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Subaru New Horizontally Opposed 4-valve Engine

Masayuki Kodama, Takemasa Yamada and Shuji Sawafuji
Fuji Heavy Industries Ltd.

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ABSTRACT

For the 1990 model year Fuji Heavy Industries will introduce Subaru "Legacy" with a newly designed horizontally opposed 4-valve engine series including a 2.2 Lt for the US market.

The new engine series which has been named "Boxer" to symbolize power has been designed and developed making the best use of the advantages of horizontally opposed engines and our twenty three years experience in producing them.

The major advantages of horizontally opposed engines are low noise and vibration, with high specific power and design flexibility which are well featured in these new engines.

This paper is intended to provide a brief overview of the new engine program with descriptions of unique design features.

INTRODUCTION

After the last oil crisis in the early 1980's, the market tendency for the automobile engine has been toward higher specific power with much emphasis on low and medium speed torque, and more design flexibility to satisfy customer's various preferences.

To meet these market demands, Subaru started to develop an entirely new engine series from about four years ago.

The task force called NEP (New Engine Project) was formed to analyze present status, and to establish initial engine concept.

Most of the members of the project were under thirty years old.

It is our basic philosophy to supply customers with a niche in an individualized and over supplied market place, and it is necessary to create engines of high power and sufficient design flexibility.

In 1966, the front wheel drive (FF) "Subaru" with horizontally opposed 1.0 Lt engine was first introduced for the Japanese market when the most of the cars had the front engine and rear drive (FR) layout of those days.

Though the engine and transmission of the "Subaru" was mounted longitudinally in the same manner as the other FR vehicle, FF was possible because of the short length of the engine.

The reason for the selection of FF was for its high path controllability which we have been persueing as our basic philosophy.

In 1972, the four wheel drive (4WD) "Subaru" was introduced using the same drive train layout with the rear wheel drive system added to obtain higher traction and path controlability.

The advantages of our drive train layout, applied on the "Subaru" for twenty three years are as follows.

- no 2nd order shaking force
- light power plant weight
- good weight distribution
- low power plant gravity center
- low engine height for slant nose

Recently, the market tendency is toward the better maneuverability for which the popular FF transverse layout may not be adequate for high output engine.

Accordingly some high power vehicles adopt FR because of its good weight distribution. However, we believe, to meet these market demands, our layout is the best because of the merits mentioned above.

Furthermore, when the more sophisticated control technique such as 4WD MP-T or torque split mechanism is combined with this drive train layout, it is possible to supply the market with more niche vehicles of higher performance with maximum controllability.

Of course, the drive train layout is not only suitable for such a high performance car, but also is fitted to an economical car because of its high flexibility such as we have produced for years on some models.

For a car with high path controllability, the engine with high specific power is required and to be compatible with the highly flexible drive train layout, the engine with sufficient design flexibility is also needed, both of which are the development objectives of the "Boxer" engine.

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ENGINE CONCEPT

When designing an engine of high performance and sufficient flexibility, what is most important is engine rigidity which is the root of all engine requirements such as high power, reliability, fuel economy, low noise and vibration, low friction etc.

The horizontally opposed engine consists of two relatively short crankcases tightened together by bolts on each crankshaft bearing housing, which results in the higher strength with less weight than other engine layouts.

Seeing that the recent tendency to adopt balancer shafts on relatively large volume in-line four cylinder engines, to cancel 2nd order shaking force, the horizontally opposed engine has been found to be less expensive than those engines with balancing shafts.

We, therefore, took it to be quite natural to inherit the advantages of the "Horizontally Opposed Engine" and as a result, we believe, this new engine series has achieved the development objectives of perofrmance and design flexibility with the highest level reliabilities.

The basic common structures of the new horizontally opposed engine series are a water-cooled, five bearing crankshaft, aluminium high pressure die-cast crankcase and four-valve per cylinder of either DOHC or SOHC.

The fig. 1 and 2 show the longitudinal and cross-section of the 2.2 Lt SOHC engine of US version and 2.0 Lt DOHC Japanese version.

DESIGN FEATURES AND PHILOSOPHY

To design a highly rigid engine, homogeneity has been our important design feature, because any local high stress or temperature always causes some trouble.

The engine of the previous model had three crankshaft main bearings, therefore right and left crankcases are bolted in three places. However, the new engine has five bearings, and the crankcases are also secured in five places.

This not only increases the entire engine rigidity but also homogenizes the engine stiffness.

Looking at table 1, maximum horse power of 220 PS is obtained in the 2.0 Lt DOHC with turbo charger and intercooler, of which weight is only 147 Kg owing mainly to this homogenized stiffness of the engine.

A great deal of attention has been also paid to secure the necessary homogeneity, such as cooling, lubricating, fuel and air supply system too.

Beside homogeneity, "well balanced" has been the 2nd major design feature to be accomplished. This is best realized in the valve train mechanism of this engine.

Generally speaking, a horizontally opposed engine has a larger bore and smaller stroke than other engine layouts to shorten engine width, and a cylinder pitch per bank is also longer because half of the cylinders are located on each bank.

When applying a complicated multi valve mechanism, the characteristics of a horizontally opposed engine give relatively large useable space around the cylinder head to the designer without any unoptimized component or combination of elements.

In the SOHC four valve engine, keeping the valve diameter the same as other DOHC engine layouts, it is possible to locate the spark plug in the center of cylinder to shorten the flame travelling distance with a "well balanced" combustion chamber and a highly rigid valve train. Further every detail of the engine design has been checked in this respect to beeing "well balanced" mechanism.

As mentioned before the engine design flexibility is the major objectives of the development to meet any market demand.

One of the design features to realize this was a high power (over 100 PS/Lt) and normal power engine (60 PS/Lt) could share the same structural dimensions without causing any cost or weight penalty to each other.

Seeing that the weight of 1.8 Lt engine in the table 1, which has the same basic dimensions as the 220 PS engine, is comparable to other engines

Displacement (cc)	1820	1994	1994	2212
Bore×stroke (mm)	87.9×75	92×75	92×75	96.9×75
Valve mechanism	SOHC 4valve	DOHC 4valve	DOHC 4valve	SOHC 4valve
Compression ratio	9.7	9.7	8.5	9.5
Fuel system	SPI	MPI	MPI	MPI
NA or Turbo	NA	NA	Turbo	NA
Max power (ps)	110/6000	150/6800	220/6400	132/5400
Max torque (kgf・m)	15.2/3200	17.5/5200	27.5/4000	19.0/4400
Max rpm	6500	7500	7500	6500
Weight (kg)	118	130	147	121
Market	Japan	Japan	Japan	USA

Table 1 "Boxer" engine discriptions

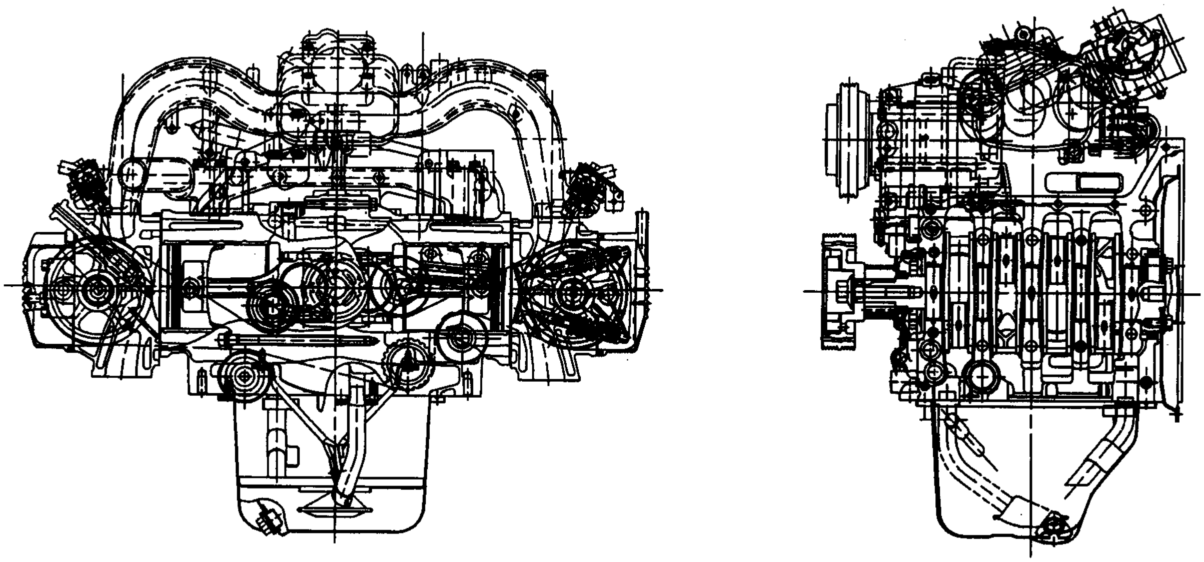

Fig. 1 2.2 Lt SOHC 4 valve US version

with almost the same performance and weight, we believe that our initial targets have been successfully achieved.

The other major objective of this program was to develop the more efficient engineering systems, so that the development time could be shortened while using advanced technology.

A CAD system has been utilized from the beginning and through the entire development period there has never been a drawing done by hand.

The design study speed is about three to ten times faster than by hand while enabling us to select the best one among many studied alternatives.

Many CAE methods have been developed, some of which were installed in CAD systems for on-line analysis to avoid any interruption of the designer's thinking.

However, at the same time, much efforts have been paid to reflect the designer's "craftsmanship" on the engine design because it is impossible to evaluate the entire design itself in the sense of homogeneity and "well balanced" only through FEM or any other CAE method except by an engineer's design sense.

Production facility flexibilities were none the less important than those of the engine to meet ever changing market demands.

Manufacturing engineers were assigned to work closely with the project members so that the new "Boxer" series engine was sufficiently compatible with new production technologies. Furthermore, the engineers from the main component suppliers were also consulted from the first of development

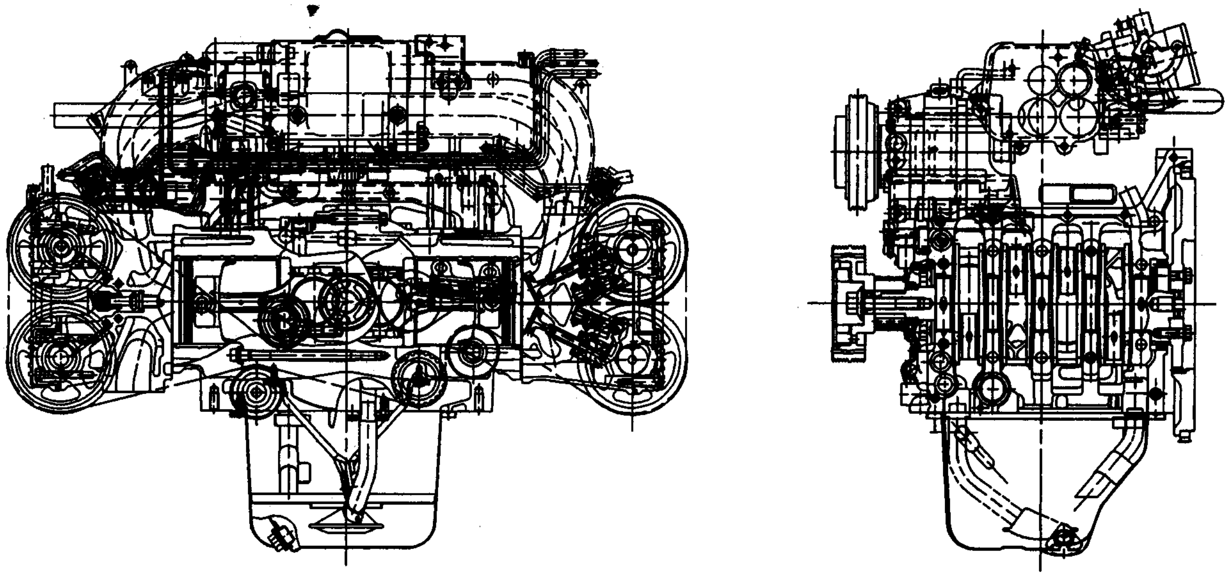

Fig. 2 2.0 Lt DOHC 4 valve NA Japanese version to ensure that parts could be supplied within required quality and cost levels.

TECHNICAL FEATURES

CRANKSHAFT AND MAIN BEARINGS

The crankshaft is made of forged high carbon steel with five main bearings and eight counter weights.

Extensive analytical works were done at the start of an engine design applying the state of the art analysis techniques. Main and connecting rod bearing load, oil film thickness, and dynamic stress analysis with the fly wheel attached were major items to be studied. (See fig. 3)

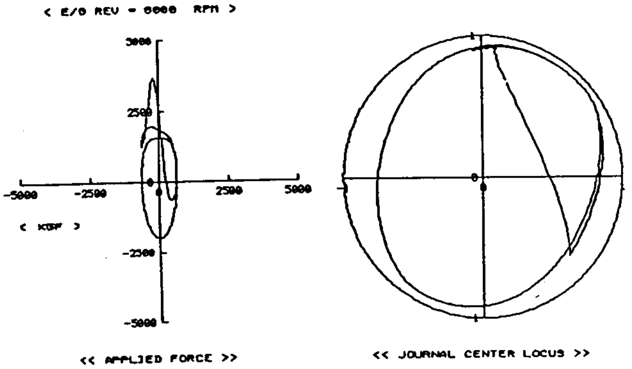

Fig. 3 Bearing load and oil film thickness

Differing from an in-line engine, the main and connecting rod bearings and web widths are the major determinants of entire engine length in horizontally opposed or V type engine.

The large overlap of main journal and crankpin allow extremely thin crankwebs, resulting in light weight, and short overall length. (See fig. 4)

The diameter of the main bearing is 60 mm and 52 mm for the connecting rod which seems a little larger than other layout engines with 18.5 mm overlap.

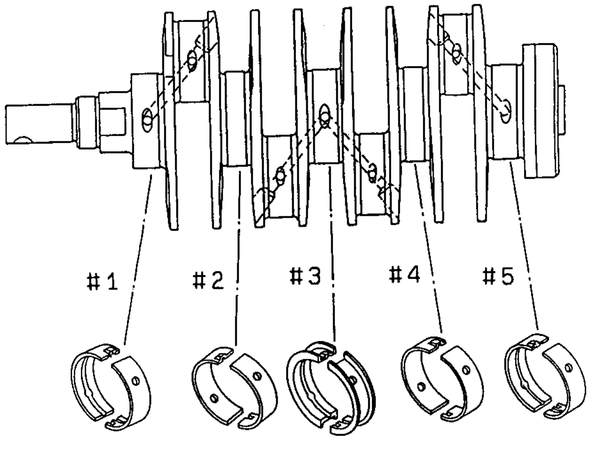

Fig. 4 Crankshaft and bearings

However, our analysis shows that the stiffness increase of a crankshaft associated with a large overlap has sufficient effect on decreasing overall metal friction more than the increase caused by the larger metal bearing diameter.

The counter weight effect on metal load decrease is 16% at 6000 rpm at full throttle (NA) on #1, 3, 5 bearings.

The axial thrust bearing with integral thrust collars is placed at #3.

The main journals and crank pins have circumferential fillets that are deep rolled for fatigue strength improvement.

The metal clearance of DOHC with turbo engine is controlled within narrower tolerance than a normal engine. A double mass harmonic balancer is adopted to disperse the torsional and bending vibration up to the 7500 rpm of maximum operating speed. (See fig. 5)

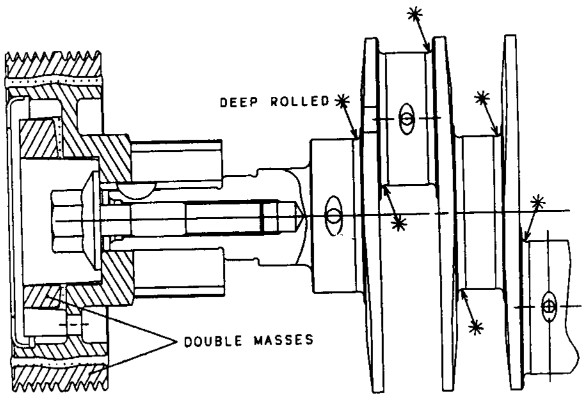

Fig. 5 Fillet roll and double mass damper

CRANKCASE

The crankcase is made of high pressure die cast aluminium with cast-in cast iron cylinder liners--dry liners. The crankcase overview is shown in fig. 6.

One of the most difficult aspects of designing high pressure diecast aluminium crankcase is the oil passage, because drilling an oil passage is almost impossible because of oil leaks caused by cavities within the cast aluminium.

More than 50 cases had been studied before we could make a satisfactory oil passage with no machining, some of which are shown in fig. 7.

From the start of the engine development, the metal molding design to cast a crankcase proceeded to secure casting productivity and to meet the manufacturer's capabilities.

Light weight, high rigidity, and good cooling characteristics were achieved by adopting the open-deck configuration.

The horizontally opposed cylinder arrangement requires two separate crankcase right-hand-side and left-hand-side.

The heads of the tightening bolts of the two

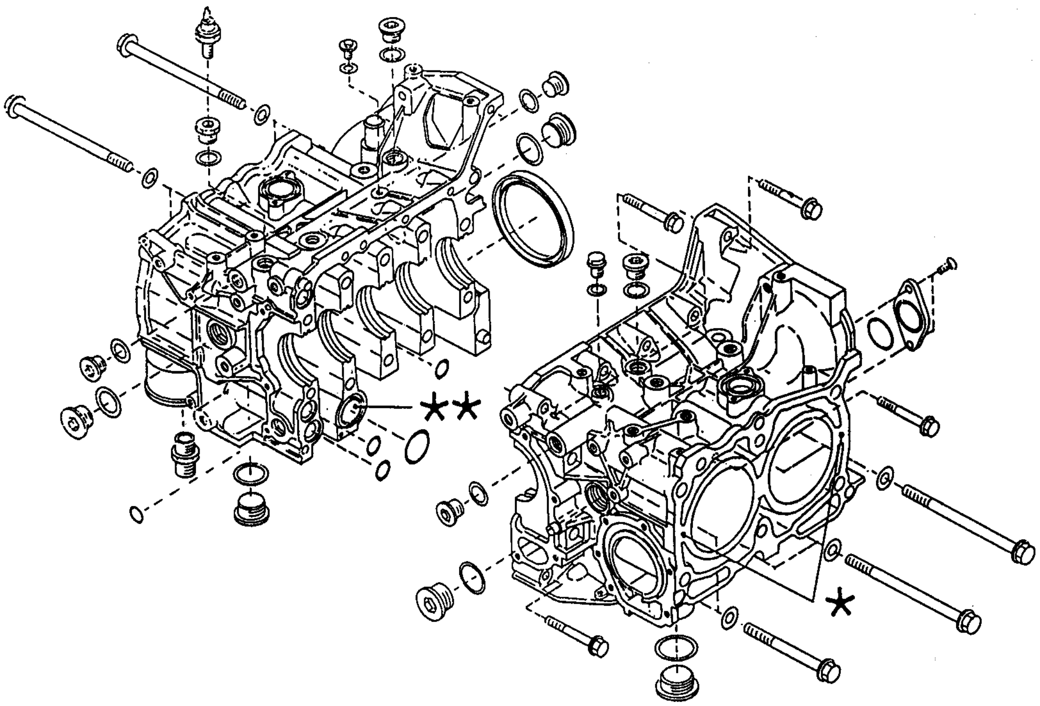

Fig. 6 Crankcase

opposing cases are placed in the water jackets in order to minimize the bolt pitches.
Special sealers are used for the bolts.

Another interesting feature of this crankcase is a water dam which separates the water jacket into upper and lower sections.
(See fig. 6 * mark)
This works not only for the homogeneized cooling but is also effective to increase the rigidity of the entire crankcase and cylinder bore.

The cylinder pitch is 113 mm which is relatively long making for better cooling between the two cylinders.

For the DOHC 2.0 Lt turbo version, medium pressure diecast aluminium crankcase is utilized to secure the higher rigidity necessary with a closed deck. The sand core with a special surface treatment is incorporated within this medium pressure diecasting. The bank off-set is 54.5 mm.

At the front center of the crankcase, the oil pump is located which is driven by the crankshaft. The water pump is mounted on the front left, so the space caused by the bank offset is well utilized.
The water passage from left to right crankcase is under part of #2 bearing housing as seen in fig. 6. (** mark)

FEM and other CAE methods were applied to optimize the crankcase structure, especially on the bore distorsion analysis and effective allocation of ribs around the head bolt bosses.

CONNECTING ROD AND ROD BEARING

The connecting rod and cap are made of forged steel with a lead-bronze bushing pressed in at the small end for the full floating piston pin to achieve maximum durability. (See fig. 8)
The rod bolts are machined with spiral spline on their reamed portion and lightly press-fitted in to the connecting rod. The bolt diameter is 9 mm.

Particular care has been taken in design of the connecting rod to minimize its mass including

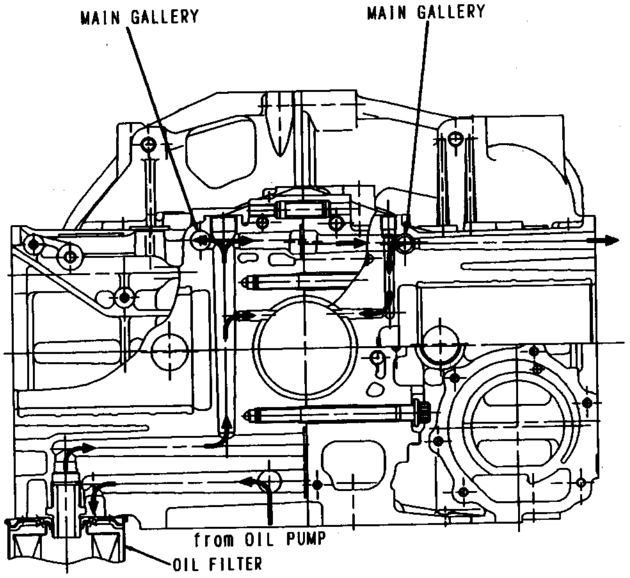

Fig. 7 Oil passage from filter to main galleries

the piston, because moving part masses play an important role in noise and vibration even in a balanced engine as an over-all and the internal forces applied within an engine locally have a great acoustic effect.

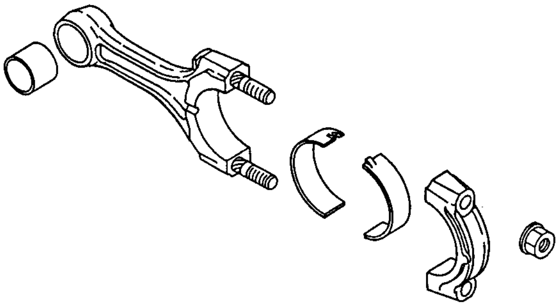

Fig. 8 Connecting rod

FEM has been used also for the purpose to optimize cap shape so as to minimize rod metal width taking into account a cap deformation. An infrared stress analysis method was adopted to confirm the results.
The aluminium base sinter metal is used as a connecting rod bearing material, because of its excellent affinity to the steel crankshaft.

PISTON AND PISTON RINGS

The piston is made of heat resistant and low expansion cast aluminium alloy, having the slapper type skirt which saves weight and contact area. (See fig. 9)

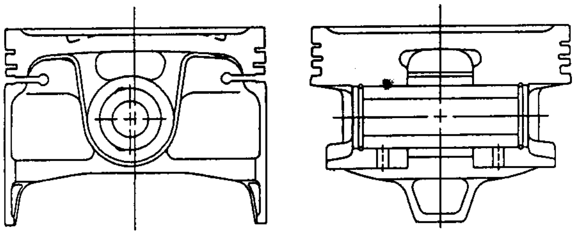

Fig. 9 Piston of 2.2 Lt

The piston pin is offset from the centerline of the piston in order to eliminate piston slap noise. The piston head has depressions for valve head clearance.

The piston for the normal power version is a slit in oil ring groove type to regulate the heat flow from piston crown to the skirt area to keep piston clearance relatively small for less noise.

On the other hand the high power version piston is a thermalflow type to stand the high heat load at full throttle.

However, unlike other high performance engines with cast iron crankcase, what is called autothirmatic piston is not necessary because of the aluminium crankcase.

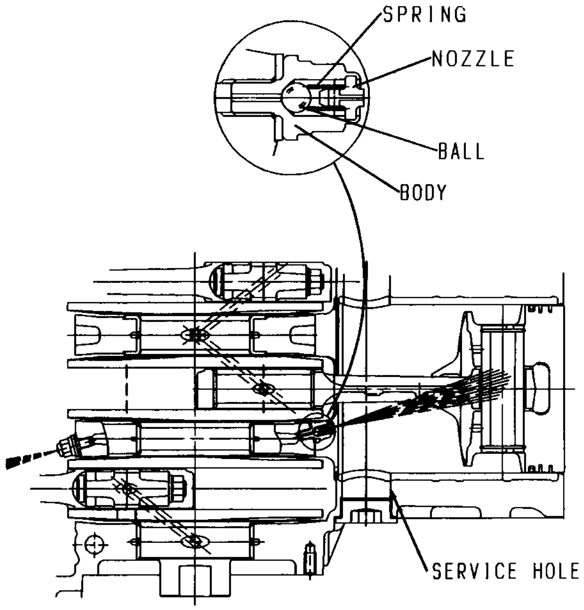

Fig. 10 Service hole and oil jet

To ensure correct heat distribution, oil jets to cool the piston are incorporated in the high power engine as shown in fig. 10.
Two oil jets are fitted on each of the #2 and #4 main bearing housing to cool No. 1, 2 and No. 3, 4 pistons respectively, where there is no oil flow to the connecting rod through crankshaft. The oil jets regulate the oil flow which cools the pistons, so that the main lubrication oil line pressure is not affected.
In addition, special anodized treatment is applied to the top ring groove for further durability.

The piston shape and clearance are optimized for hydrodynamic oil film for highest wear resistance and minimum friction.
Piston pin bore is also optimized to fit piston pin deflection.

When installing a piston, the service holes are used to put the piston pin and circlip into piston pin hole. (See fig. 10)
Piston pin diameter is 23 mm and made of high carbon steel.

Three piston rings are used, two compression

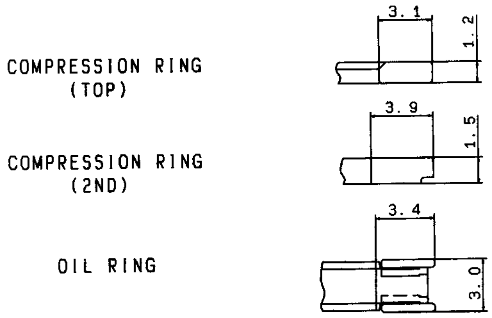

Fig. 11 Piston rings of 2.2 Lt

rings and one oil ring. The top ring is barrel-faced having an inner bevel cut and is made of steel and with chromium plating on the sliding surface. (See fig. 11)

For DOHC version, molybdenum disulfide coating is applied to improve break-in characteristics.

The second ring is taper-faced with an outer scraper, and is made of ductile cast iron.
The oil control ring is a multiple-piece type which has upper and lower rails and an expansion spring with a rotation prohibitor. (See fig. 12)

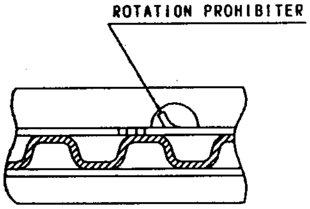

Fig. 12 Rotation prohibitor

These rings offer optimum oil consumption, friction, blow by sealing and durability.

CYLINDER HEAD GASKET

The cylinder head gasket is the heat and pressure-resistant carbon type with a hooked steel core. (See fig. 13)

The bore grommet with steel wire ring inside is formed as a part of the heat plate over the gasket and enables it to withstand the high pressure and temperature of the combustion gas.

A rubber grommet is used around the high pressure oil passage for perfect sealing.

Silicon coating is applied on the entire surface to improve the initial sealing function.

CYLINDER HEADS

Both DOHC and SOHC cylinder heads are made of cast aluminium alloy.

The compact pentroof-shaped combustion chamber with centrally located spark plug was adopted. The valve arrangement is cross-flow four valves per cylinder with two intake and two exhaust.

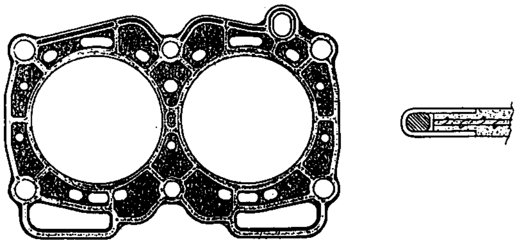

Fig. 13 Cylinder head gasket

The study of the phenomena within a combustion chamber will continue as long as the internal combustion engine will be used, applying state of the art techniques available at that time.

Using burn rate computer simulation and LDA techniques, the combustion chamber shape was optimized according to engine performance expected by customers owing to the valve train mechanism.

For the SOHC engine, relatively narrow valve angle of 30 degrees was adopted for the compact modified pentroof combustion chamber to emphasize the low and medium speed range torque.

The spark plug is located between the two intake valves of 32 mm diameter which was considered the best combination for a fast burn at low speed and excellent performance at high speed. (See fig. 14)

With these optimizations, associated with combustion stability and regulated internal EGR, without an external EGR system, the 2.2 Lt US version meets the current emission requirements.

For the DOHC version, 52 degrees valve angle is adopted and intake valve diameter is 36 mm, in which high speed performance has more emphasis than the SOHC version. (See fig. 15)

However physically allowable maximum intake valve diameter is around 40 mm which was not adopted, because the combustion chamber shape is optimized for high speed air breathing efficiency and low speed combustion stability.

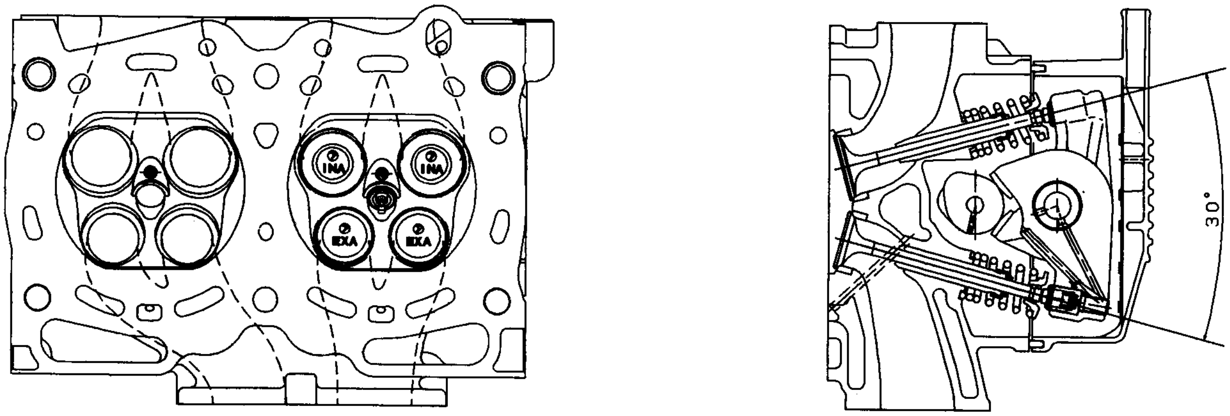

Fig. 14 SOHC 4 valve cylinder head

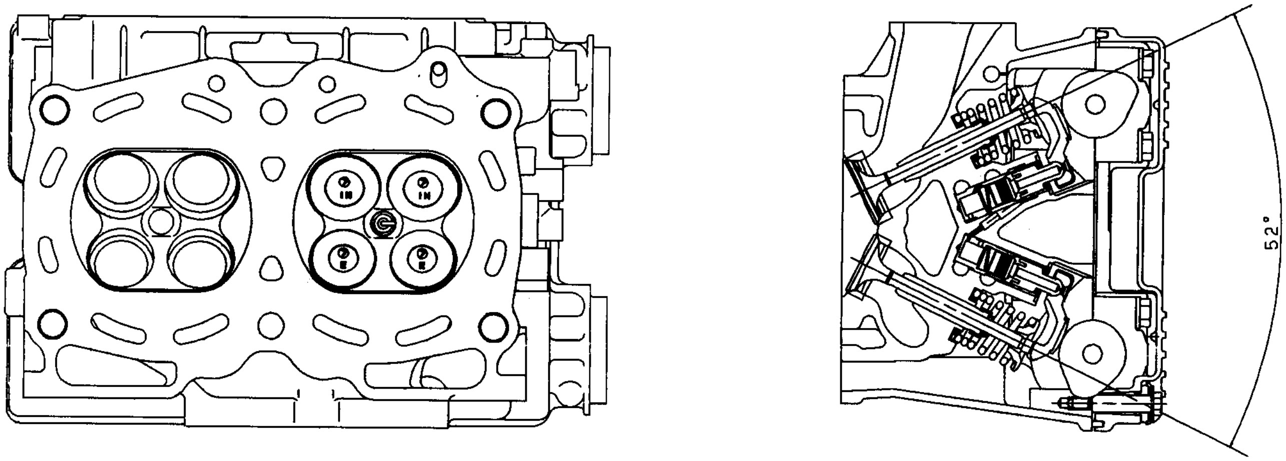

Fig. 15 DOHC 4 valve cylinder head

The port shapes were optimized before casting, through testing of models engraved on plastic called chemical wood by a NC machine connected directly to a 3D CAD system.

A water passage between two exhaust valve seats is drilled to cool exhaust valves and seats at high engine speeds.

The head bolts are torqued to their yield points in order to maintain stable axial forces.

VALVE TRAIN AND CAMSHAFT

SOHC valve train layout is shown in fig. 16. All rocker arms are supported by one rocker shaft secured to the cylinder head through three cast iron supports.

Rocker arms are all aluminium with sinter metal slipper for the cam contact foot. The exhaust valve rocker arm drives two valves so that the forces acting on the arm are symmetrical.

A lead aluminium bushing is pressed into either intake or exhaust rocker arm as a contact face with steel rocker shaft to achieve maximum durability.

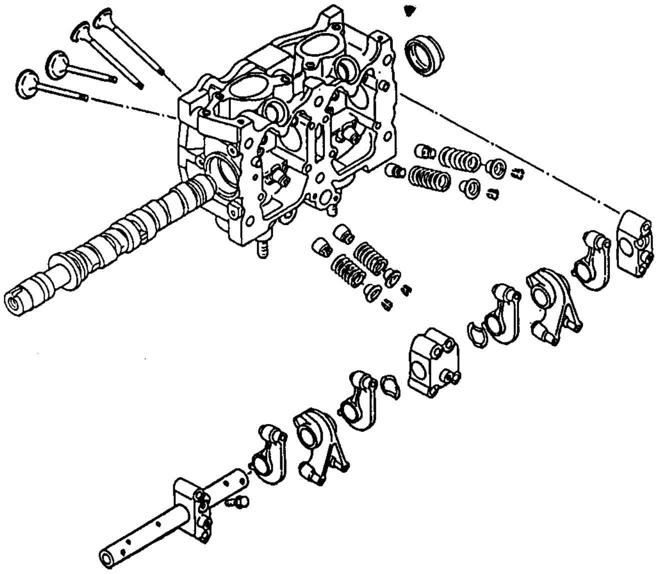

Fig. 16 SOHC valve train

Hydraulic lash adjusters (HLA) are incorporated by all valves for the reduction of valve train noise and to be maintenance free.

Camshafts are made of cast hardenable iron which provides good affinity with the rocker arm slipper surface made of sinter metal.

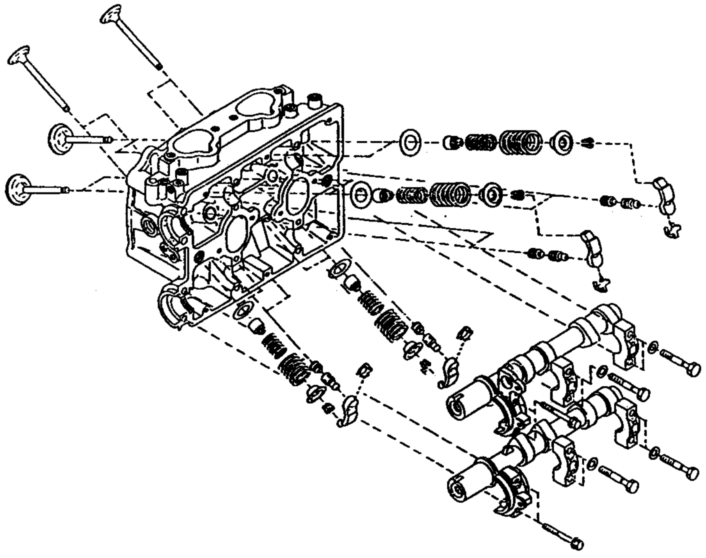

Fig. 17 DOHC valve train

As shown in fig. 17, in DOHC valve layout, swing arms are used to drive valves with end pivots in which hydraulic lash adjusters are incorporated.

Since relatively heavy lash adjusting mechanism is not included in the moving parts of valve train, higher revolutions are expected, keeping the valve opening angle to be small. Same as SOHC, sinter metal slipper is welded on cam contact area of swing arm to maintain excellent durability. Camshafts are directly run on the aluminium cylinder heads and the housing covers.

Through a CAD CRT the designer can check the consistency of his valve mechanism as an on-line base, by just inputting some numbers peculiar to the system, so that he can continue the designing without any interruption of thinking.

An oil passages around hydraulic lash adjusters are carefully designed so that air within the oil is promptly separated out and does not go into the lash adjusters.

Oil shower was also adopted for the lubrication of the cam lobe on the DOHC version.

CAMSHAFT DRIVE SYSTEM

One timing belt of 32 mm width was adopted for the camshafts drive for both the right and left hand cylinder heads.

In the DOHC version a timing belt drives four camshaft pulleys. The belt teeth pitch is 8 mm, with double canvas construction and improved belt teeth shape. The water pump is driven by the back of the timing belt.

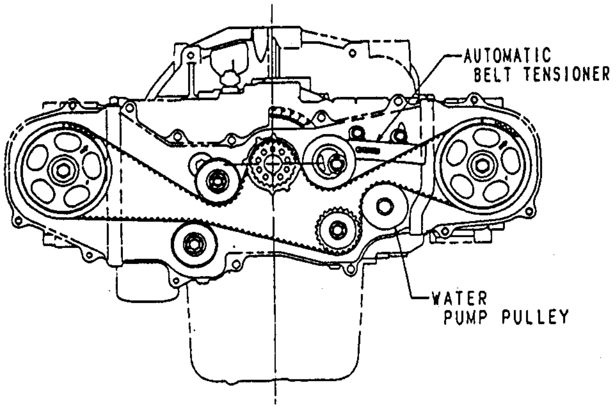

Fig. 18 Camshaft drive system

Basic design concept of camshaft drive system is to make the system as rigid as possible using an automatic belt tensioner to keep belt tension constant in all situations which is advantageous for low belt noise and smooth valve gear movement. (See fig. 18)

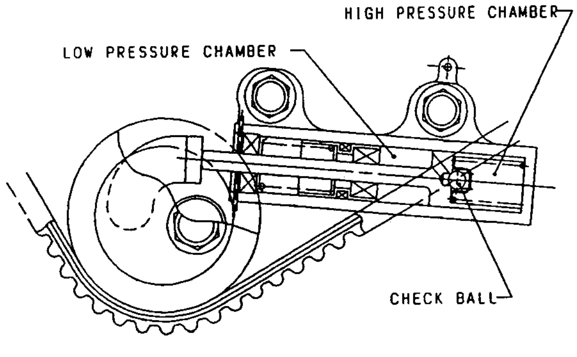

Fig. 19 Automatic belt tensioner

Automatic belt tensioner is necessary, when driving the water pump by belt to avoid any slippage caused by tension slack. The principle of an automatic tensioner is the same as a HLA with a check valve located between the high and low oil pressure chambers as shown in fig. 19.

The automatic belt tensioner pulley is located on the slack side of the timing belt.

All timing belt gears are covered by heat resistant plastic covers to prevent any foreign material entering in the belt system.

They are mounted on the crankcase by bolts with rubber dampers which separates the covers from crankcase to minimize noise radiation.

COOLING SYSTEM

Extensive tests were conducted to study the relationship between engine cooling and performance as a part of the development activity of the "Boxer" engine.

The purpose of the study was to find out the factors affecting the knock limit especially at low engine speed. The first factor is the intake air temperature and the second one is the temperature around the exhaust valve seats.

Cylinder wall or cylinder head squish area wall temperature does not affect knock limit as long as the temperature is not excessively high.

However, the most important finding is very simple, that, homogenious cooling between any cylinder is the greatest factor which affects knock limit.

Because the non-uniform temperature distribution distorts the engine causing the increased friction and temperature rise locally within the engine which results in further non-uniform intake air temperature rise between the cylinders owing to the heat transfer from the engine to the intake air.

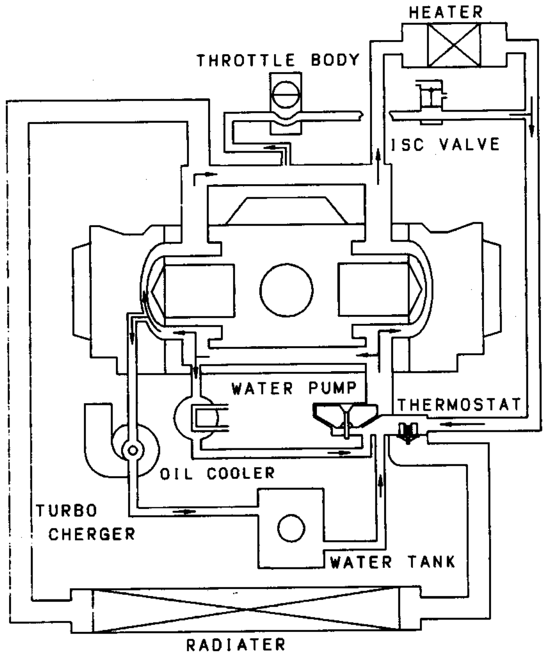

Fig. 20 Cooling system DOHC with turbo

Therefore water passages were carefully designed for even cooling between the cylinders which agrees with our program objective to pursue a homogeneized and "well balanced" engine. (See fig. 20)

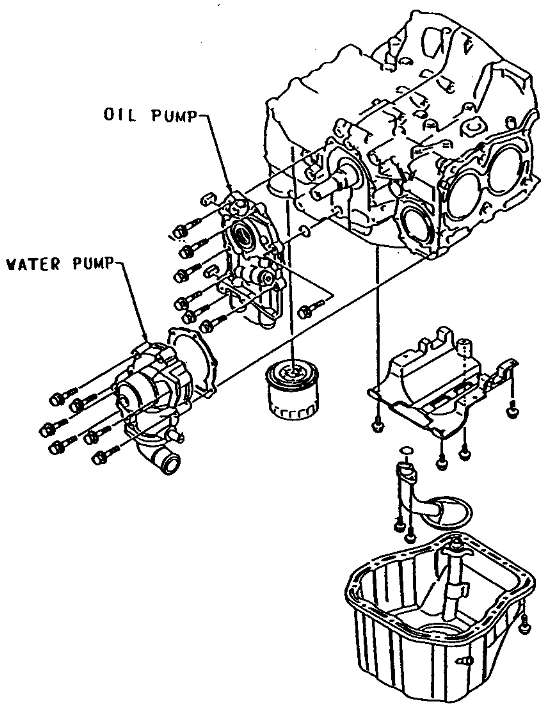

Fig. 21 Layout of water pump and oil pump

The water pump is located at the front lower left hand of crankcase. (See fig. 21)

The pump body is made of aluminium diecast which contains the shaft and bearing with a mechanical seal and a cast iron impeller.

Water flow from the pump branches off to the right and left crankcases at the outlet of the pump.

Firstly it flows into the lower part of the crankcase and goes to the cylinder head exhaust valve area. Then cooling water flows up to the intake valve area and into the upper part of crankcase making a U-turns within a cylinder head. Water passages between the crankcase and cylinder head are suitably arranged by cylinder head gasket holes so that the front and rear cylinders are cooled evenly.

Flow patterns of the two crankcases are the same.

Through an outlet in the upper part of the crankcase, cooling water flows into the radiator. Some of the cooling water bypasses to the bottom of the thermostat chamber through heater core.

Flow from the radiator goes into thermostat chamber in the water pump body through the thermostat valve and within the chamber it is mixed with bypassed flow from the heater core.

The thermostat controls this mixture ratio so that the water temperature going into the engine is always constant. All water flow within engine is directed from bottom to top for the purpose of excellent vapor separating function. With this effective cooling system, temperature deviation around cylinder head gasket gas-gromet is less than 20°C even in the DOHC turbo model.

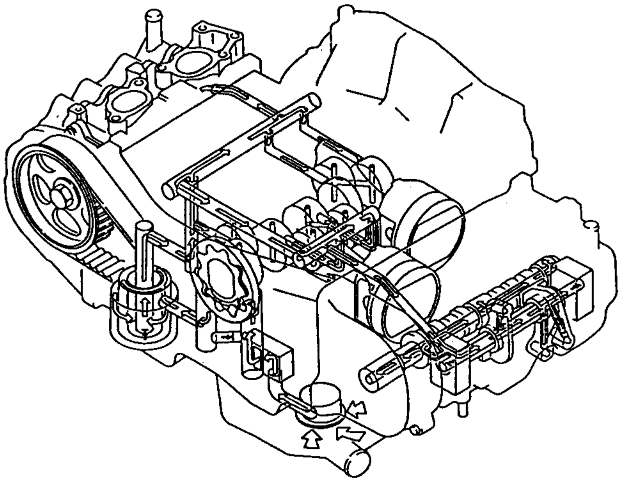

Fig. 22 Lubrication system

LUBRICATION SYSTEM

Fig. 22 shows oil passage diagram of the SOHC version.

The oil pump is the torocoid-type with inner and outer rotors made of sintered iron, driven from the crankshaft directly.

The oil pump body is made of high pressure diecast aluminium with oil pressure relief valve in it as shown in fig. 23.

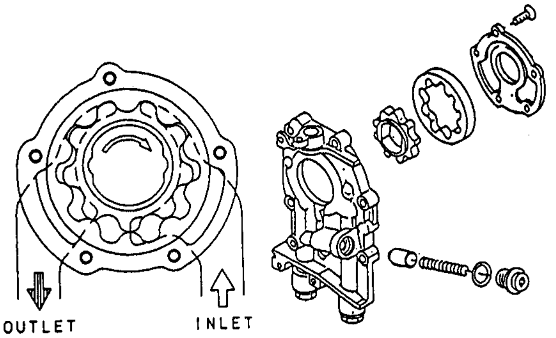

Fig. 23 Oil pump

The back plate of pump is steel to secure rigidity.

Inlet and outlet ports of the pump are well arranged so that some amount of the oil stays in the pump rotor chamber to work as a priming oil in case of drain back caused by a long period of no use.

While engine is running, relatively large amounts of oil rotate with the crankshaft increasing engine friction, if a suitable countermeasure is not incorporated.

Oil flow from the left bank cylinder head flowing into the oil pan through the oil passage in the lower part of crankcase is in the same direction as oil flow rotating with crankshaft.

However, oil flow from right cylinder head into the oil pan is against the direction of crankshaft rotation and runs against the oil flow rotating with crankshaft, which makes the oil in the pan swell and aerate.

Extensive development work on the oil pan shape, oil strainer, windage tray and crankcase has resulted in excellent oil and air behavior control inside of the engine.

Specifically, much attention on the windage tray was paid in the design and development to prevent oil flow from colliding and to scrape off the oil rotating with crankshaft to decrease internal friction and to lower oil temperature.

Oil from the oil pump is routed to the full flow oil filter, after the pressure has been regulated.

From the filter the oil flows to the main oil galleries running along the upper side of the crankcases, and then to each main bearing and connecting rod bearing. The orifice in the main oil gallery adjusts the pressure of the oil flow to the cylinder heads which is supplied to the valve trains and camshafts.

In the SOHC version, the relief valves are installed in the oil hole at both ends of the valve rocker shaft to provide stable oil pressure for the hydraulic lash adjusters.

In the DOHC version, oil from cylinder head is introduced into oil galleries to supply oil to HLA and cam bearings. The relief valve to control the oil pressure to HLA is installed at the inlet of the gallery.

ENGINE COMPUTER CONTROL SYSTEM

The entire computer control system of 2.2 Lt SOHC is shown in fig. 24 and that of 2.0 Lt DOHC with turbo version is in fig. 25.

The engine control system itself is situated much closer to the driver than mechanical parts and the driveability of the car is almost the product of the control system itself, therefore more human factors like "Kansei" have been emphasized to develop the system.

It owes much to the variety of the control systems to meet the diversity of the field demands, because the nature of an electric control system itself is very versatile contrary to mechanical systems. Therefore to ensure effective development activities, the basic strategy which is commonly shared among the systems of the engine series was established.

Accordingly, one of the common design features of the system is the crank angle sensor.

Since engine revolution angle signal is the base of all controls, the preciseness of this signal is in essence for high performance, quick response and reliability.

Magnetic type pick-up is adopted which is situated in the oil pump housing.

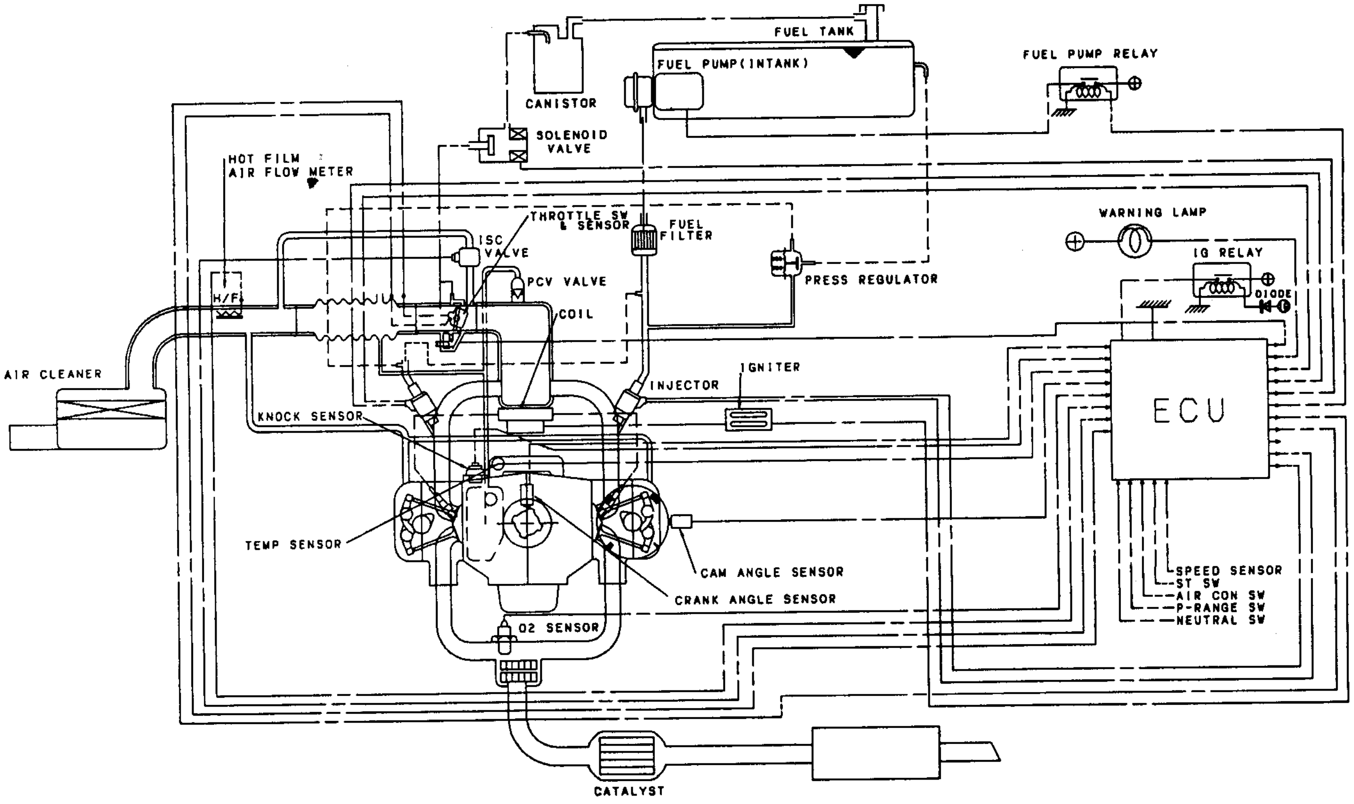

Fig. 24 Engine computer control system 2.2 Lt SOHC 4 valve

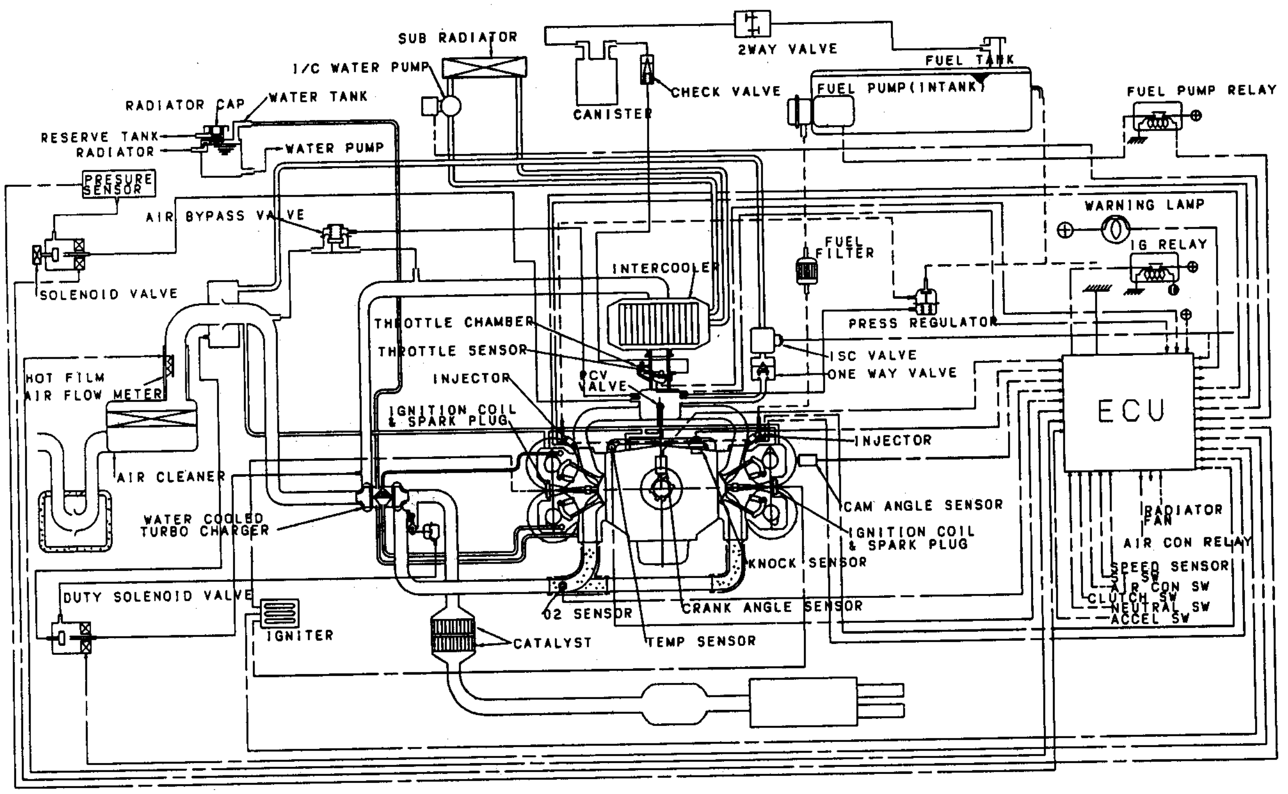

Fig. 25 Engine computer control system 2.0 Lt DOHC 4 valve with turbo

On the crank sprocket for the camshaft drive six protruding teeth are located. As shown in the fig. 26 the bosses are located unevenly, around the circumference of the sprocket where angular velocity fluctuation is minimal to secure the accuracy of sensing.

Owing to the zero cross point sensing, though sensing radius is relatively small, the resolution of the sensor is excellent.

The sensor also works as crank revolution speed sensor.

On the camshaft pulley, cylinder number discriminator (called cam angle sensor) is adopted by the same principle as the crank angle sensor.

The duplication of signals not only brings higher precision but also increases the safety margin as a back up system. The other feature of this engine control system is the multi usage of timers. Twelve timers in all are used.

The reason for our choice is that timer control is most suitable to build up control logics because of the compatibility between digital timer and digital computer which is controlled by a quartz clock.

As shown in the control system diagram, ignition and injection systems are controlled totally by an electronic control unit (ECU) with a 16 bit micro computer and 32K ROM.

The control system strategy was of course designed to enhance the basic engine characteristics.

The major items controlled by ECU are as follows:

- Fuel injector control
- Air fuel ratio adaptive control
- Ignition timing map control
- Idle speed control
- Diagnosis

and in addition to the above for the DOHC with turbo version,

- Turbo charger boost control
- Radiator fan control

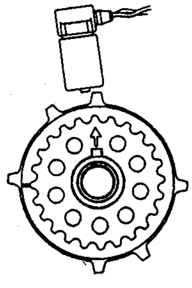

Fig. 26 Crank angle sensor

As shown in the system diagrams, the fuel system adoped is multipoint fuel injection. Injector is bottom flow type to lower fuel temperature inside of the injector for better hot fuel handling. Fuel control uses hot film type air flow meter with the closed loop adaptive control system by an oxygen sensor in the exhaust manifold.

Sequential injector control is adopted on all models with MPI system owing to the 16 bit high speed ECU. Injection timing is so controlled that the end timing of injection may not be within valve over lap period.
Within control strategy of fuel injection, the mathematical models were applied to compensate the discrepancy between air flow meter reading and actual airflow.

The response time of the air flow meter itself is very quick, however, the multi sample averaging system to measure the meanvalue of pulsating airflow causes a response delay. Further, the volume between air flow meter and engine causes response delay or over shoot according to the opening or closing of the throttle valve.

Based on the throttle opening sensor signal, in the transient condition, measured air flow is adjusted according to the mathematical model which results in very good response, avoiding any engine flat spot caused by over rich or lean mixture which is beneficial to exhaust emission and fuel economy too.

During warm up condition, the same theory is applied which ensures excellent warm up drivability, low emission, and better fuel economy also.

Absolute pressure sensor of 2.0 Lt DOHC turbo version ensures excellent turbo performance in a high altitude areas. For 2.2 Lt SOHC version, the same sensor is applied, with which automatic transmission shift schedule is optimized according to the altitude.

Ignition system adoped for 2.2 Lt SOHC version is a two coil system which either the front or rear pair of spark plugs fire simultaneously at each crankshaft revolution.

This system results in higher spark energy because of the longer current on period, and better looking of the engine without long spark plug leads. (See fig. 27)

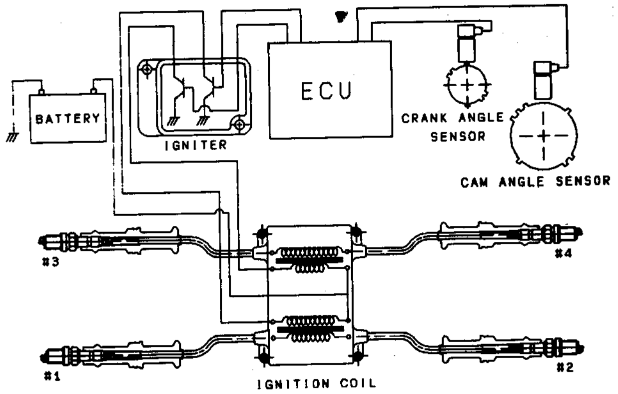

Fig. 27 Two coil ignition system 2.2 Lt SOHC 4 valve

The ignition system for 2.0 Lt DOHC with turbo version is one coil for one spark plug system, to supply sufficient spark energy at high speed and full throttle conditions through reduced coil inductance and longer dwell angle.

Also the spark plug of this version is a platinum electrode type, for the purpose of higher reliability of the ignition system. Functions included in the ignition control strategy are base airflow versus RPM look up and timing modifiers according to water temperature, fuel enrichment, and transmission state. Also, ignition timing adaptive control by knock sensor is incorporated.

Another ignition timing control application is to curb vehicle jerking during transient condition by altering the ignition timing according to the fluctuation of angular velocity of crankshaft.

Reliability of engine control system depends largely on the electric connectors. For this new engine, water-proof cylindrical connectors, partly with gold plates were adopted.

With the excellent software and high speed 16 bit computor, we believe that the "balance" between the engine and its control system has been accomplished, so that the new "Legacy" can respond to any customer's expectation.

INTAKE SYSTEM

Before testing the intake and exhaust system, computer analysis using the fuluid dynamics is conducted to optimize volumetric efficiency and noise reduction.

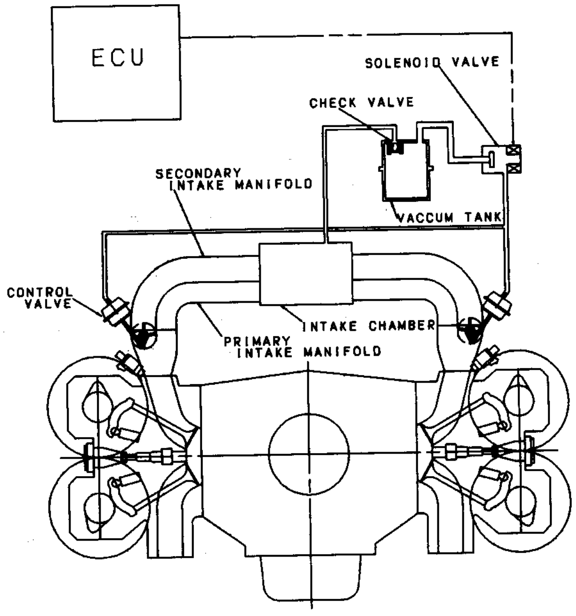

Fig. 28 Variable intake system DOHC

For 2.0 Lt DOHC 4 valve NA version, the dual mode induction system is incorporated to enhance volumetric efficiency at either low and high engine speed by altering resonance point according to the open or close of the control valve. (See fig. 28)

Fig. 29 shows the calculated volumetric efficiency.

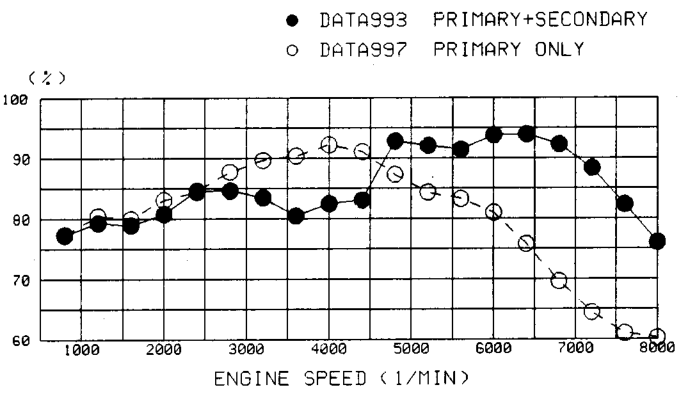

Fig. 29 Volumetric efficiency

TESTING and RESULTS

While the initial engine design was in process, a comprehensive test program was established which contained the overall test matrix consisting of bench tests, vehicle tests and component tests with their testing time tables.

To make the development activities effectively, this test program has been shared by all the departments relating to this project.

Further, the information of the test status and results have been exchanged periodically and the mechanism to review and adjust the test program has been extablished according to the progress of the project. From the first the new "Boxer" engine was destined for "Legacy" of the 1990 model.

The test programs of the engine and vehicle were therefore, synchronized in the early development phase.

Another interesting feature of testing was the best use of a laboratory computer.

The capacity of ROM of ECU has been increasing according to the increased complexity of engine control systems taking more time for us to determine the constants in ROM.

Using test benches and a laboratory computer, constants were automatically determined.

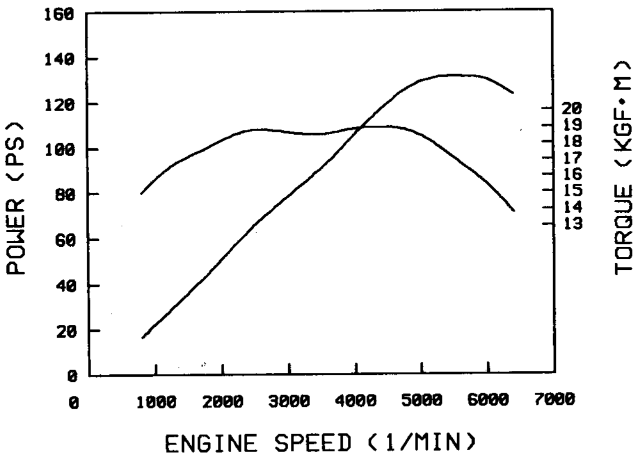

Fig. 30 Performance curve 2.2 Lt SOHC 4 valve

This system is effective not only to set the constants in ROM of a steady state engine condition but also of transient conditions like the accelaration enrichment co-efficient, using mathematical models representing intake air and fuel flow. It was also possible to watch the ECM behavior by this system comparing step by step the expected engine phenomena and the actual one.

Using this system, the speed and accuracy of the development of the engine control computer has been increased greatly.

Folloing are a few of the many test results of the "Boxer" engine series. In fig. 30 and 31, the performances curves of each engine are shown. The output power of 2.0 Lt DOHC with turbo version is excellent with it's 220 PS.

Specific weight of 0.67 kg/ps is one of the highest on record which we believe is the greatest accomplishment of this development.

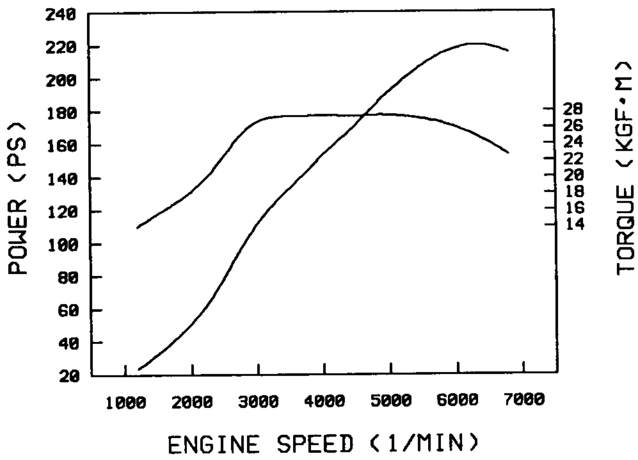

Fig. 31 Performance curve 2.0 Lt DOHC 4 valve with turbo

In fig. 32, a fuel consumption graph of the 2.2 Lt SOHC MPI version is shown. The nature of the "Boxer" engine's high combustion effeciency is proved with it's compact combustion chamber.

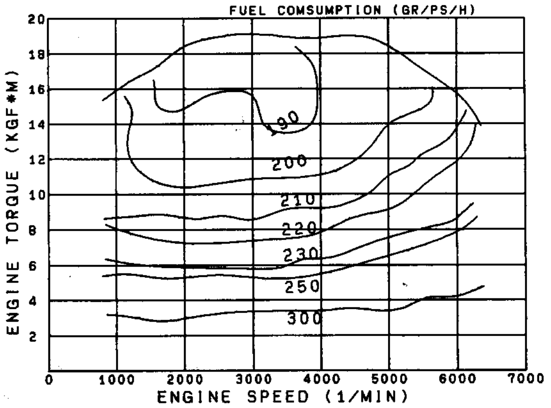

Fig. 32 Fuel consumption curve 2.2 Lt SOHC 4 valve

Even having a low pistion speed because of its relatively short stroke, much efforts to lower drag within the engine have resulted in low friction characteristics.

Lastly, fig. 33 and 34 show vibration level of our horizontally opposed engine "Boxer" and in-line four cylinder engine with the same displacement as the "Boxer".

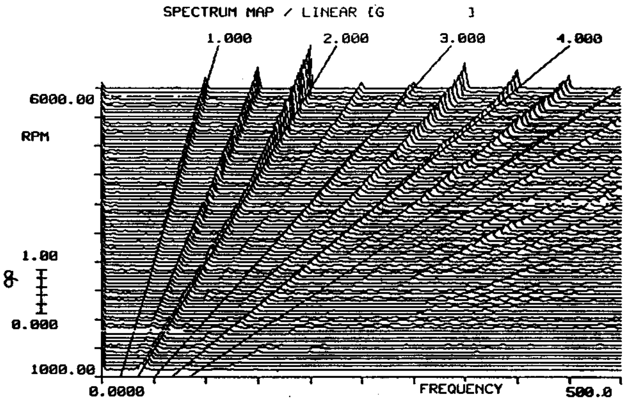

Fig. 33 Vibration level of "Boxer"

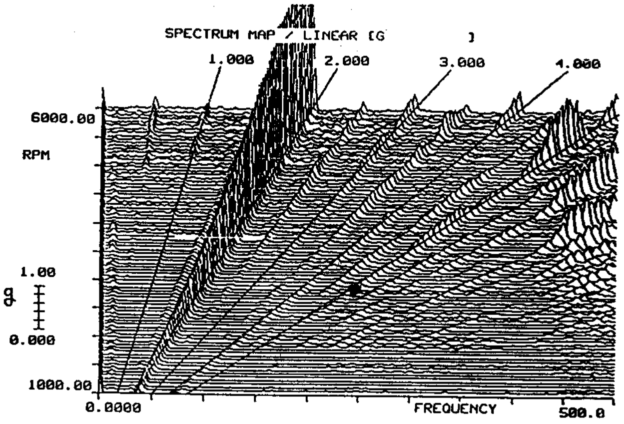

Fig. 34 Vibration level of in-line 4

It is clear that the "Boxer" engine has no 2nd order vertical shaking force. This low vibration characteristics is very beneficial when converting from front wheel drive to four wheel drive.

CONCLUSION

The "Boxer" engine was born. The initial development objectives were the high specific power and design flexibility.

Looking at the test data in the previous paragraph, we believe that the objectives have been fully attained with the sufficient reliability, durability and high quality.

Further, our design philosophy of the engine with homogeneity and "good-balanced" have been also realized, mainly by the cooperation between the dedicated people in it's development of the "Boxer" applying state of the art development technology and process. (See fig. 35)

With this new engine, we will continue to pursue the high performance vehicle with high path contrallability and at the same time, the economical car of easy driving, making the best use of our drive train combined with the "Boxer" engine.

Acknowledgement

The authers would like to offer their sincere appreciation to all the people dedicated in the development of the "Boxer" engine.

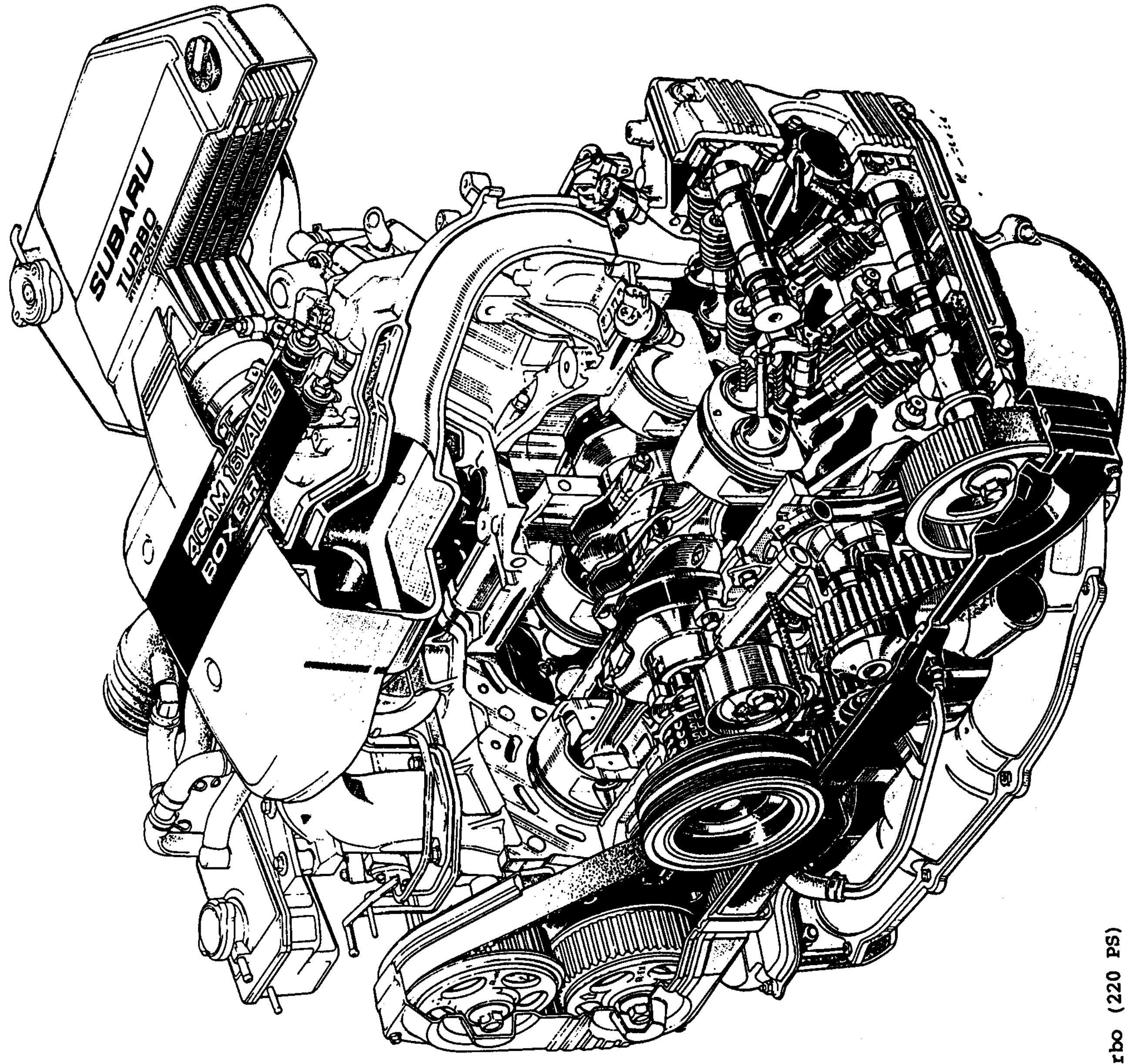

Fig. 35 2.0 Lt DOHC
4 valve with turbo (220 PS)