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ABSTRACT

The 1ZZ-FE engine is a newly developed in-line 4-cylinder, 1.8-liter, DOHC 4-valve engine mounted in the new Corolla. Abounding in new technologies including the laser-clad valve seat, high-pressure die-cast aluminum cylinder block, and the small-pitch chain drive DOHC, coupled with the fundamentally reviewed basic specifications, the new engine is compact and lightweight, offering high performance and good fuel economy. Anticipating even more stringent emission regulations in the future, in addition to the revision of the engine body, the layout of the exhaust system has been improved to enhance warm-up performance of the converter.

DESIGN CONCEPT AND TARGET

From the viewpoint of the global greenhouse, one of the most important tasks for the automotive engine is to reduce the emission of carbon dioxide by improving fuel economy. Toyota has already introduced lean burn engines, a direct injection gasoline engine and other fuel efficient engines into the market. But while these engines require special devices, it has become more important to improve fuel consumption by optimizing basic specifications and adopting new technologies to each component. Moreover, in order to meet worldwide market demands and to meet various countries' emission regulations, development of this new engine was necessary.

The 1ZZ-FE engine has been developed around the following concepts with the following targets:

(1) To enhance potential for cleaner exhaust emissions and better fuel economy by optimizing basic specifications.

(2) To improve engine performance and to make its body even more compact and lightweight by re-examining each engine component.

1) High performance

Aiming for ease-of-handling, keep maximum output and torque at the top of its class (Figs. 1 and 2), while attaining flat torque characteristics.

2) Lighter in weight

Build the lightest engine among those employing aluminum engine blocks (Fig. 3)

3) More compact

Shorten the overall length of the power plant for possible installation in front-engine, front-drive vehicles, while reducing the overall height and width.

4) Emission regulation compliance

Configure a low-cost, simple construction engine and ensure emission regulation compliance.

5) Vibration and noise

Improve performance and, at the same time, meet or exceed the level of the previous engine model which had a good reputation in the market.

6) Parts reduction

Drastically reduce the number of parts used, thereby reducing the overall weight and cost and improving ease of assembly and cost.

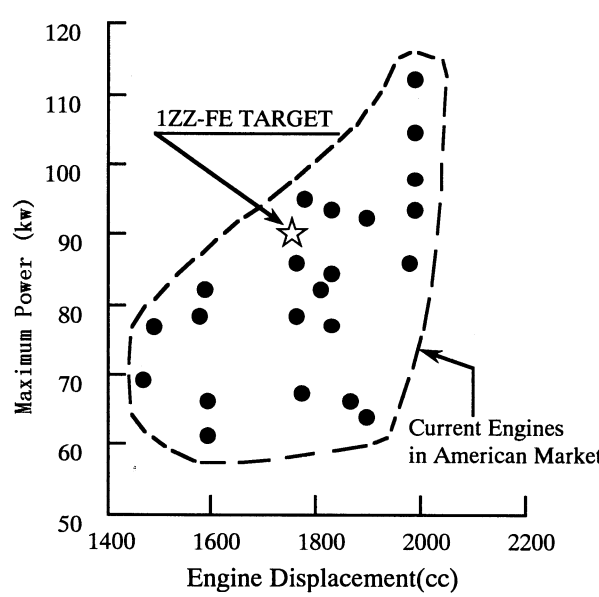


Figure 1. Maximum Power Comparison

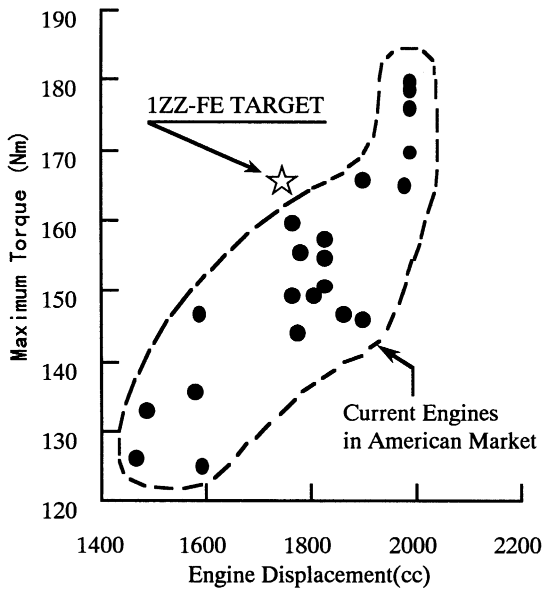


Figure 2. Maximum Torque Comparison

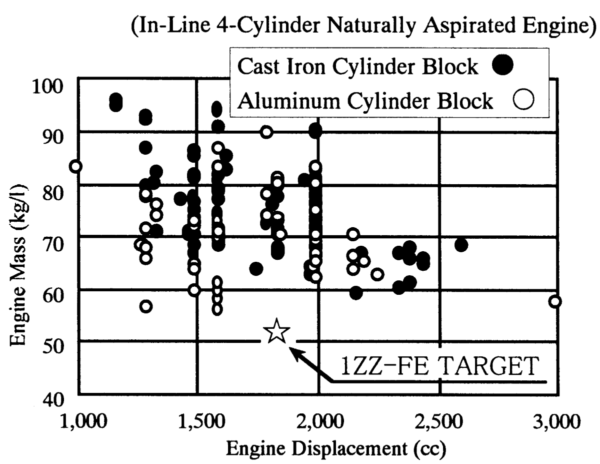


Figure 3. Mass Comparison

SPECIFICATION

Table 1 lists the basic specifications of the 1ZZ-FE engine. Fig. 4 shows cross-sections of the engine and Fig. 5 shows the appearance of the engine and a comparison of dimensions with the previous engine.

Table 1. Engine Specifications

Name	1ZZ-FE
Type	Water-cooled, gasoline, 4-cycle
Displacement(cc)	1794
Arrangement & No. of Cylinders	4-cylinder, In-line
Type of Combustion Chamber	Cross-flow, pentroof
Valve mechanism	4-valve, DOHC, chain drive
Fuel system	Multi-point injection
Bore × Stroke(mm)	79.0 × 915
Compression ratio	10.0:1
Valve head dia.	Intake, 32mm ; Exhaust, 27.5mm
Cylinder bore spacing	87.5mm
Crankshaft pin-journal dia.	44.0mm
Crankshaft main-journal dia.	48.0mm
Connecting rod length	146.65mm
Emission control system	TWC, λ-control
Max. power(Kw/rpm)	89/5600
Max. torque(Nm/rpm)	165/4400
Dimensions(L × W × H mm)	639 × 565 × 62

HIGH PERFORMANCE AND GOOD FUEL ECONOMY

Fig. 6 shows the performance curve of the 1ZZ-FE engine. Compared with the previous engine, the specific fuel consumption has been greatly improved over the entire range. In addition, the engine's maximum output and torque have been improved and, at the same time, a moderate torque curve is achieved by eliminating torque drops in the low-to-mid-speed range for easy-to-handle output characteristics.

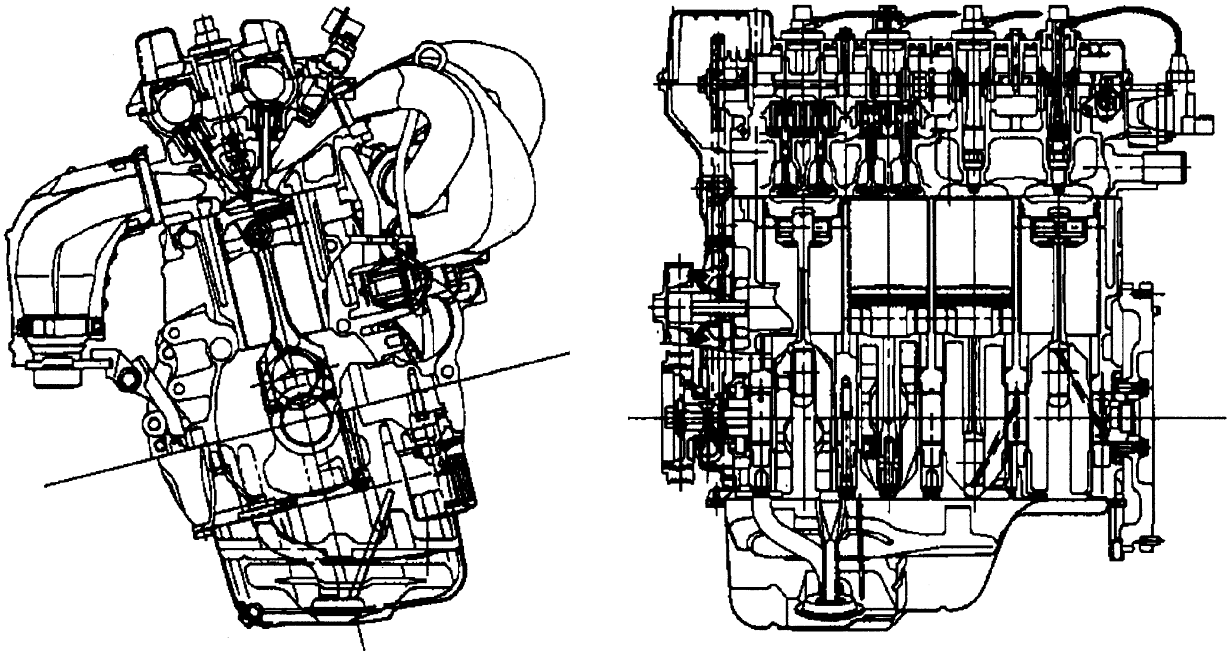


Figure 4.   1ZZ-FE Engine Cross-Sections

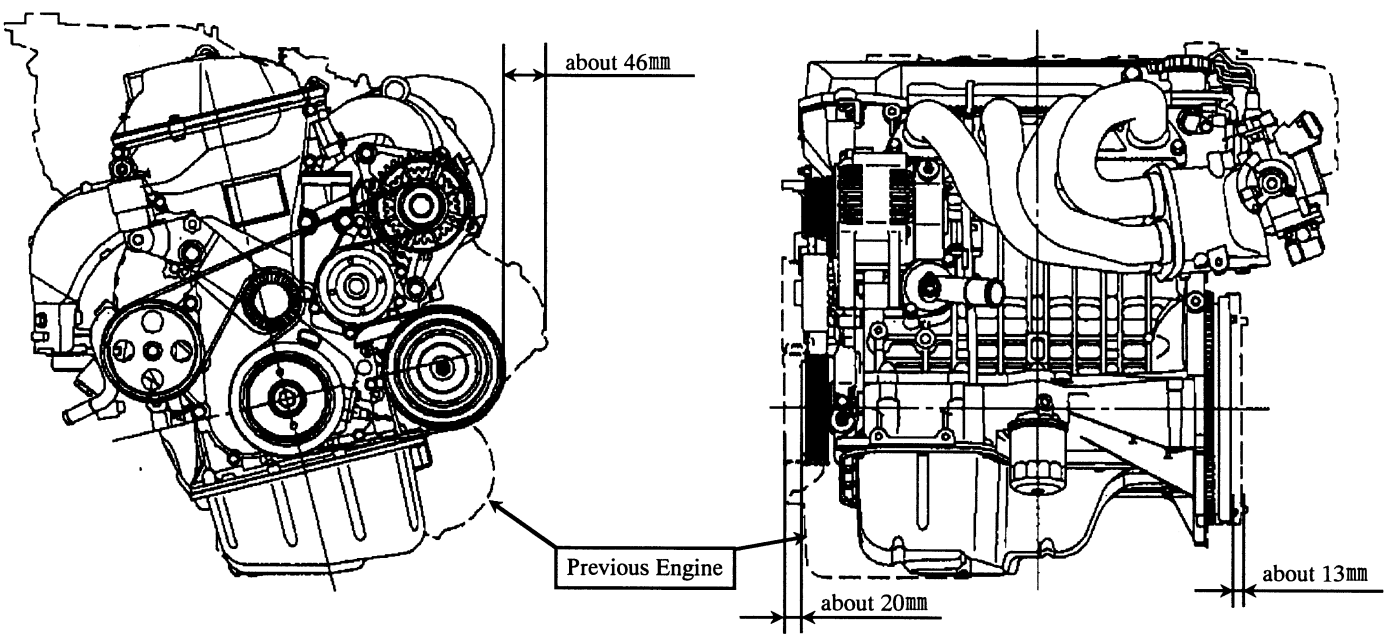


Figure 5.   1ZZ-FE Appearance and Comparison of Dimension

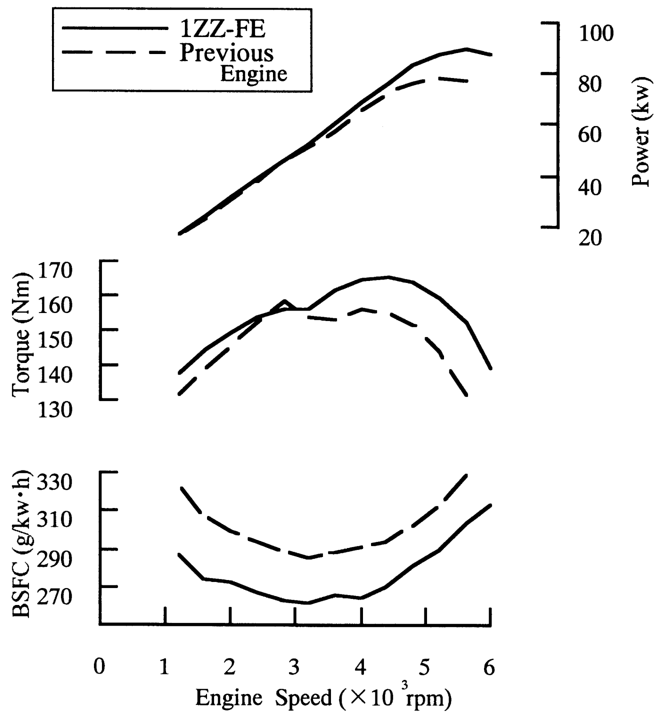


Figure 6. Engine Performance Curves

Regarding actual vehicle fuel economy, a Corolla with a 4-speed automatic transmission achieved 36.8 mpg on the U.S. LA#4 combined fuel economy test mode (FTP and HFET). This represents an increase of approximately 5% over the previous model which had already adopted various technologies to improve fuel economy.

The following paragraphs elaborate on the new technologies incorporated in the engine to achieve said performance, along with a discussion of each of the technologies.

BORE AND STROKE – The bore and stroke for the 1ZZ-FE engine has been optimized for greater fuel economy and examined in Fig. 7. Line (1) in Fig. 7 shows the ratio of improvement in fuel economy over the previous engine when the bore and stroke values are varied in the new engine. It is an estimate based on the relationship between the bore and stroke ratio and the specific fuel consumption of ten different Toyota engine models. In the estimate, the compression ratio, the L/R ratio (the ratio of connecting rod length to crank radius) and the effects of piston ring tension are fixed. It is considered that the longer the stroke, the more compact the combustion chamber, which results in better thermal efficiency and, hence, increased fuel economy. Line (2) in Fig. 7 shows the estimation of specific fuel consumption over the previous engine when L/R ratio is varied in the new engine. An appropriate connecting rod length is selected here by fixing the cylinder block maximum height to restrict the engine's overall height.

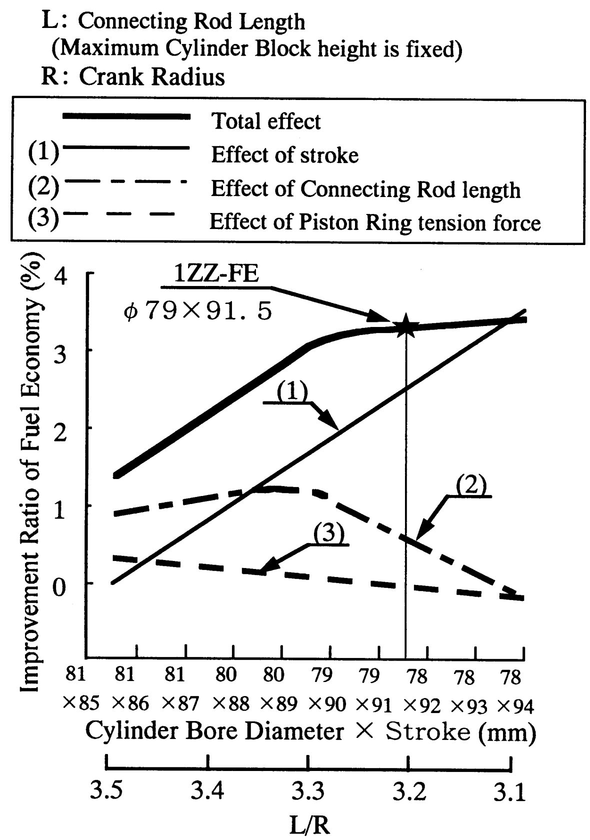


Figure 7. Relation of Stroke to Improvement Ratio of Fuel Economy

This estimation is based on the actual specific fuel consumption that was measured by changing the L/R ratio (λ=3.0, 3.3 and 3.6) of the previous engine. When this ratio is made bigger than necessary, specific fuel consumption cannot be further improved. This is because the increase in the connecting rod mass causes 1 friction to increase. When the stroke is made longer, the piston speed increases, adversely affecting oil consumption. It therefore becomes necessary to increase piston ring tension. Line (3) of Fig. 7 is the estimate made on the influence of this increased piston ring tension on specific fuel consumption. The thick solid line in Fig. 7 is the combination of effects (1) through (3). Following a close discussion, a long stroke (79 × 91.5) has been selected with an L/R ratio of 3.205 for the 1ZZ-FE engine.

Although the fuel specification of the 1ZZ-FE engine is regular gasoline, the adopted high compression ratio (10.0:1) has been achieved with a compact combustion chamber and improved anti-knock quality which is discussed later. Therefore, fuel economy is consistent with high performance.

FRICTION REDUCTION – For the cylinder block, in order to improve cylinder bore circularity and straightness during actual operation, a new cooling system, (which is explained later), has been developed. This, in turn, has enabled a reduction in piston ring tension. Also passage holes are provided in the cylinder block wall located above the crankshaft bearing hole. As a result, the air at the bottom of the cylinder flows smoother, and pumping loss (back pressure at the bottom of the piston generated by the piston's reciprocal movement) is reduced to improve the engine's output. For the crankshaft, in addition to reduced pin diameter, pin length and journal length, the precision and surface roughness of the pins and journals have been improved. Additionally, the crankshaft bearings have adopted single-cut turning to further reduce friction. For the piston, the piston skirt has been shortened to reduce the sliding surface area. For the camshaft, the surface roughness of the journals and cam lobes have been improved and the width of the cam lobes has been reduced to minimize friction.

LASER-CLAD VALVE SEAT – Fig. 8 shows the cross - sections of the laser-clad valve seat and the conventional shrink-fit seat ring type for comparison. The laser-clad valve seat is a layer of highly wear-resistant alloy directly formed in the cylinder head body by using a laser. The laser-clad valve seat eliminates the need for a space in the cylinder head into which separate seat rings are shrink-fit. This has enlarged the valve seat diameter both for the intake and exhaust by 1 mm, thus improving the induction efficiency over the conventional shrink-fit seat ring type. Fig. 9 compares the performance of the laser-clad valve seat in the pre-prototype stage with that of the shrink-fit seat ring. The elimination of the shrink-fit space enabled the water jacket to be placed closer to the valve seat, which has helped decrease the temperature of the combustion chamber wall, thereby enhancing anti-knock quality. All in all, it has been possible to obtain a valve diameter greater than that of the previous engine's despite a more compact combustion chamber and a smaller bore, thanks to the adoption of the laser-clad valve seat and the enlarged valve angle.

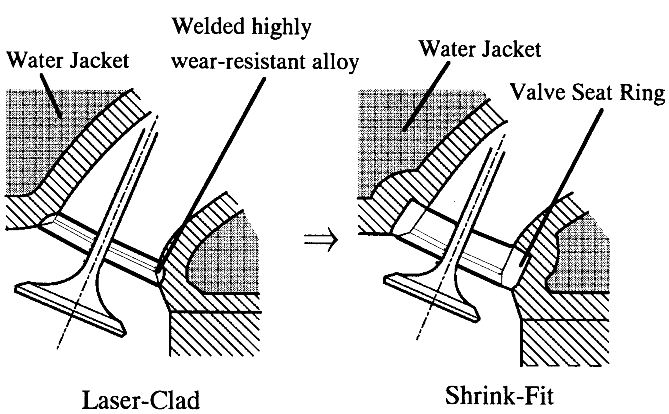


Figure 8. Adoption of Laser-Clad Valve Seat

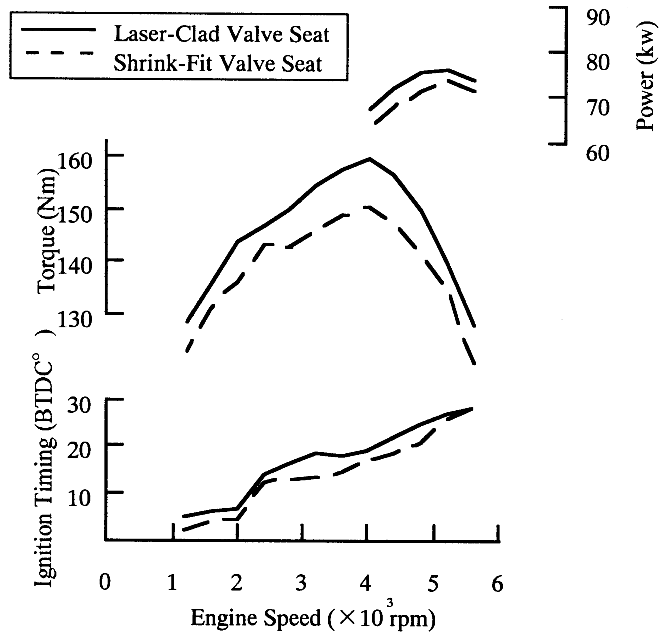


Figure 9. Effect of Laser-Clad Valve Seat

TAPER SQUISH COMBUSTION CHAMBER – The squish area formed by the piston top and cylinder head bottom surface has been tapered by being inclined along the cylinder head combustion chamber wall (Fig. 10) . This taper squish shape reduces the masking portion around the intake valve when it is open, increasing intake air volume (Fig. 11). Moreover, in the early stage of combustion, this taper squish helps combustion pressure to increase gradually and, at the latter part of combustion, increases the burning velocity (Fig. 12), thereby en-hancing anti-knock quality. It is inferred that the increase of flow velocity to the squish area promotes the flame propagation to the end of the squish area upon piston descent (Fig. 13). Fig. 14 shows the benefits of the improved performance in the prototype stage.

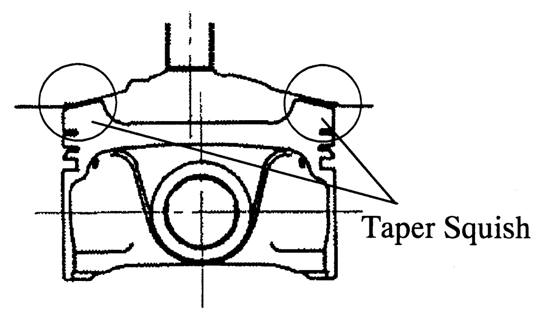


Figure 10. Taper Squish Combustion Chamber

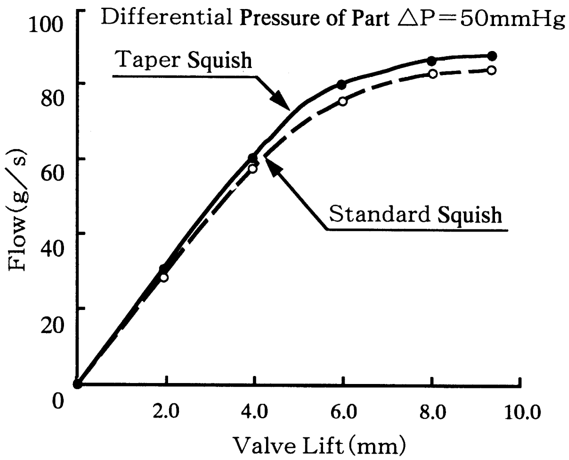


Figure 11. Comparison of Flow Rate Characteristics

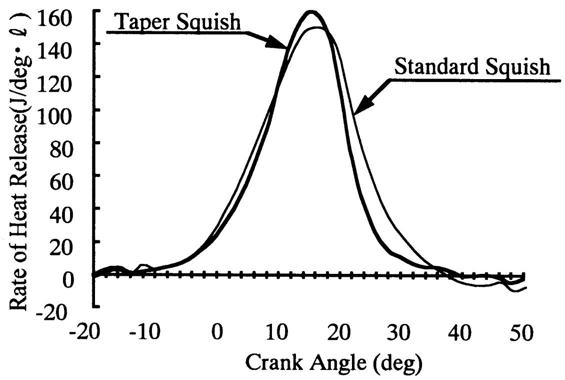


Figure 12. Comparison of Combustion Pattern

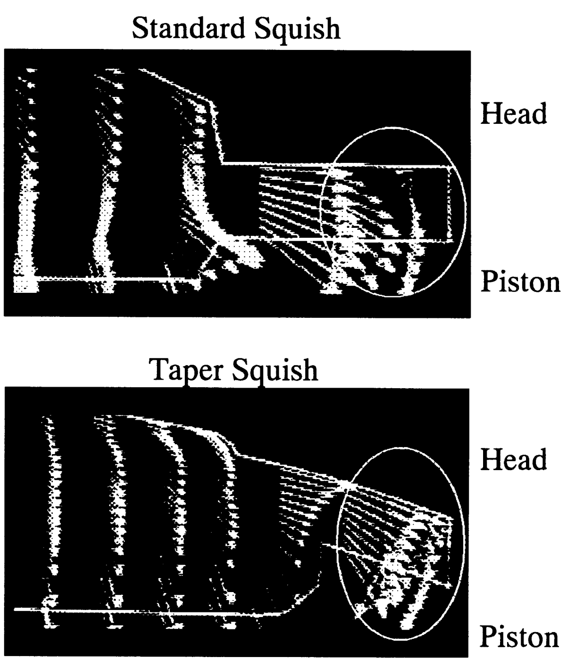


Figure 13. Comparison of Flow Velocity at Squish Area (CFD Simulation)

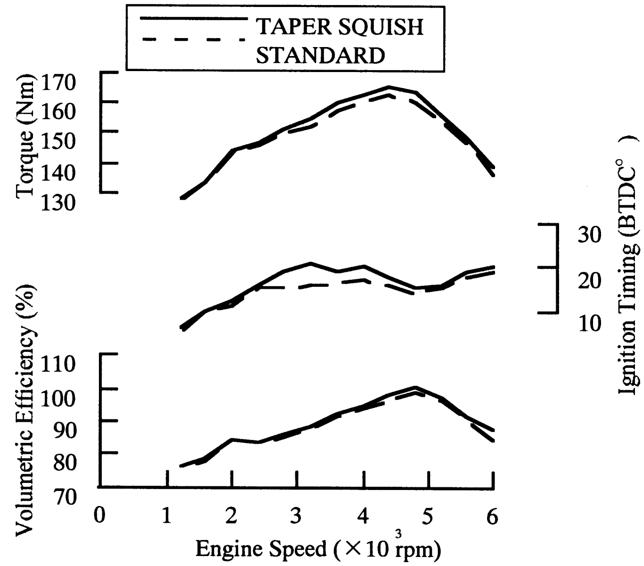


Figure 14. Effect of Taper Squish Combustion Chamber

COOLING SYSTEM – The flow of the engine coolant makes a U-turn in the cylinder block to prevent stagnation, thereby ensuring uniformity of the cylinder bore wall temperature between the cylinders. The entire coolant mass flows up from the cylinder block to the front of the cylinder head and then front to the rear (Fig. 15). This increases the flow velocity in the cylinder head, which helps decrease the combustion chamber wall temperature. During the basic planning stage of 1ZZ-FE, CFD was used practically to develop this cooling system construction and these passage areas.

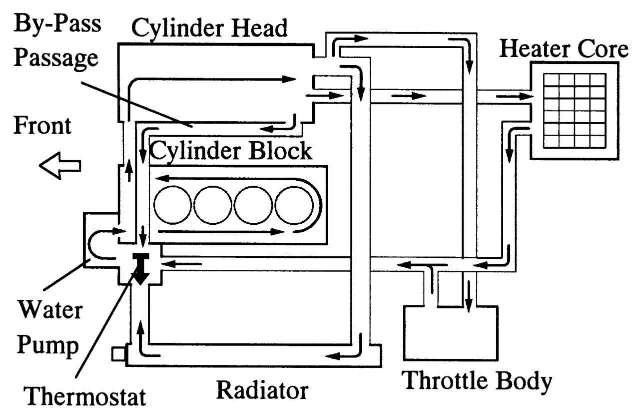


Figure 15. Cooling System

IGNITION SYSTEM – A DIS (Direct Ignition System), which eliminates the distributor, was adopted in the 1ZZ-FE engine to improve the ignition timing accuracy with a high compression ratio and to enhance the overall reliability of the ignition system. This system consists of a crankshaft position sensor which directly detects the crank position from a sensing plate attached to the front end of the crankshaft, a phase sensor which detects cylinder number by a boss on the rear end of the intake camshaft and two sets of ignition coils integrated with the igniter.

INTAKE MANIFOLD – An aluminum pipe is used as the intake manifold. It has been bent and shaped into a three-dimensional form, allowing a lightweight and compact intake manifold with a large diameter and a long port (41 × 413) to be employed for improved low-to-mid-speed torque. The sections from the throttle body through each port have been connected in a straight line to prevent a drop in induction efficiency at high-speed due to turbulence (Fig.16).

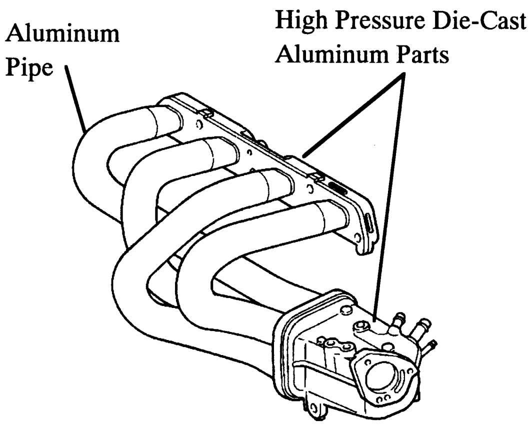


Figure 16. Intake Manifold

LIGHTWEIGHT AND COMPACTNESS

The following innovative technologies have been incorporated to make the new engine 23% lighter (Fig.17) and more compact by 15mm in overall length, 27mm in overall width, and 19mm in overall height, when compared to the previous engine. The length from the front end of the crank pulley to flywheel has also been shortened by 33mm to make the overall length of the power plant shorter. This improves the ease of installation in front-engine front-drive vehicles.

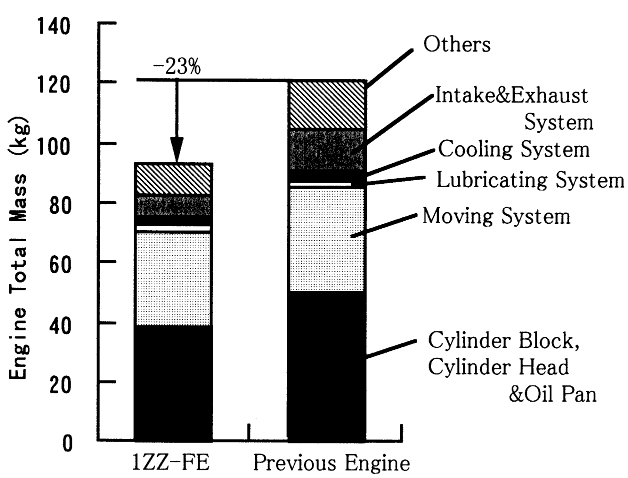


Figure 17. Engine Mass Comparison

CYLINDER BLOCK – The cylinder block is a high-pressure aluminum die casting of an open-deck con-struction with thin cast-in iron liners. It is 32% lighter than the previous cast iron block and offers greater production efficiency. The water pump swirl chamber, the inlet housing and by-pass passage lead are integrated into the high-pressure aluminum die-cast cylinder block, contrib-uting to a compact body. To counteract casting cavities which can occur in the thick wall portions produced from body integration and at the crankshaft main journals, the production procedure uses a pin to squeeze these thicker portions (Fig.18).

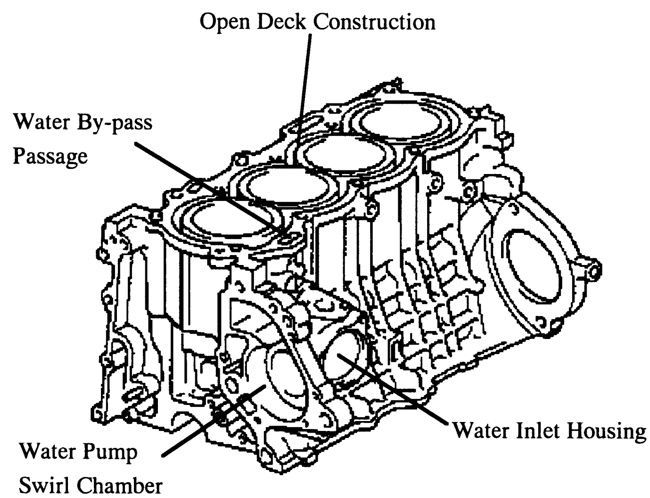
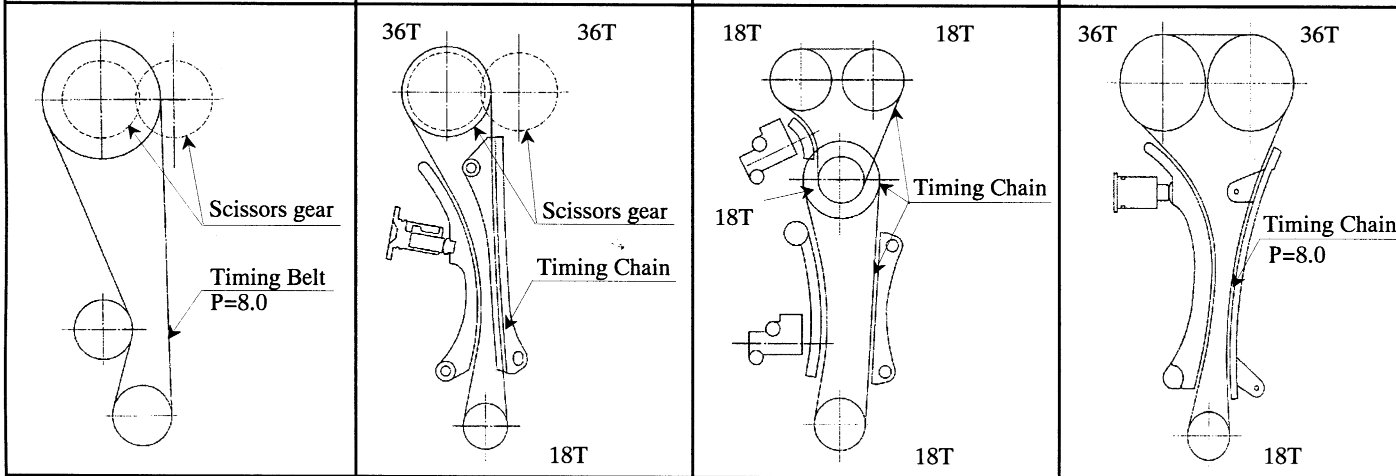


Figure 18. Cylinder Block

CAMSHAFT DRIVE SYSTEM – The four different chain drive systems shown in Fig. 19 were considered for determining the basic specifications. The timing belt in No.1 is the lightest, though system No.4, which uses a single chain to directly drive both the intake and exhaust camshaft from the crankshaft, has been found to be advantageous. It uses a small-pitch (8mm) chain to make the system affordable in terms of the overall length, the number of parts used and cost. In drive system No.4, it is necessary to provide a wider pitch between camshafts than in drive system No.1 even though the cam sprockets were made smaller by adopting the small-pitch chain. Nonetheless, it meets the dimensional requirements originally planned for 1ZZ-FE and was thus adopted. The chain cover generally takes up a large percentage of the chain drive system in terms of mass and cost. In 1ZZ-FE, the chain cover has been integrated with the water pump swirl chamber cover and accessories bracket, thereby realizing an even lighter, more compact cost effective system than that examined in Fig. 19.

	No.1	No.2	No.3	No.4



	No.1	No.2	No.3	No.4
Mass Comparison(%)	100	126	121	110
Min.Camshaft Pitch(mm)	75	75	75	96
Reduction of Engine overall length(mm)	0	-8.8	-8.8	-8.8
Number of parts Comparison(%)	10	109	100	88

Figure 19. Comparison of Camshaft Drive System

ACCESSORIES LAYOUT – For the accessories drive, a serpentine belt drive system has been employed which uses a single V-ribbed belt. Since it requires only one crank pulley stage, the overall length has been shortened. Further, the use of a bracket for the exclusive purpose of mounting each accessory to the engine body has been eliminated for weight reduction. At the same time, by not using the bracket, each accessory can be mounted closer to the engine, which contributes to an overall smaller cross-wise dimension.

OTHER TECHNOLOGIES – The thickness of the flywheel mounting flange on the crankshaft has been reduced to shorten the overall length of the power plant. The overall height of the engine has been reduced by changing the shape and layout of the intake manifold. And the cylinder head cover shape has been changed to minimize the increase of the overall height by adopting the longer stroke. In addition to the intake manifold, stainless pipe is also used for the exhaust manifold to drastically reduce the weight of the intake and exhaust systems. At the same time, these pipes can deform during a frontal impact, lengthening the shock absorbence zone at the front of the vehicle.

CLEAN EMISSIONS

The intake and exhaust systems are laid out in reverse compared to a traditional layout so that the exhaust manifold is located at the rear of the engine when it is in a front-engine front-drive vehicle. This made the distance between the engine and the under-floor converter shorter and improved the warm-up performance of a converter. Thanks to this exhaust system layout, the under-floor converter has the same warm-up performance as the manifold converter which has traditionally been located on the front side (Fig. 20). Instead of the conventional two-hole injectors, the new engine is equipped with four-hole injectors which are capable of atomizing fuel into even finer particles. The injector is mounted in the cylinder head, thereby reducing the distance between itself and the combustion chamber. This helps prevent fuel from adhering to the wall surface at the intake port, thus reducing HC emissions and improving fuel consumption. This arrangement has made it possible to comply with the U.S. TLEV emission regulation without using a manifold converter or a start catalyst and elimination of the EGR system was also made possible. At the same time, it has enabled us to cope with future regulations which will become even more stringent.

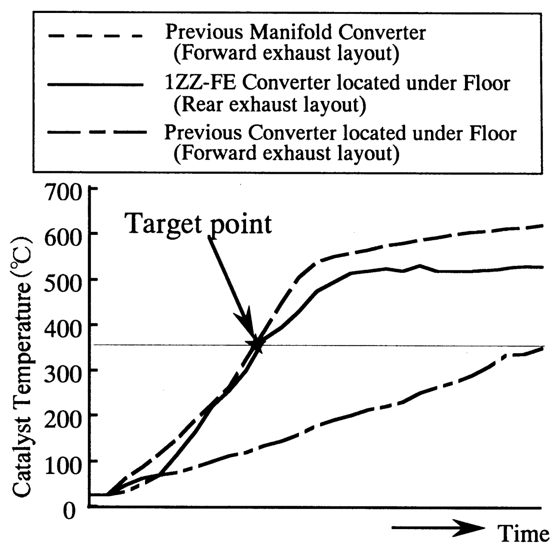


Figure 20. Catalyst Warm-up Performance

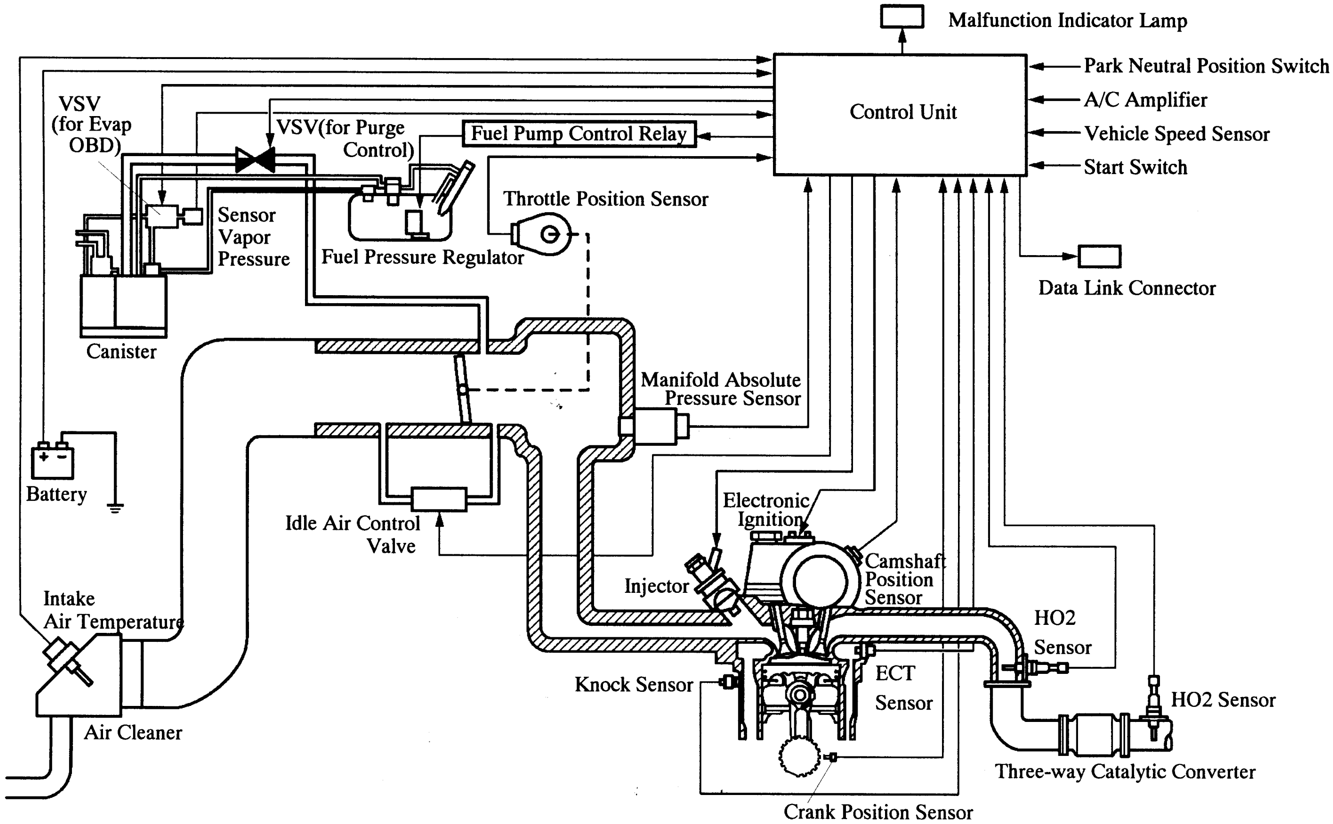


Figure 21. Engine and Emission Control System

ENGINE CONTROL – To further improve drivability and emission control performance, the following technologies were adopted.

1) Individual injection system with 4-hole injector.
2) Twin O2 sensor system
3) Knock sensor system

Fig. 21 shows the engine and emission control system.

QUIETNESS

REDUCTION OF RAMBLING NOISE AND BOOMING NOISE – The cylinder block is a half-skirt construction in conjunction with a high-pressure aluminum die-cast lower crankcase which ensure better sound dampening performance than that of a conventional aluminum oil pan. This reduces the number of parts used, lowering overall costs (Fig. 22). The lower crankcase is of a ladder-frame construction with cast iron crankshaft bearing caps cast-in. A reinforcement rib has been added to its rear end, as in the cylinder block, and a stiffener plate has been integrated to enhance the overall rigidity of the power plant. These shapes are designed based on FEM analysis. In addition to improved rigidity, these added stiffeners also reduced an opening located beneath the No. 3 and No. 4 cylinders, which could be the wave node of power plant resonance in a 4-cylinder engine. Compared with a cast aluminum oil pan construction, cost reduction was attained by either integrating or eliminating a total of 15 parts, including crankshaft bearing caps and a rear oil seal retainer. Fig. 23 compares 1ZZ-FE's lower crankcase construction to a conventional cast aluminum oil pan construction in terms of vibration and noise levels.

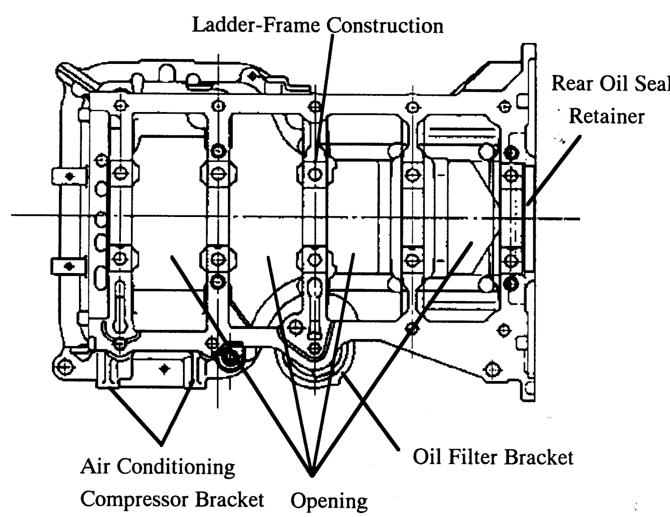


Figure 22. Lower Case

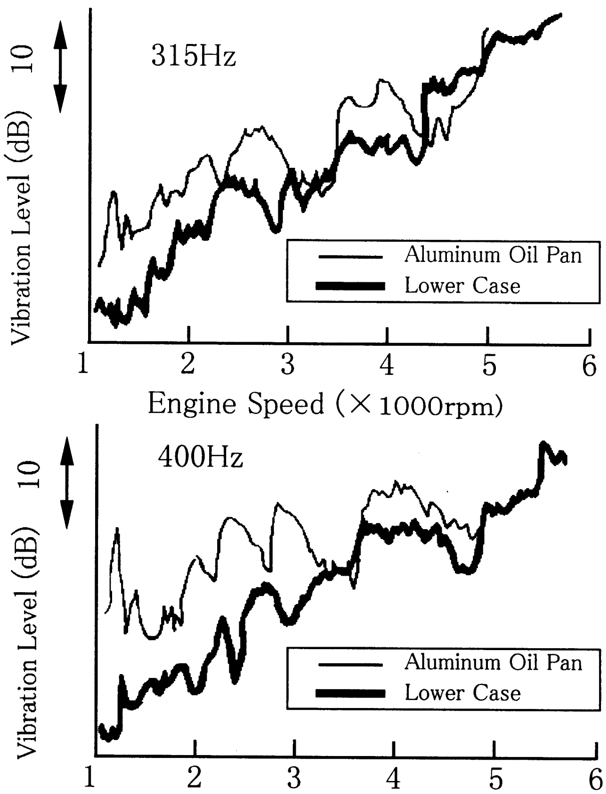


Figure 23. Effect of Lower Case

Bending resonance at the overhang from the crankshaft main journals at the front and rear ends of the crankshaft is a possible cause of rambling and booming noise. In this engine, the crankshaft front and rear ends have been made shorter, as we touched upon earlier in this paper, thereby raising the resonance point. In addition, the mass of 15% of all parts that make reciprocating motion has been reduced, which has resulted in a reduction of 12% in rotary secondary reciprocating inertia force. The mass of moving parts in the valve train has also been reduced by about 20%, thereby reducing excitation forces. Fur-ther-more, to improve timbre of the intake system, the length of each port up to the surge tank and throttle valve of the intake manifold has been made equal to each other, which reduces the semi-primary component of noise.

REDUCTION OF RADIANT NOISE – To reduce radiant noise from the engine, curved surfaces and ribs were placed at optimized locations on the side of the cylinder block and lower case. The lower case with ladder-frame construction, however, had no adverse effect on radiant noise from the lower case side. As to the chain system, by employing a small-pitch single roller type chain, contact noise between the chain and the sprocket has been reduced. At the same time, the chain cover surface has been made into a curve with steps added to the curve to avoid large flat-surface areas, thereby enhancing surface rigidity.

PARTS REDUCTION

Some parts have been built into large-sized parts such as cylinder block and cylinder head. Also, shimless lifters have been employed and the scissors gear has been eliminated. All this adds up to a 23% parts reduction.

GOOD SERVICEABILITY

To simplify the service jobs performed in the field, an automatic tensioner for the V-ribbed belt has been employed. This makes the inspection and replacement of the V-ribbed belt much easier. To further incorporate main-tenance-free parts, a timing chain and DLI (distributor-less ignition) have been employed, which eliminates the need of inspection and service jobs for these parts.

SIMULTANEOUS ENGINEERING

In the basic planning stage of the 1ZZ-FE engine, production technologies which can be incorporated into the new engine or possible topics of production technologies to be developed in line with the development of the engine have been examined with the in-house production technology divisions and suppliers. To improve performance, a mass-production technology of laser-clad valve seat has been developed. To achieve lightweight and compactness, a technique has been developed (touched upon earlier in this paper) that uses a squeeze pin to prevent casting cavities from occurring in the die-cast aluminum cylinder block. Technology for welding to high-pressure die-cast aluminum parts has been developed for the intake manifold, thus making the engine lighter in weight and improving production efficiency. By adopting 3D design for the cylinder head, die construction and production efficiency could be evaluated in the early stages of development. This enabled shorter prototype lead times. Working towards the goal of reducing the number of parts used, a highly productive automatic shimless lifter assembly line has been developed to eliminate shims. Other technologies which have been developed along with the development of the new engine include: a cost reducing technology that rolls the ring gear of the fly-wheel in one-piece and the parts-integrating, low cost casting method for the high-pressure die-cast aluminum cylinder block lower crankcase. In addition, to ensure ease of assembly, the entire development stage starting with the initial prototype conception has been examined to employ structures which permit easy installation and reduce the number of fastening parts.

CONCLUSION

The 1ZZ-FE engine has improved fuel economy without any special device by optimizing basic specifications and adopting new technologies to each component. With all the new technologies explained in this paper, the 1ZZ-FE has satisfactorily achieved the targets cited earlier, balancing performance, fuel eco-omy, mass, compactness, and exhaust emissions at a high level. This will make it possible to meet market requirements worldwide.

ACKNOWLEDGMENTS

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