Chapter 3

Chronicle of Rotary Engine Development

The Birth of the Rotary Engine

■ Dream of the Young Wankel

Felix Wankel
■ In 1957, in cooperation with NSU, Dr. Wankel completed the type DKM engine. It was the world's first engine to generate power by rotating motion alone. In 1958, he completed a more practical type KKM that became the basis of the current rotary engine.

The rotary engine began with the improbable dream of a 17-year-old German boy named Felix Wankel in the summer in 1919. In the dream, he went to a concert in his own hand-made car. He even remembers boasting to his friends in the dream, "my car has a new type of engine: a half-turbine half-reciprocating engine. I invented it!" When he woke up in the morning, he was convinced that the dream was a premonition of the birth of a new type of gasoline engine.

At the time, he had no fundamental knowledge about internal combustion engines, but he intuitively believed that the engine could achieve four cycles—intake, compression, combustion, and exhaust—while rotating. This intuition actually triggered the birth of the rotary engine, which had been attempted countless times by people all over the world since the 16th century.

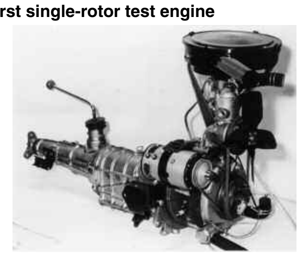
The rotary engine has an almost perfectly smooth operation; it also meets the most stringent technical standards. Wankel's dream and intuition went on to steer his entire life.

■ Research Starts

In 1924, at the age of 22, Felix Wankel established a small laboratory for the development of the rotary engine, where he engaged in research and development.

During World War II, he continued his work with the support of the German Aviation Ministry and large civil corporations, both of whom believed that the rotary engine would serve the national interest once it were fully developed. They held that the rotary engine, if fully exploited, could move the German nation and its industries toward greatness.

First single-rotor test engine



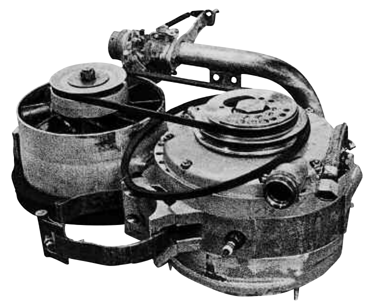
After the war, Wankel established the Technical Institute of Engineering Study (TES) and continued his work on the research and development of the rotary engine and the rotary compressor for commercial use.

One prominent motorcycle manufacturer, NSU, showed a strong interest in Wankel's research. NSU generated a great deal of enthusiasm among motorsports fans as they were repeat winners of many World Grand Prix championships. NSU was also attracted by the ideal concept of the rotary engine. After creating a partnership with Wankel, NSU promoted Wankel's research and focused on the rotary engine with trochoid housing as being most feasible.

■ First Wankel Engine

Before that, however, NSU completed development of the rotary compressor and applied it to the Wankel-type supercharger. With this supercharger, an NSU motorcycle set a new world speed record in the 50cc class, marking a top speed of 192.5 km/h (recorded at Bonneville salt lake flats). In 1957, Wankel and NSU completed a prototype of the type DKM rotary engine, which combined a cocoon-shaped housing with a triangular rotor. This was the birth of the rotary engine.

The DKM proved that the rotary engine was not just a dream. The structure, however, was complicated because the trochoid housing itself rotated; that made this type of rotary engine impractical. A more practical KKM with a fixed housing was completed a year later, in 1958. Although it had a rather complicated cooling system that included a water-cooled trochoid with an oil-cooled rotor, this new KKM was a prototype of the current Wankel rotary engine.



KKM 400
■ The NSU-built single-rotor prototype engine sent to Hiroshima from Germany with its technical drawings. This had a chamber volume of 400cc.

■ In Search of the Ideal Engine

In November 1959, NSU officially announced the completion of the Wankel rotary engine. Approximately 100 companies throughout the world scrambled to propose technical cooperation plans; 34 of them were Japanese companies.

Mazda's president, Mr. Tsuneji Matsuda, immediately recognized the great potential of the rotary engine, and began direct negotiations with NSU himself. Those negotiations resulted in the formal signing of a contract in July, 1961. The Japanese government gave its approval.

The first technical study group was immediately dispatched to NSU, while an in-house development committee was organized at Mazda. The technical study group obtained a prototype of a 400cc single-rotor rotary engine and related drawings, and saw that the "chatter mark" problem—traces of wavy abnormal wear on the rotor housing that caused the durability of the housing to significantly deteriorate—was the most critical barrier to full development. It remained a problem even inside NSU.

Chatter marks are score marks formed in the wall of the trochoid housing by apex seals at the three apices of a rotor, and are traces of juddering of the seals against the housing wall. With a maximum apex seal sway angle of 28 degrees and axial velocity of 7000rpm (twice the speed of a reciprocating engine's velocity of 37 m/s), these chatter marks are evidence of abnormal wear.

Mazda, while testing the NSU-built rotary engine, made its own prototype rotary engine, independently designed in-house, in November 1961. Both engines, however, were adversely affected by chatter marks. Practical use of the engine was not possible without solving that problem first.

■ Nail Marks of the Devil

In April, 1963, Mazda newly organized its RE (Rotary Engine) Research Department.

Under Mr. Kenichi Yamamoto, chief of the department, 47 engineers in four sections—investigation, design, testing, and materials-research—began exhaustive efforts in research and development. The main objective was the practical use of the rotary engine: namely, mass production and sales. However, this was dependent on solving the most critical engineering issue, the chatter mark problem.

These chatter marks occurred on the inner wall of the trochoid housing, where the apex seals on the triangular rotor juddered instead of sliding smoothly.

The RE Research Division called them Devil's Nail Marks and found that they were made when the apex seal vibrated at its inherent natural frequency.

To change the natural vibration frequency and damping capacity of the seal to prevent such abnormal vibration, Mazda engineers drilled a horizontal hole, 2.5 mm in diameter, in the metal seal to produce a cross-hollow seal which helped prototype engines to complete 300 hours of high-speed continuous operation.

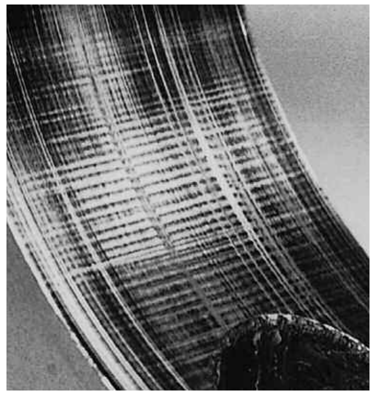
This breakthrough technology, however, was not adopted in the mass-produced rotary engines, but served to promote further research into the apex seal in the areas of materials and structure.

Moreover, in the initial stage of rotary engine development, another problem was thick white smoke caused by oil leaking into the combustion chamber. This also led to excessive oil consumption and was regarded as another barrier to commercialization.

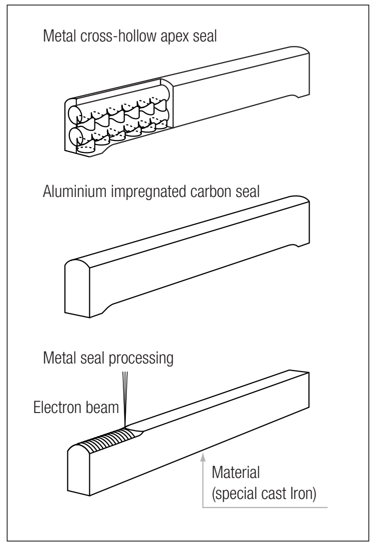
The cause of the problem was inadequate sealing, and with the cooperation of the Nippon Piston Ring Co., Ltd. and the Nippon Oil Seal Co., Ltd. Mazda designed a special oil seal which proved to be a solution.

Mr. Tsuneji Matsuda
■ As the President of Mazda, he took the initiative in proposing and obtaining the approval of a technical cooperation plan with NSU for the development of the rotary engine.

Mr. Kenichi Yamamoto
■ As the chief of the RE research department, he played a key role in developing Mazda's rotary engine. Later served as President and then Chairman of the company.



Chatter Marks
■ The durability of early rotary engines was severely affected by these wavy traces of abnormal wear on the inside surface of the trochoid housing.



Cosmo Sport, the Phoenix Project and Onward to the RX-7

■ Towards the Series-Production 2-Rotor Engine

In the early 1960s, during the initial development stage of the rotary engine, Mazda designed and investigated three types of rotary engine: those with two rotors, three rotors, and four rotors. The single-rotor version, prototypes of which were completed by NSU, could run smoothly at high speeds, but in the low speed range it tended to be unstable, with high levels of vibration and a lack of torque. This is due to the fact that a single rotor engine has only one combustion phase per revolution of the output shaft, resulting in a large torque conversion, which is a basic characteristic of this engine format.

Mazda then decided to develop a two-rotor engine, in which the torque fluctuations were expected to be at the same level as a 6-cylinder 4-stroke reciprocating engine.

The first two-rotor test engine, the type L8A (399cc single chamber volume), was an original Mazda design and was mounted in a prototype sports car (type L402A, an early prototype of the Cosmo Sport) designed specifically for the rotary engine.

In December 1964, another two-rotor test engine, type 3820 (491cc single chamber volume) was designed. It soon evolved into the mass-production trial-type L10A. The 60 Cosmo Sport prototype cars in which this engine was installed were driven for over 600,000 kilometers in Japan, during which Mazda collected critical data that was used in the preparation of the series production model. Once in production, the L10A designation given to the prototype became the type designation of the 1968 Cosmo Sport.

Moreover, in recognition of the large potential of the rotary engine, Mazda invested heavily in imported and exclusive machine tools, and proceeded with the trial manufacturing of multi-rotor rotary engines, including three and four-rotor versions. Those prototypes were installed on a prototype mid-engine sports car, the Mazda R16A. Test drives were carried out on a high speed test circuit at Miyoshi Proving Ground, completed in 1965. The course was the most advanced in Asia at that time.

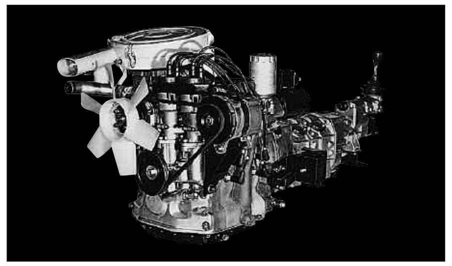
■ World's First Two-Rotor Rotary Engine

On May 30th, 1967, Mazda began selling the world's first two-rotor rotary engine car, the Cosmo Sport.

It featured a 110-horsepower type 10A engine (491cc single chamber volume) equipped with newly developed apex seals made with pyro-graphite, a high-strength carbon material, and specially processed aluminum sintering. This apex seal was the result of Mazda's independent development work and proved durable through 1,000 hours of continuous testing. Even after a 100,000 km test drive, it showed only slight wear of just 0.8 mm and an absence of chatter marks.

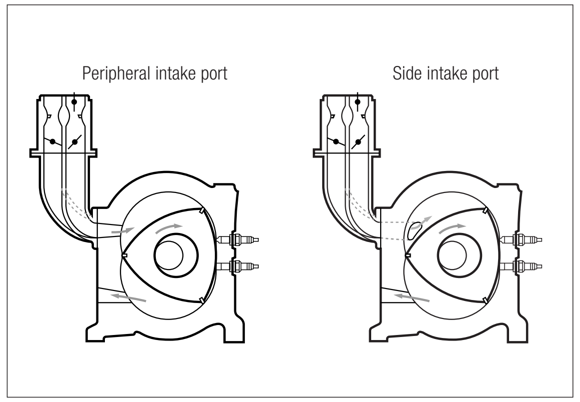
The intake system featured a side-port configuration coupled with a two-stage four-barrel carburetor, to keep combustion stable at all speeds. For the ignition system, each rotor was equipped with two spark plugs so that stable combustion could be maintained in cold and hot weather conditions alike, as well as on urban streets and expressways.

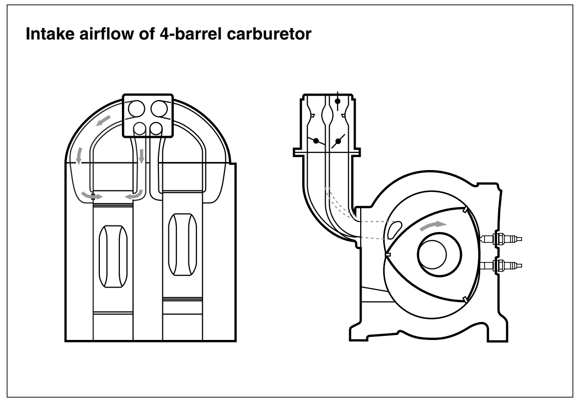
The Cosmo Sport was road-tested over a 6-year period and more than 3 million kilometers. The year after it went on sale, Mazda entered Cosmo Sport in the gruelling endurance race, "Marathon de la Route" of 1968. The car finished fourth in the race against formidable competition from Europe, and its futuristic styling and superb driving performance delighted car buffs throughout the world.



First Two-Rotor Engine
■ In 1967 Mazda announced the world's first commercialized two-rotor unit, the type 10A with output of 110PS.

Cosmo Sport
■ Launched in 1967, the Cosmo Sport powered by a 10A rotary engine amazed people with its performance and unique design.





■ Development of Low-Emission Rotary Engines

After starting mass-production of the type10A two-rotor engine in 1967, Mazda decided to expand its application beyond the Cosmo Sport (which represented, after all, a relatively small market) and installed it in other sedan and coupe models for larger volume production, acquiring many new customers along the way.

Mazda also planned to export rotary engine cars to the world market.

In 1970, exports to the United States began. At the time, the U.S. government was actively preparing for the introduction of the Muskie Act, the most stringent automobile emissions standards the country had yet devised.

From the latter half of the 1960's, close attention was being paid to the severe smog problem in cities such as Los Angeles, and governments were beginning to take the issue of air pollution very seriously. In response, Mazda started research into the reduction of exhaust emissions in 1966, while continuing early-stage developmental work of the rotary engine itself.

Compared with the reciprocating engine, the rotary engine tended to emit less NOx but more HC (Hydrocarbons).

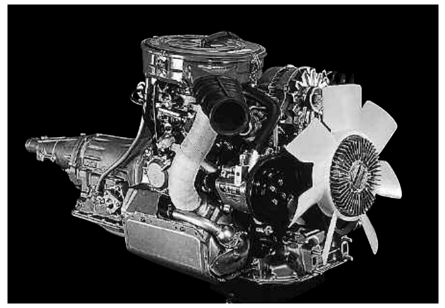
To clear the emission standards of the Muskie Act, Mazda promoted the development of an advanced catalyst system, but as a more realistic solution also developed a thermal reactor system that could rapidly be introduced. The thermal reactor was a device that burned HC in exhaust gas to reduce HC emissions. This thermal reactor system was fitted to the first U.S.-bound export car with a rotary engine, the Model R100 (domestic name: Familia Rotary Coupe), which met the U.S. standards of that year. Later, while other car manufacturers all over the world stated that early compliance with the Muskie Law standards was impossible, Mazda reported in a public hearing with the U.S. government that the Mazda rotary engine could meet the standards.

In February 1973, the Mazda rotary engine cleared the U.S. EPA Muskie Act test, while shortly before, in November 1972, Mazda launched the Japanese market's first low-emission series-production car equipped with a Rotary Engine Anti-Pollution System (REAPS).

■ The Phoenix Project (The Fuel-Economy Challenge)

During the 1970s the world went through a stormy

The Luce AP
■ The second generation Luce made its debut in 1973, with the first low emission version equipped with a 13B engine introduced the following year.



13B Rotary Engine
■ Mazda's largest twin rotor RE at 672cc per rotor chamber. The engine debuted in the Luce of 1973. At the time, it was the most powerful automobile engine in Japan.

period in international political relations, as many developing nations began to flex their muscles and use their oil resources as a political weapon. The “Oil Crisis” was the result.

With most Middle-Eastern oil-producing countries restricting their exports, global oil prices soared.

In response, car manufacturers began the development of mass-market cars with dramatically improved fuel efficiency. Mazda realized that a drastic reduction in fuel consumption had now become critical to the survival of the rotary engine and initiated the “Phoenix Project” targeting a 20 percent improvement in fuel economy for the first year of research and development, followed by a 40 percent improvement as the ultimate goal.

The company began by challenging the engineers to improve the fundamentals of the engines, including improving their combustion systems and carburetors, and concluded that fuel economy could be raised by 20 percent as targeted. Further development, including enhancing efficiency by incorporating a heat exchanger in the exhaust system, finally led to a 40 percent rise, the ultimate goal.

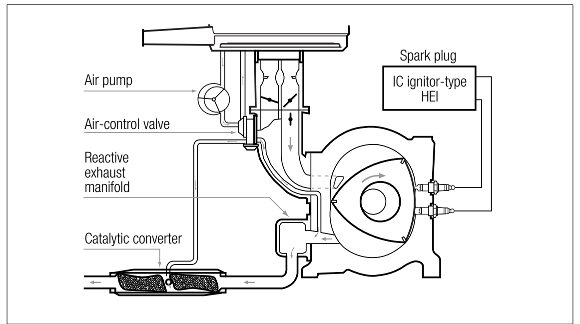
The success of the Phoenix Project was reflected in the sporty Savanna RX-7, launched in 1978, which proved once and for all that the rotary engine was here to stay. Thereafter, the world’s first catalytic converter system for the rotary engine was successfully developed, and fuel economy was even further improved. Soon afterward, fundamental engine improvements like the reaction-type exhaust manifold, the high-energy ignition system, the split secondary air control, and the two-stage pellet catalyst system, were developed in succession. The manifestation of all those developments was the lean-burn rotary engine that soon appeared on the market.

■ Six-port Induction System for Greater Fuel Economy and Power

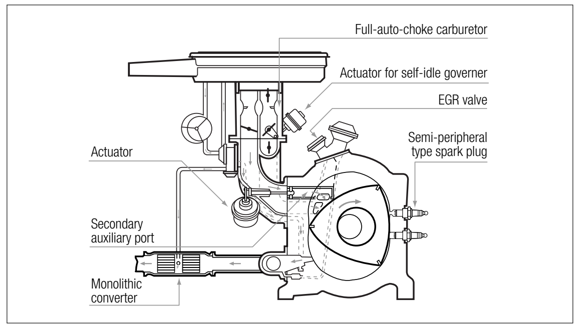
After its success in developing a low emission system and improving the rotary engine’s fuel economy, Mazda adopted a six-port induction system and two-stage monolithic catalyst for its type 12A engine (573cc single chamber volume).

The six-port induction system featured three intake ports per rotor chamber, and by controlling these intake ports in three stages fuel economy could be improved without sacrificing performance at high speeds.

This system, coupled with the two-stage monolithic catalyst would further the rotary engine’s advance.

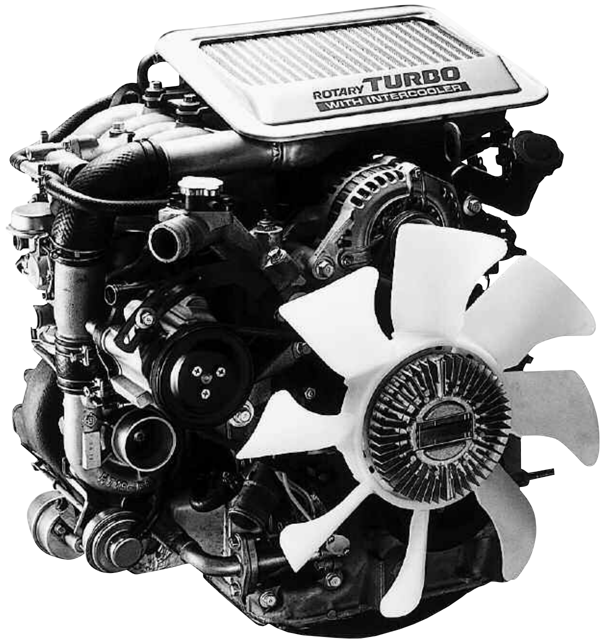


Lean-Burn Rotary Engine
By introducing a catalytic converter as a device to purify exhaust emissions, leaner mixture settings were achieved.



Six Port Induction System
A variable-intake system which utilized the design features inherent to the rotary engine to enhance power and fuel economy.

The Turbo Rotary Era



13B Rotary Turbo Engine
■ The second generation RX-7 made its debut in 1985, featuring a 13B rotary engine boosted by a Twin-Scroll Turbo. The engine produced a maximum output of 185PS.

■ RE Turbo and Dynamic Supercharger

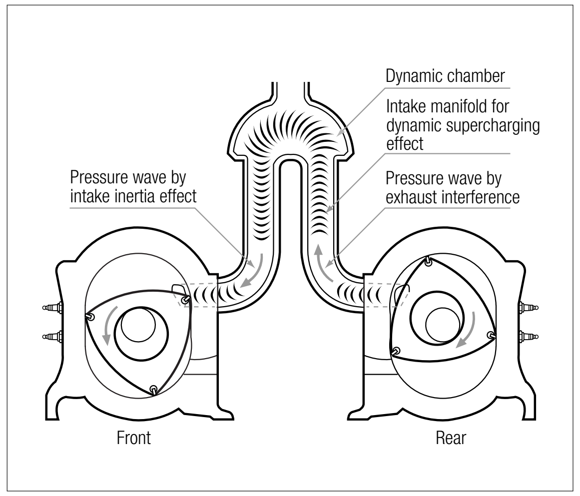
The Cosmo RE Turbo, which went on sale in 1982, was the world’s first rotary engine car equipped with a turbocharger. Compared to a conventional reciprocating engine, the rotary engine’s exhaust system inherently offered more energy to drive a turbocharger; in short, the rotary engine was better suited to the turbocharger.

Moreover, the Cosmo RE Turbo was the world’s first series-production rotary engine car equipped with an electronically controlled fuel injection system.

The Cosmo RE Turbo was the fastest commercial car in Japan at that time and it clearly demonstrated the attractiveness of the rotary engine. Shortly after came the debut of the “Impact-Turbo”, developed exclusively for the rotary engine and responsible for even further improvements in response and output.

The “Dynamic Supercharging” system was adopted in 1983 for the naturally aspirated (NA) rotary engine, type 13B. This system dynamically increased the intake air volume without turbo or mechanical supercharger, by utilizing the induction characteristics peculiar to the two-rotor rotary engine.

With the six-port induction system and a dual injector system with two fuel injectors per chamber, the 13B rotary engine came equipped with this dynamic supercharging system and achieved significant output increases regardless of the speed range. The dynamic supercharging system was further improved in 1985 through changes in the surge tank configuration.

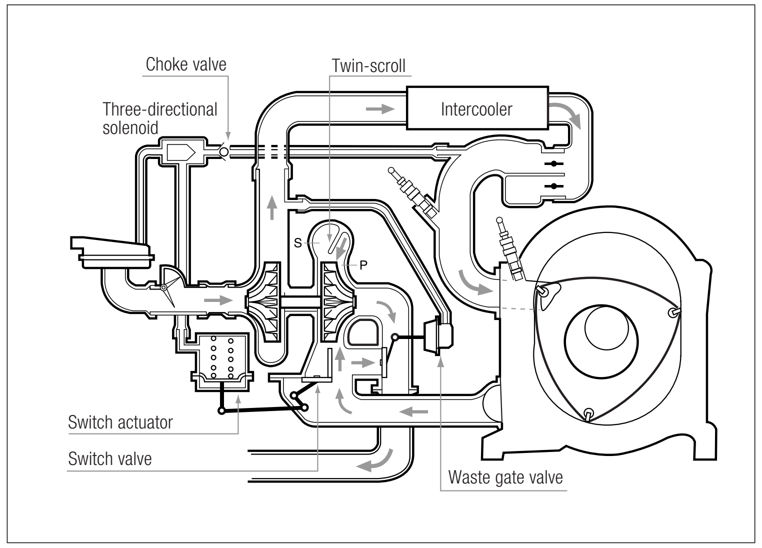


Dynamic Supercharging System
■ This system, with neither turbo nor supercharger, offers drastically improved charging efficiency over conventional designs by utilizing pressure waves generated inside the intake manifold by the sudden opening and closing of the ports.

■ Twin-Scroll Turbo

To improve the driving performance of the turbo rotary engine, the second generation Savanna RX-7 adopted the 13B engine with a Twin-Scroll Turbo to minimize turbo lag. The Twin-Scroll Turbo divided the exhaust intake scroll of the turbine into two passages so that exhaust could be supplied step-wise. With this configuration, the single turbocharger acted as a variable turbo and efficiently covered a wide range of speeds.

In 1989, the Twin-Scroll Turbo evolved into the Twin-Independent-Scroll Turbo, which had a more simplified configuration. When this new turbocharger was coupled with other improvements in the engine, it provided more outstanding low-speed torque, improved responsiveness, and upgraded driving performance.



Twin-Scroll Turbo System

■ This system helps to reduce turbo-lag, a traditional drawback of the turbo-engine. The duct feeding exhaust gas to the turbine was split into two, one of which was closed by a valve to accelerate exhaust gas flow at low speeds.

■ Dual Fuel Injector

Since 1983, Mazda's electronically-controlled fuel injection system for rotary engines has featured two injectors in each rotor chamber. Generally speaking, a larger nozzle is better for high-performance output as it can supply larger amounts of fuel. For more stable combustion at low speeds, however, a smaller nozzle is preferable as it can atomize fuel better.

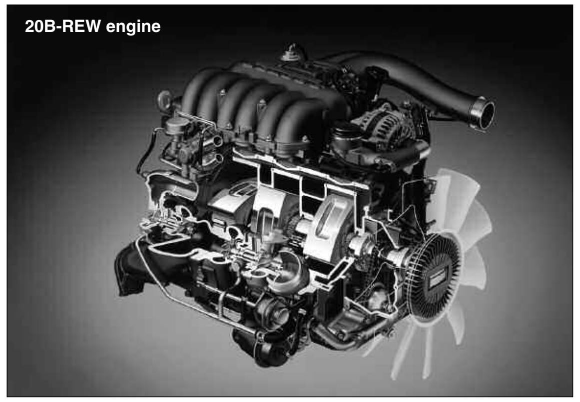
The dual injector was developed to cover the requirements of controlling fuel injection over a wide range of engine operations. The two-rotor 13B-REW and the three-rotor 20B-REW rotary engines were both equipped with air-mixture injectors, underwent further evolution of the dual fuel injectors, and achieved radical improvements in fuel atomization.

Today, the RENESIS engine powering the RX-8 has an ultra-atomizing system, and a description of the system is given earlier in this booklet.

■ Type 20B-REW Rotary Engine

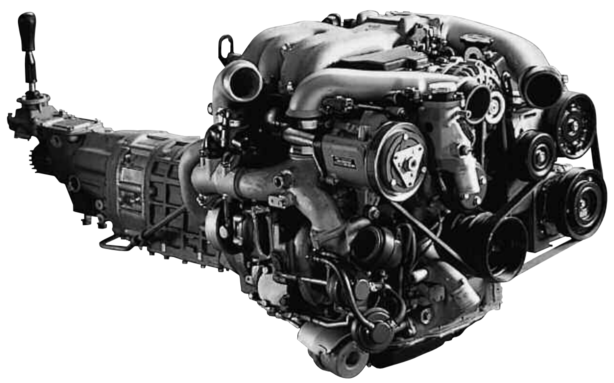
In 1990, the Eunos Cosmo, with its three-rotor 20B-REW rotary engine, went on sale after a continuous quarter-century of research and development into the rotary engine. While the two-rotor engine produced a smooth operation equivalent to the 6-cylinder reciprocating engine, the three-rotor engine exceeded that of the V8 engine and even approached the level of a V12.

However, a difficult engineering problem stood in the way of mass-manufacturing the multi-rotor rotary engine. When the rotary engine was planned with an in-line multi-rotor configuration, only two choices in designing the eccentric shaft were feasible: coupling it through joints, or making one of the fixed gears on the rotors split-assembled. Since the early stages of development in the 1960s, Mazda had focused on the coupled eccentric shaft layout because the fixed gear split layout was considered too complicated for mass production., but now the company considered how to design the joints. The successful solution discovered in the 1980s was to use tapered joints in connecting the shafts. When the three-rotor engine was developed, extensive driving tests for performance and durability were carried out, including participation in international sports car racing activities like the famous Le Mans 24 Hours race.


20B-REW engine

■ Sequential Twin-Turbo

Development of the Sequential Twin-Turbo, first adopted in 1990 on the type 20B-REW and type 13B-REW rotary engines, was based on the unique engineering concept of utilizing two turbochargers in sequence. At low speeds, only the first turbocharger operates, and at higher speeds the second turbocharger kicks in. The use of two turbochargers enabled excellent forced-charging capacity and yielded high output. Running two turbochargers simultaneously also had the added benefit of reducing back-pressure on the exhaust, which in turn contributed to even higher performance.



13B-REW engine with sequential twin turbo

■ The 13B-REW turbocharger employed abradable seals to minimize the gap between turbine blades and housing, producing an ultra-high-flow turbine that combined lower inertial mass with high flow volume to achieve an outstanding maximum power output of 280 PS (206 kW).

As mentioned previously, the rotary engine is inherently suited to use with a turbocharger thanks to characteristics that include a more dynamic exhaust flow caused by the sudden opening of the exhaust port, and a short and smooth manifold. To fully utilize these features, the uniquely shaped Dynamic Pressure Manifold was adopted to guide the exhaust gas into the turbocharger over the shortest distance.

The 13B-REW engine with sequential twin turbochargers installed in the third-generation RX-7 was revised in 1998 to deliver 280 PS (206 kW) maximum power.

RX-7