed use.

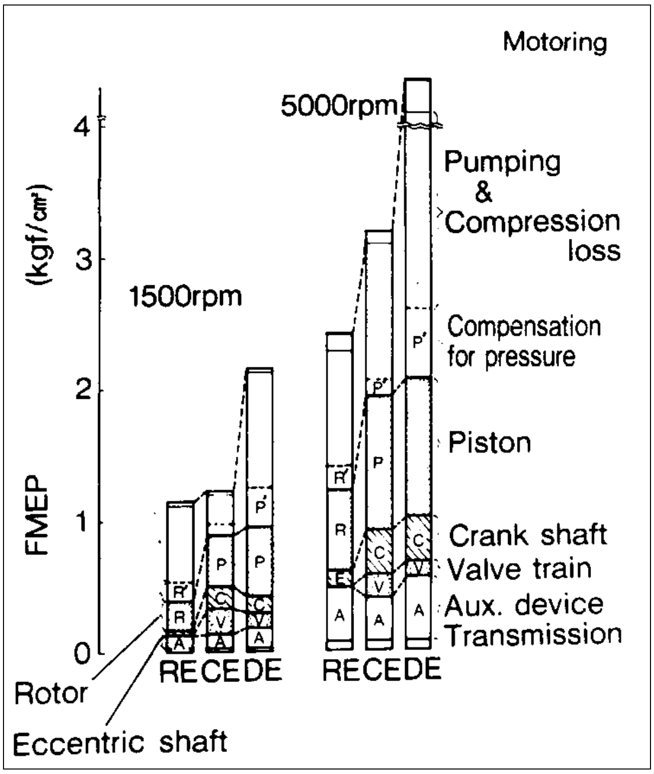

Fig. 1. Friction Loss of RE, CE, DE

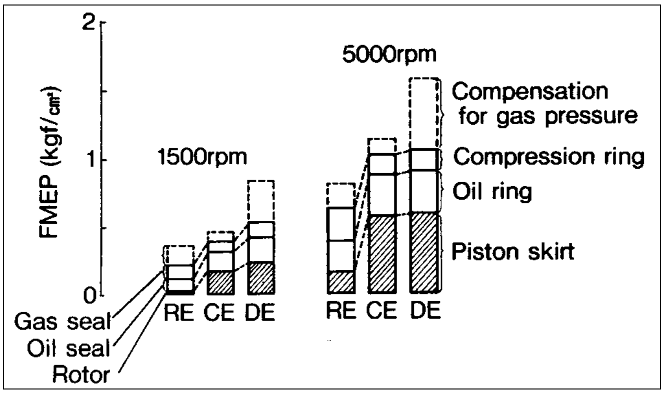

Fig. 2. Friction Loss of Rotor and Piston

However, the friction of the gas seals is greater than that of the piston rings. Moreover, as shown in Fig. 2[9], the gas seal friction is affected significantly by gas pressure, because the gas seals are affected by the pressure under the gas seals over a larger area and longer period than are the piston rings. Therefore, one problem is to reduce the back pressure area of the gas seals. On the other hand, it is important to reduce the gas leakage especially in the range of low engine speed.

IMPROVEMENT OF APEX SEAL LUBRICATION

Direct Supply of Lubricating Oil.

The lubricating conditions for the apex seals sliding on the trochoid surface get more and more sever by increasing the output performance. The direct oil supply system[10], as shown in Fig. 3, enabled the lubricating oil consumption to be reduced to 1/3 - 1/5 of that of conventional manifold supply system.

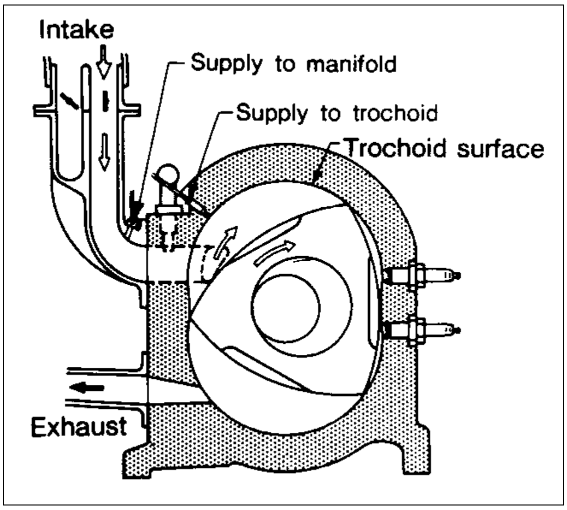

Fig. 3. Direct Supply of Lubricating Oil

Surface Treatment on Cr-Plating of Trochoid.

The inner surface of an aluminum alloy rotor housing is formed by a trochoid-shaped sheet metal with hard chromium plating on it, as shown in Fig. 4. The Micro Channel Porous (MCP) Cr-plating[11] is the most advanced pattern. Its surface has been made further resistant to wear by providing pinpoint pores for better oil retention and distribution. By using the MCP Cr-plating, the wear of the trochoid wall has been reduced 50% compared with that of the conventional pin point porous plating.

To further reduce friction and wear of apex seals under poor supply of liquid lubricants, a fluorocarbon resin coating[12] was applied on the MCP chromium-plated trochoid wall. The result was that the above coating enabled the wear of apex seals to be reduced to 1/8 of that of the conventional MCP Cr-plating especially under green engine conditions, because the fluorocarbon resin, a solid lubricant, has no-sticking and low-friction characteristics. Fig. 5 shows a mechanism of conformability between apex seal and Cr-plating with and without the fluorocarbon resin coat (it is called Un-Coherence Material coat).

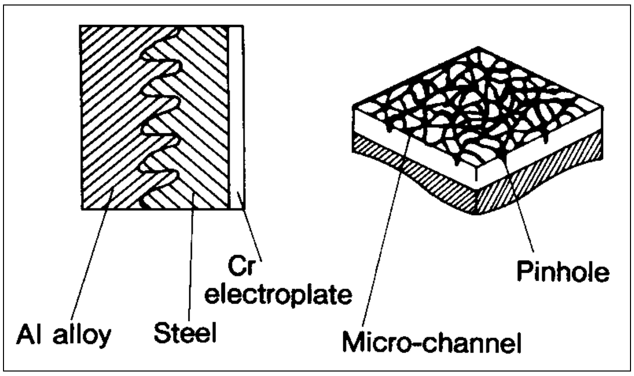

Fig. 4. Micro Channel Porous Cr-Plating

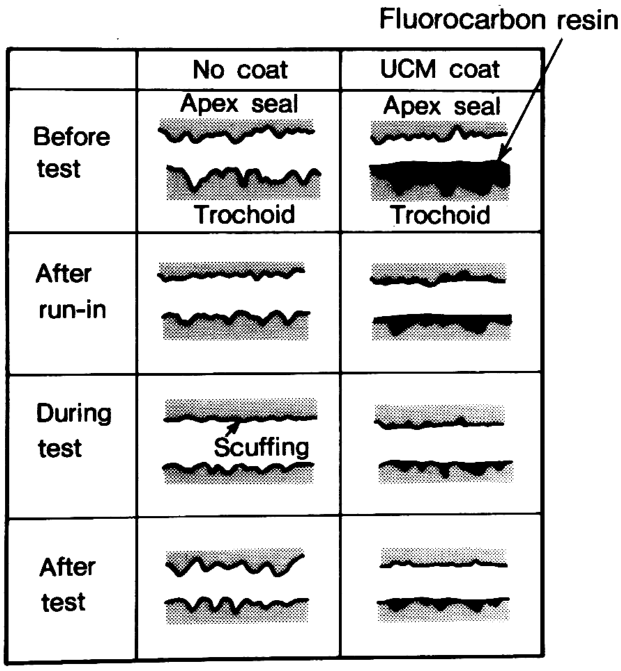

Fig. 5. Mechanism of conformability

IMPROVEMENT OF GAS SEALS

Fig. 6 shows the gas leakage characteristics of each factor[13], and Fig. 7 shows the total amount of leakage[13]. The largest leakage is due to the apex seals. However, leakage from spark plug holes, which occurs when the apex seals pass by the hole, is not negligible.

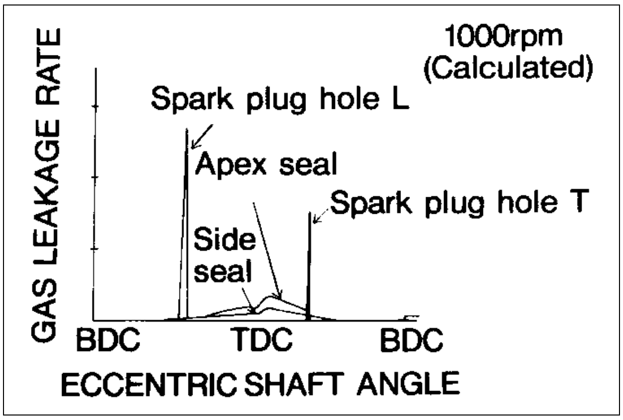

Fig. 6. Gas Leakage Characteristics

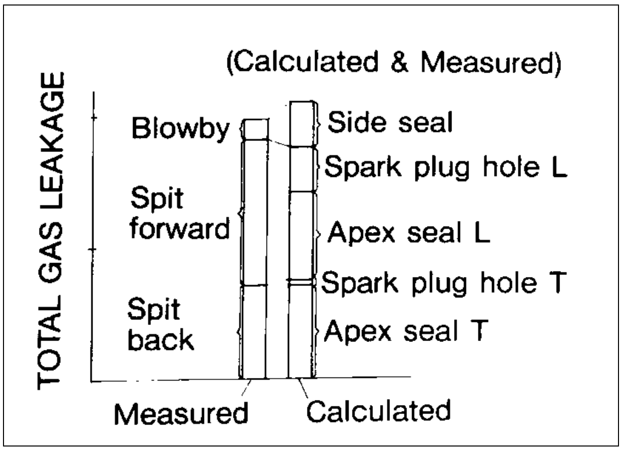

Fig. 7. Total Gas Leakage

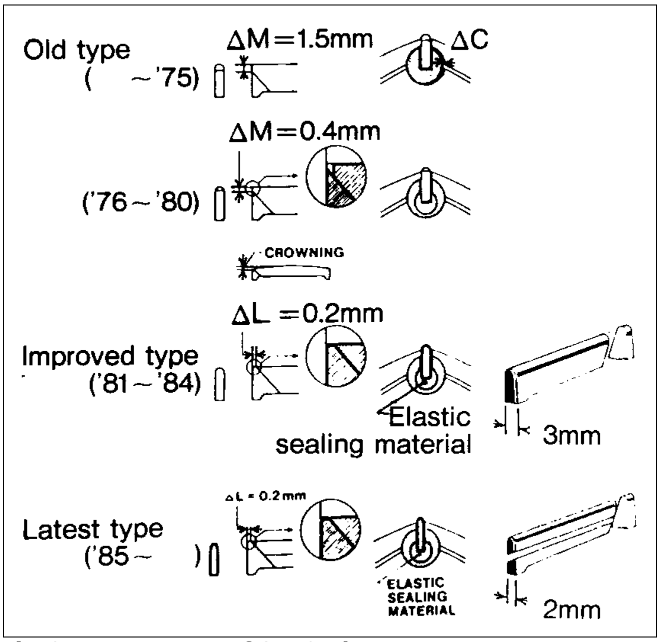

Fig. 8. Improvement of Gas Seals

To restrict leakage from apex seals, it is important to reduce clearance of the corner seals. The development of the both types of seals is shown in Fig. 8[4,5]. The most progressive apex seal consists of three pieces of reduced width, which improves their adherence on the seal channel wall. Owing to this, not only the leakage but also the friction of the apex seals were reduced.

IMPROVEMENT OF COMBUSTION

Flame propagation in the 2-spark plug RE is presented schematically in Fig. 9[14], which shows four flame fronts, TT, TL, LT and LL, generated by spark plugs, T and L, two burned gas regions and three unburned gas regions.

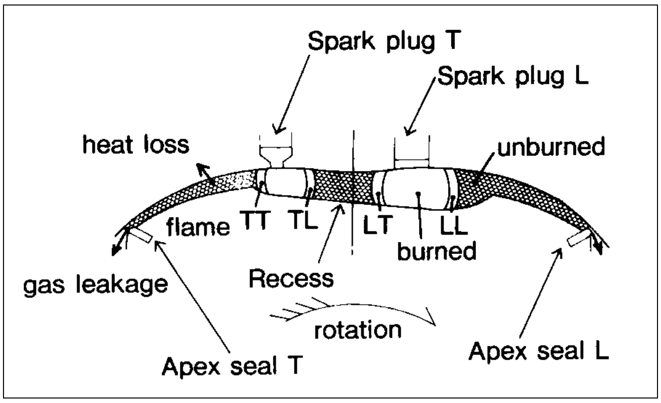

Fig. 9. Flame Propagation Model for 2-Spark Plug Rotary Engine

Squish.

In order to improve combustion in a rotary engine, it is necessary to understand the effect of squish flow on flame propagation, because the movement of the rotor generates strong squish in the direction of rotation. To this end, the patterns of squish were visualized near TDC of the compression stroke in a transparent engine by using a spark tracing technique, as shown in Fig. 10[15].

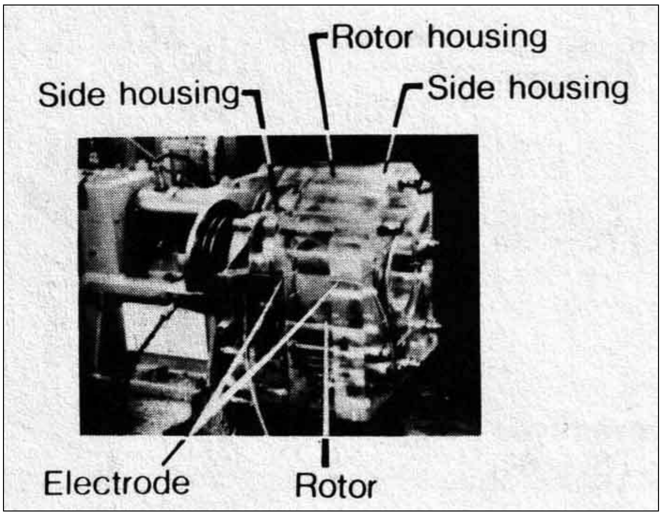

Fig. 10. Transparent Engine for Spark Tracing Technique

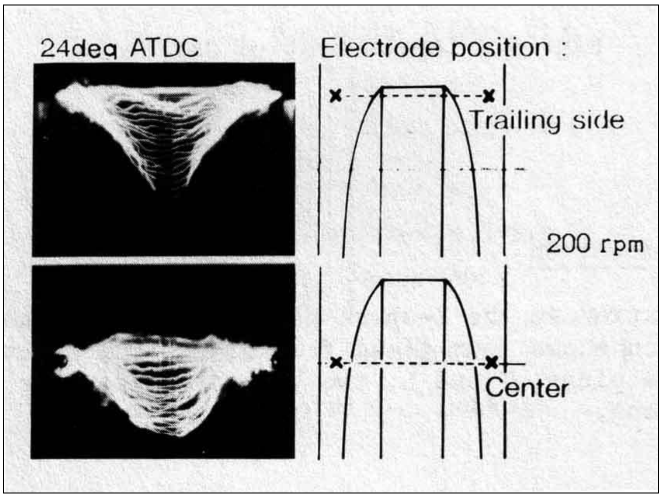

Fig. 11. Patterns of Squish Flow

The flow patterns have a convex shape in the direction of rotation, as shown in Fig. 11. In the vicinity of the trailing end of the rotor recess, the flow pattern is strongly affected by the shape of the recess,

Flame Propagation.

The relationship between squish and flame propagation was clarified by using a high-speed photo-technique and a one-directional flame propagation model14. Fig. 12 shows the location of quartz windows in the region between the two spark plugs, T and L, in the housing.

The behavior of two flame fronts, TL and LT, were observed to approach each other, as shown in Fig. 13. Although the region that can be seen is limited to the abovementioned windows, the pictures show that the flame TL propagates rapidly in the leading direction, but the flame LT moves quite slowly in the trailing direction. The behavior of all flames in the whole combustion chamber were predicted by using a combustion model which had already been verified by measurements from the ionized gap method shown in Fig. 14. The flame TT which propagates in the trailing direction from the trailing spark plug, presents a complicated phenomena, because the flame is strongly affected by the squish.

Photographic Conditions

Engine Speed	1000 rpm
Charging Efficiency	70%
Air-Fuel Ratio	13
Camera Speed	3000 f/s

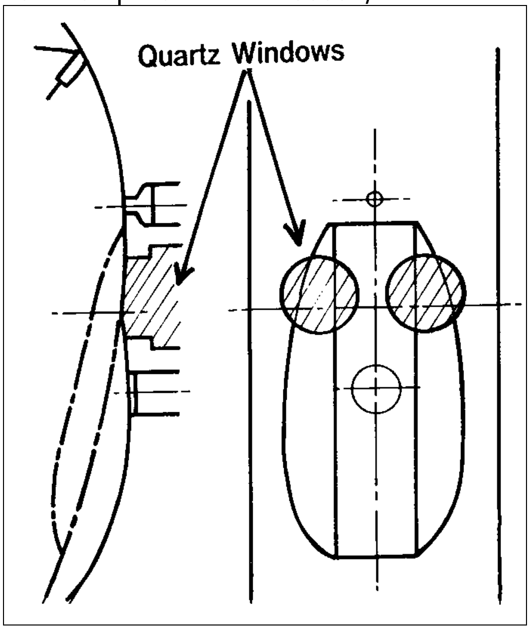

Fig. 12. Quartz Windows for Photo-technique

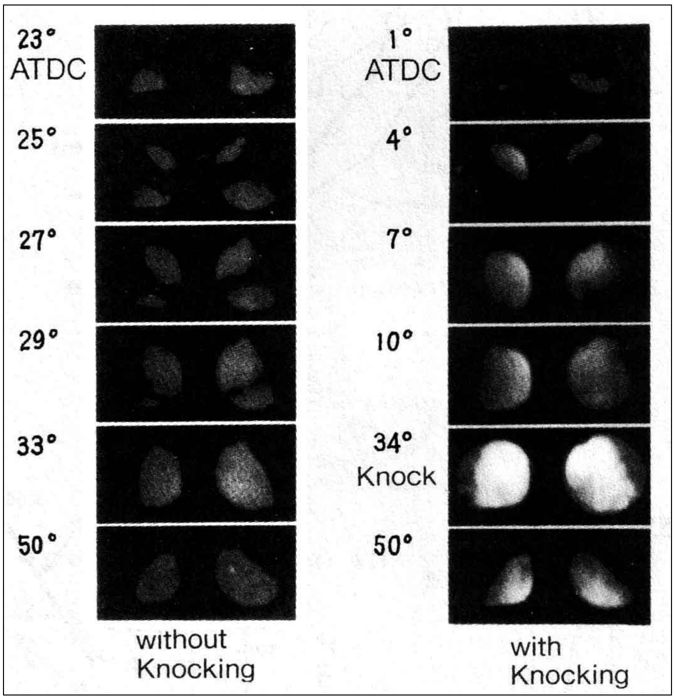

Fig. 13. Photograph of Flame Propagation

A twin-spark plug combustion is effective to improve thermal efficiency. In the RE, it is important to assist combustion by using the trailing side spark plug, because the flame in the trailing region is cooled by strong squish.

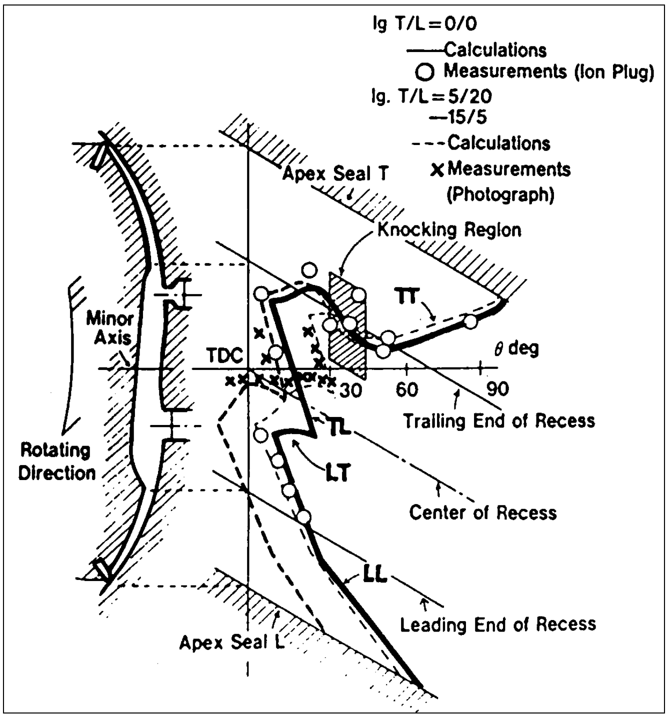

Fig. 14. Flame Propagation in 2-Spark Plug RE

Knocking.

Fig. 15 [14] shows where knocking occurs in the RE. knocking occurs in the vicinity of the trailing end of the rotor recess when strong squish is generated, as shown in Fig. 14. In the flame pictures, the knocking was observed as a very bright flame which spreaded abruptly. In order to increase the compression ratio or the charge pressure to get higher performance, it is important to improve the combustion and cooling characteristics in the region where knocking occurs.

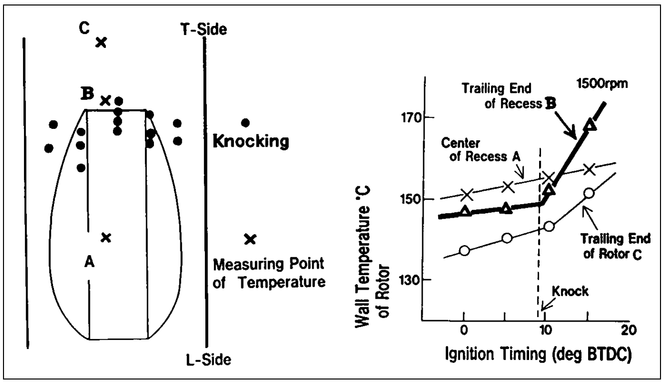

Fig. 15. Location of Knocking and wall temp of rotor

IMPROVEMENT OF CHARGING EFFICIENCY

Fuel Injector with Mixing-plate Socket.

Although the electronic fuel injection system has some benefit in charging efficiency when it is compared with the conventional carburetor system, it is still necessary to improve the atomization of the spray from the injector.

Accordingly, a new injector with a mixing-plate socket [6] has been developed, which promotes air and fuel mixing by atomizing air directed the nozzle receptacle at low engine speeds, and by a mixing-plate laving a number of small holes in an open-sided plastic tube socket at higher speeds, as shown in Fig. 16.

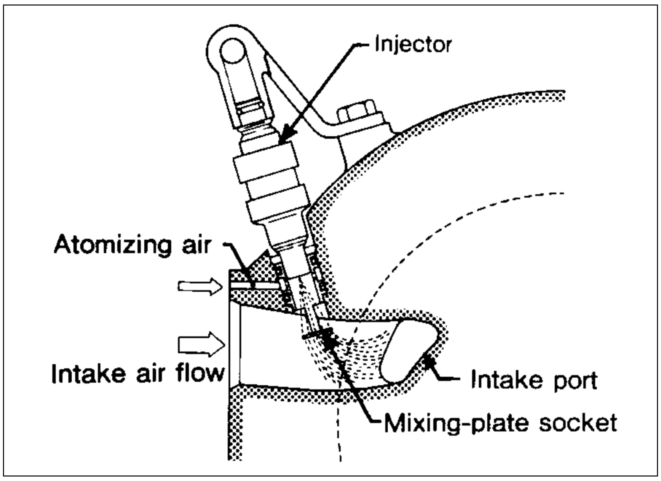

Fig. 16. Fuel Injector with Mixing-plate Socket

6-Port Variable Induction System.

The 6-port variable induction system [6] has three intake ports per one rotor, that is, the primary port, the secondary port, and the auxiliary power port, as shown in Fig. 17. The auxiliary power port is controlled by a cylindrical valve which is actuated by exhaust pressure in accordance with engine operation. The primary port has a large intake gas speed and a short period where the openings of the intake-exhaust ports overlap to improve combustion and low-end torque. The auxiliary power port increases the intake port opening area and duration to improve top-end power.

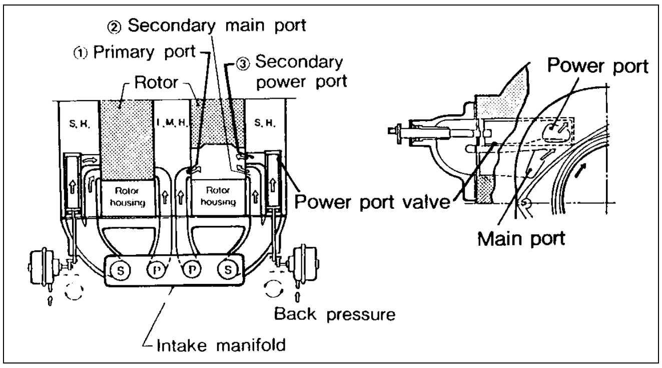

Fig. 17. 6-Port Variable Induction System

Dynamic Effect Intake System.

The dynamic effect intake system [6,8] consists of comparatively long intake passages which connect to a dynamic chamber. The system uses the effect of the pressure wave interference between the two rotors to increase charging efficiency, as shown in Fig. 18. As the intake port closes, a compressed pressure wave is generated by its own inertia in the intake passage. As it begins to open, another pressure wave occurs owing to the counter flow of residual gas from the combustion chamber into the intake passage. These two pressure waves feed more air into the other port, owing to both the quick opening-closing characteristics and the long duration intake-overlap characteristics of RE's intake ports.

Twin-Scroll Turbocharger.

In general, the use of a small turbocharger with a small A/R (where A is the sectional area of the scroll, and R is the distance between the scroll center and the turbine center) improves low-end torque and acceleration response, but remarkably drops the supercharging efficiency at higher engine speeds.

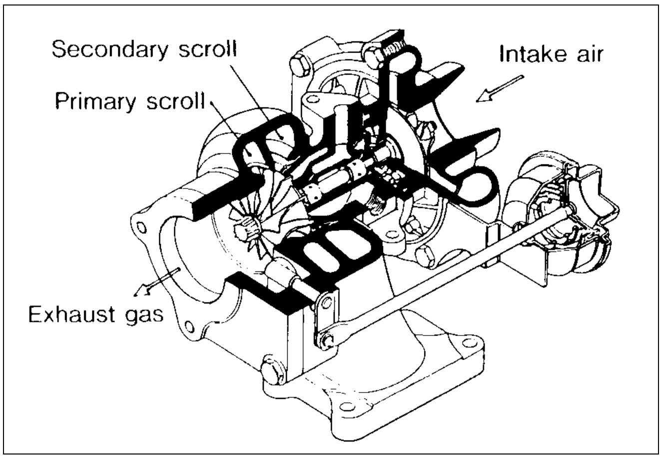

Fig. 19. Twin-Scroll Turbocharger

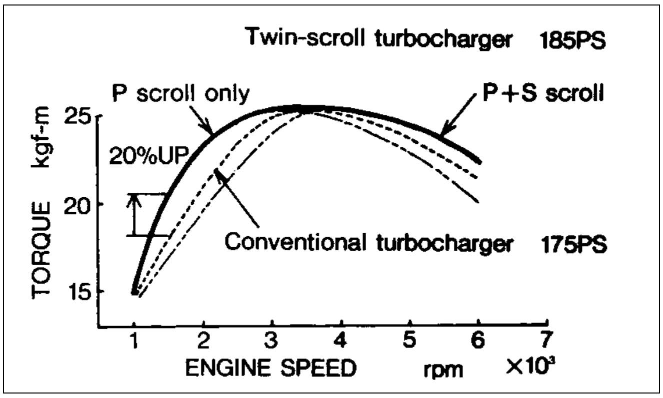

Fig. 20. Performance of Twin-scroll Turbocharged RE

To improve quick response and performance over the whole range of speeds, the twin-scroll turbocharger[7] has been introduced. Fig. 19 gives a cutaway view of the twin-scroll. By switching the scrolls to operate in accordance with engine operation, not only a small A/R (=0.4) at low engine speeds but also larger A/R (=1.0) at higher speeds can be obtained to realize excellent performance over a wide range of speeds, as shown in Fig. 20.

NEW RX-7 RE

The new RX-7 is a state of the art sports car which was developed with the intention to realize a high level combination of styling, handling, and maneuverability. The compactness and lightness of the RE allowed the low-hood profile and front-midship layout which are important factors in the superior handling of the RX-7.

Fig. 21 shows the 13B-SI (Super Injection) engine and the 13B-TC (Turbo-charged) engine for the New RX-7 [7]. The major techniques incorporated into these engines to realize these demands are shown in Table 2. The improved dynamic effect intake system, the twin-scroll turbocharger and a direct inter cooler were incorporated for higher output. The dual injector, a very short intercooler passage (therefor it is called direct intercooler) and a 8-bit, one-tip microcomputer total electronic management system were adopted for quick response. In addition, improved gas sealing and control of rotor cooling oil flow contribute to reduce fuel consumption. The dual-silencer was adopted for quietness. Improvement in the rotor housing surface lubrication, reduction of rotor weight, modification of the stationary gear fixing pins, control of the rotor cooling oil flow by a thermovalve, and the employment of water cooled turbocharger contribute to ensure durability. Because of these techniques, engine output is greatly increased and fuel economy under normal driving conditions is improved, as shown in Fig. 22.

Table 2. Major Techniques Incorporated into New RX-7's RE

	13B-SI	13B-TC
Improved 6-Port Variable Induction System	o	-
Improved Dynamic Effect Intake System	o	o
Dual Injection	o	o
Twin-Scroll Turbocharger	-	o
Direct Inter Cooler	-	o
Total Electronic Management System	o	o
Improved Gas Seals	o	o
Improved Rotor Cooling System	o	o

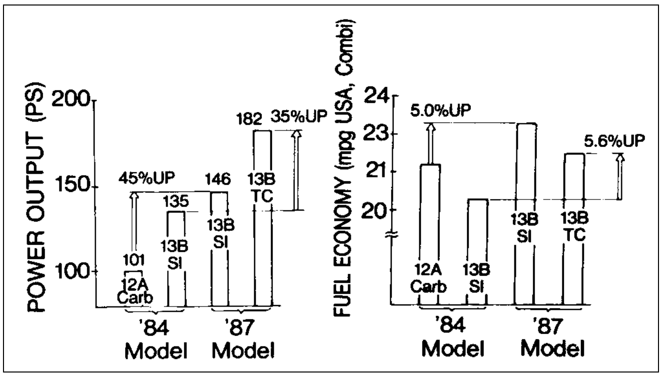

Fig. 22. Performance of New RX-7's RE

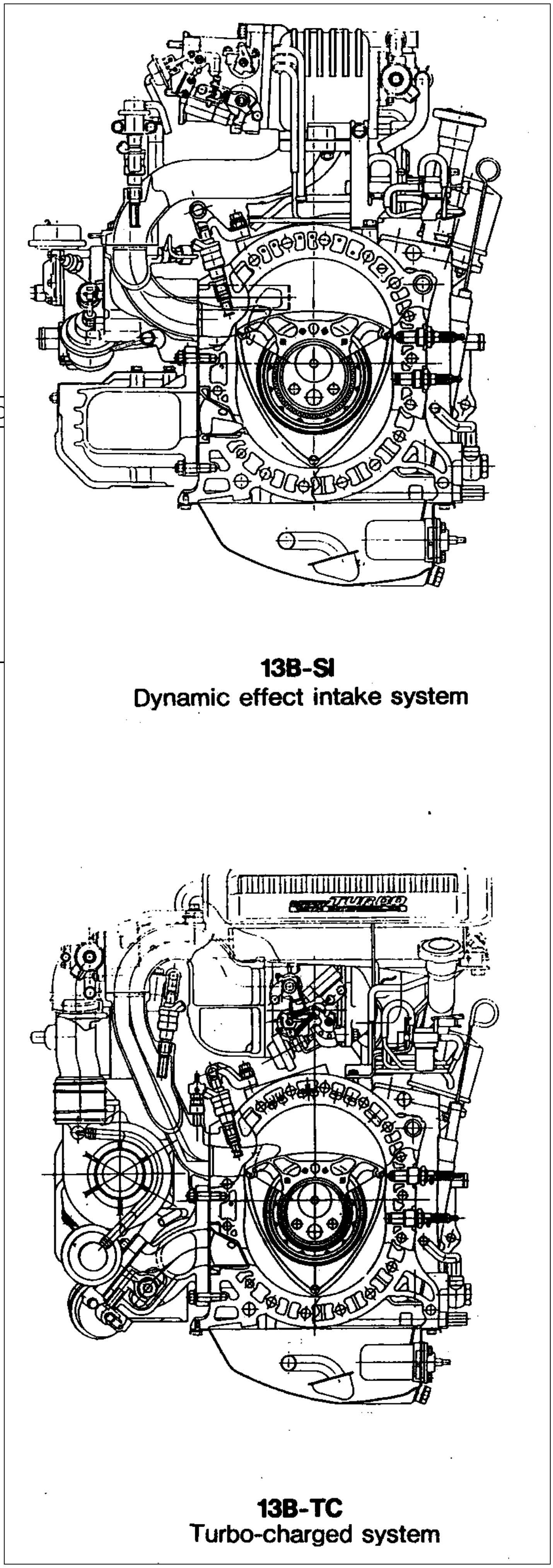

Fig. 21. New RX-7's RE

THE FUTURE OF THE RE

Because of the increasing demand to diversify automobile engines, light and compact engine designs, which will be able to contribute to imaginative styling of cars by increasing the design flexibility, will become of great importance in addition to the high performance technology for high-level drivability. For energy saving, pursuit of thermal efficiency improvement is an eternal subject, with multi-fuel combustion 1 technologies become even more important in the future.

To fulfill the above demands, research and development programs for the following future technologies are on-going now.

1. High efficiency mechanical supercharging. Multi-rotor; higher engine speed.
2. Reduction of weight and size; Extention of designing freedom.
3. Reduction of friction loss, pumping loss and cooling loss.
4. Multi-fuel stratified charge combustion. Improvement of ignitability.

Some of these are introduced below.

TISC (TIMED INDUCTION SUPER CHARGING)

The RE has great design freedom for intake port layout. TISC makes the most of this feature, as shown in Fig. 23. Part of the intake air is supercharged by a small, and thus low friction, air pump. Timing of the supercharging is controlled by a rotary valve synchronized with the output shaft. The performance improvements for the speed range for normal driving are significant, as shown in Fig. 24, and thus it is expected to be a potential super charging system in the near future.

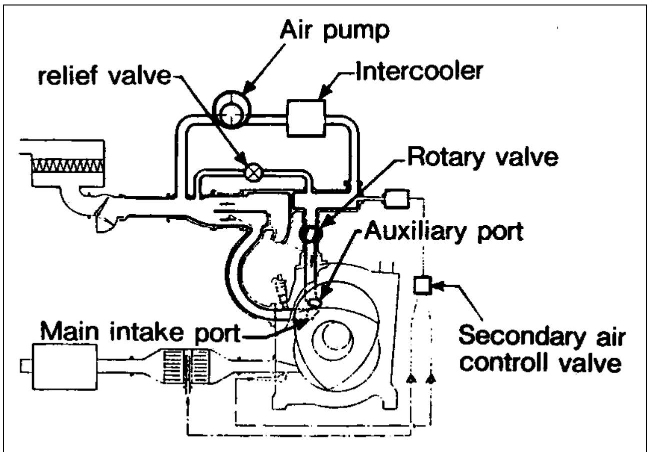

Fig. 23. TISC

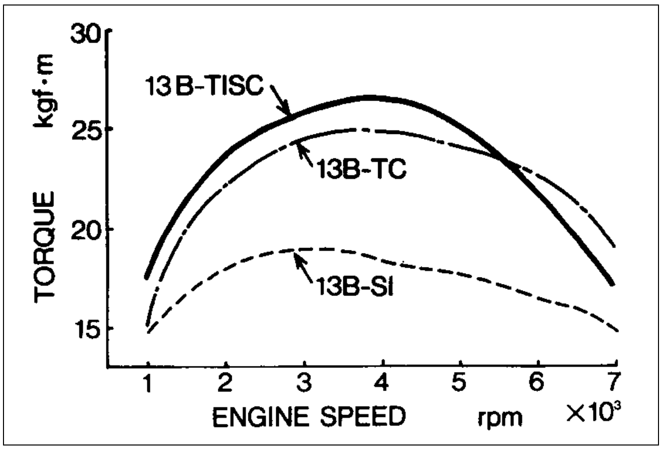

Fig. 24. Performance of TISC

LOW PUMPING LOSS RE

Reduction of pumping loss is an important subject for gasoline engines with intake air throttling. By the delayed-inlet-close cycle, ich has a connecting port between the two intake chambers of the rotor housings, pumping loss can be reduced, owing to the special configuration of the RE. As compression pressure is reduced by this technique, the friction of the gas seal, which is of great significance for the RE, is also reduced.

DIRECT INJECTION STRATIFIED CHARGE RE

The Direct Injection Stratified Charge (DISC) engine, like the diesel engine, has no pumping loss due to intake throttling. In this engine, mixture from the fuel spray is stratified in the vicinity of the ignition plug with the high-pressure fuel injection system directly attached to the combustion chamber.

The DISC engine not only increases the thermal efficiency dramatically but also improves combustion over a wide range of fuels, as compared with conventional spark ignition engines.

CURTISS-WRIGHT has actively tested and improved the DISC RE, and clarified that the RE's geometry could readily provide the requisit air motion for a stratified charge, with no ill effects to volumetric efficiency and pumping work16. As it will further improve combustion, the adiabatic engine technology will increase the potential benefits of DISC RE [17]

Therefore, the unthrottled, low heat rejection, multi-fuel DISC RE is expected to become one of the most advanced internal combustion engines.

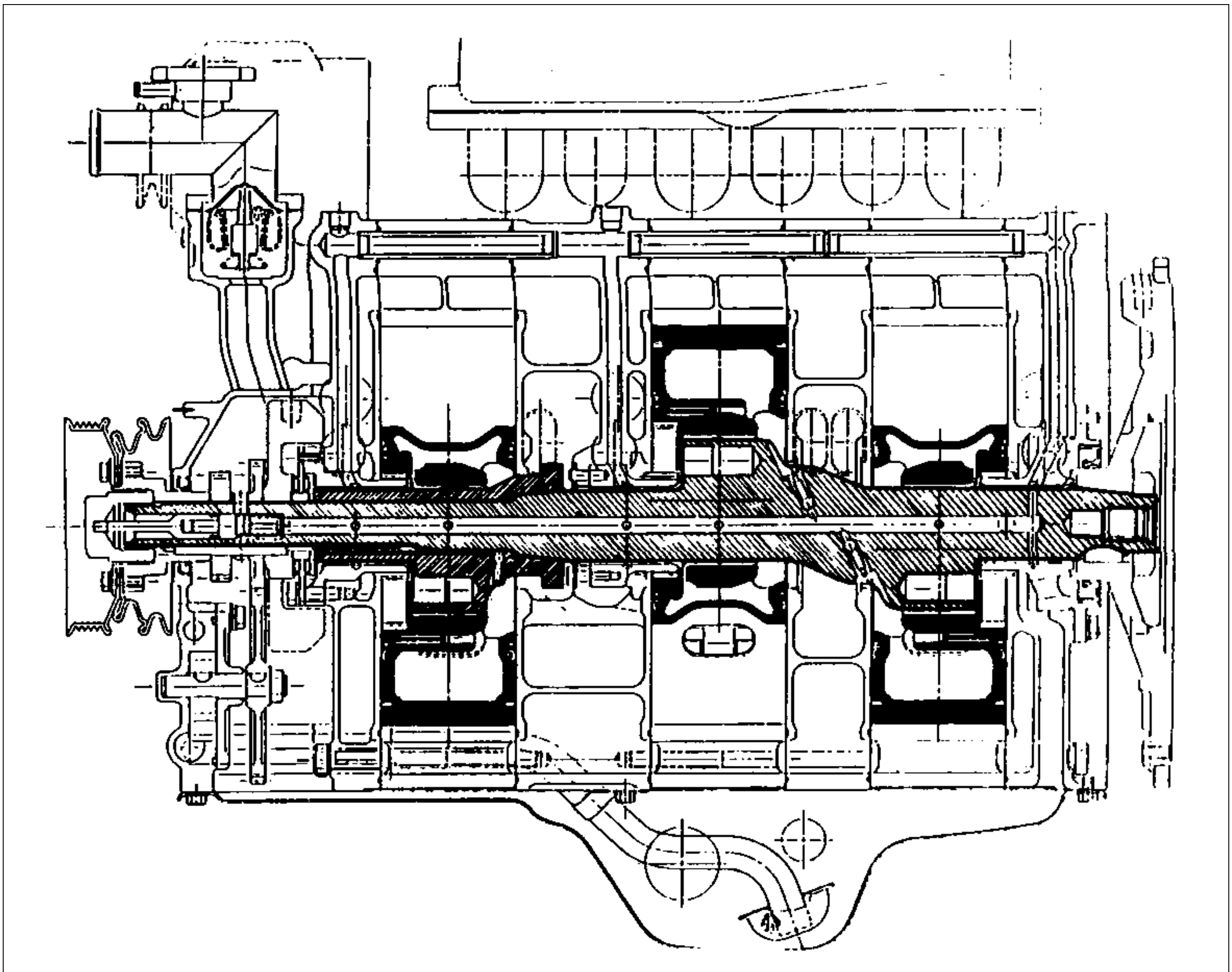

Fig. 25. Three Rotor Engine

THREE ROTOR RE

For the realization of a high grade engine which has higher output and torque, and lower NVH and thmooser revolution, a three rotor engine is now under development. As shown in Fig. 25, the output shaft has a two-piece configuration by simple conical coupling. By use of this coupling technique, a four or more rotor configuration will become possible.

CONCLUSION

The fundamental technologies of the RE, the latest techniques of the New RX-7's engine, and the future of the Mazda Rotary Engine were described. From now on, research and development on the techniques that make the most of the rotary engine's inherent features and the techniques that will meet diversified demands will be positively carried out. Regarding its automotive use in the future, we think the abovementioned RE will be a tool to realize the dreams of our individual customers.

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