2005 Heavy-Duty Engine Benchmarking Program: Teardown and Technical Assessment of the MAN D20 Engine

by

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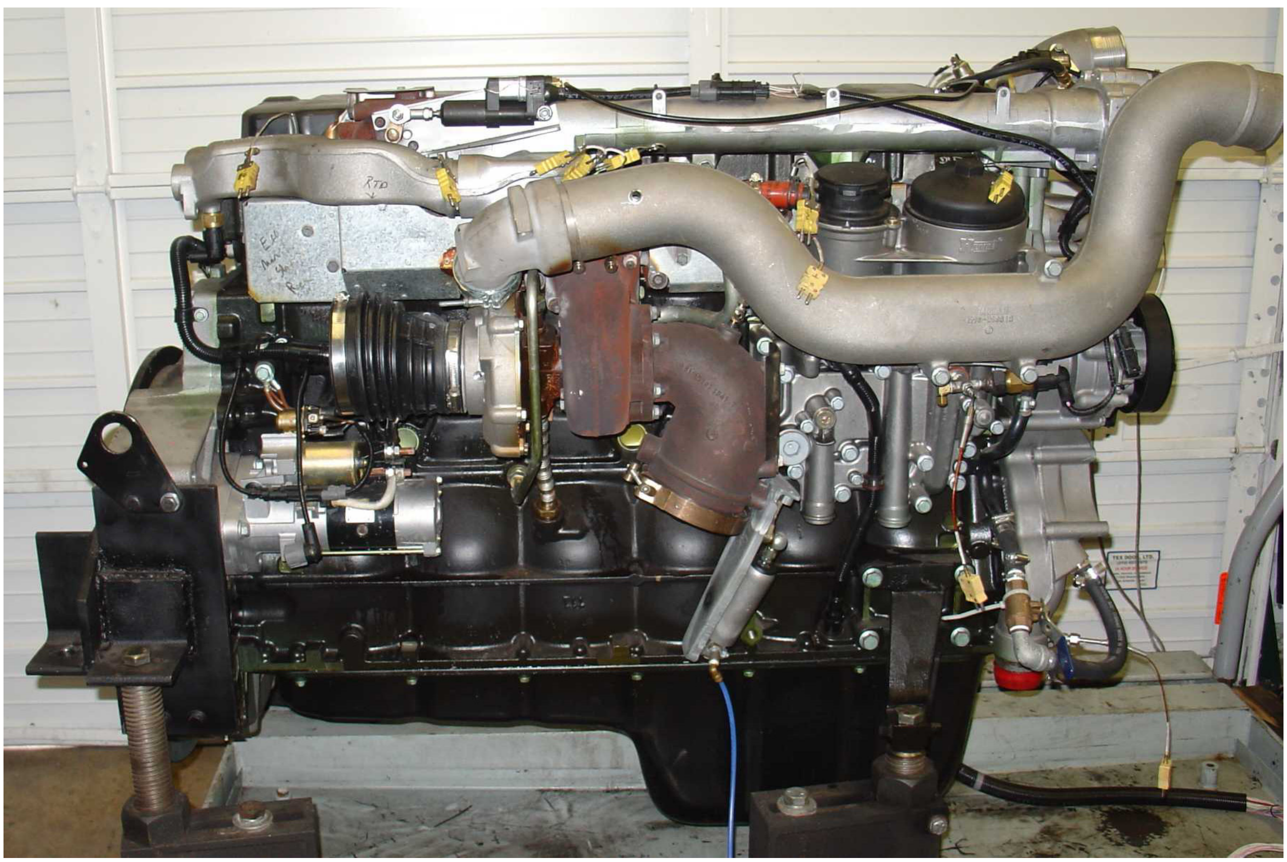

September 9, 2005

MAN D20

Heavy-Duty Engine
Benchmarking Program

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1.0 INTRODUCTION

Southwest Research Institute® (SwRI®) has prepared this report as part of its ongoing Heavy-Duty Engine Benchmarking Program. The tested MAN D2066-LF01 engine is a 2004 model year on-highway version designed to meet ECE Euro III emission regulations.

During this program, each engine is tested for steady-state performance, heat rejection, and emissions. Next, tests are conducted to determine transient control strategies. Following the performance tests, the engines are torn down for component measurements, component photography, and cylinder head flowbench testing. Finally, design features are evaluated.

Engine teardown, component photography, cylinder head flowbench testing and design features evaluation for the MAN engine are summarized in this report.

2.0 BASIC CONFIGURATION

The MAN D20 engine evaluated is the six cylinder 10.5L version, 2004 model year. This configuration is used in on-highway heavy duty trucks. MAN developed the D20 for future Euro IV emissions standards, but introduced it at Euro III emissions levels. It features exhaust gas recirculation (EGR) and a common rail fuel system. The basic engine configuration is shown in Table 1 below.

TABLE 1. BASIC ENGINE CONFIGURATION

Engine Parameter	Value
Serial Number	5050767228B2C1
Cylinder Configuration	In line 6
Camshaft Configuration	Single in-Head
Cylinder Bore Diameter	120 mm
Cylinder Stroke	155 mm
Total Displacement	10.52 L
Compression Ratio	19.0:1
Turbocharger Type	KKK Fixed Geometry
Fuel Injection System	Bosch High Pressure Common Rail
Rated Engine Power	316 kW (424 hp)
Rated Engine Speed	1900 RPM
Peak Torque	2100 Nm (1549 Lb-ft)
Peak Torque Speed	1000-1400 rpm
Charge Air Intercooling	Chassis Air-to-Air
Exhaust Gas Recirculation	High Pressure Water-Cooled

Figure 1. MAN D20 Engine (front right view)

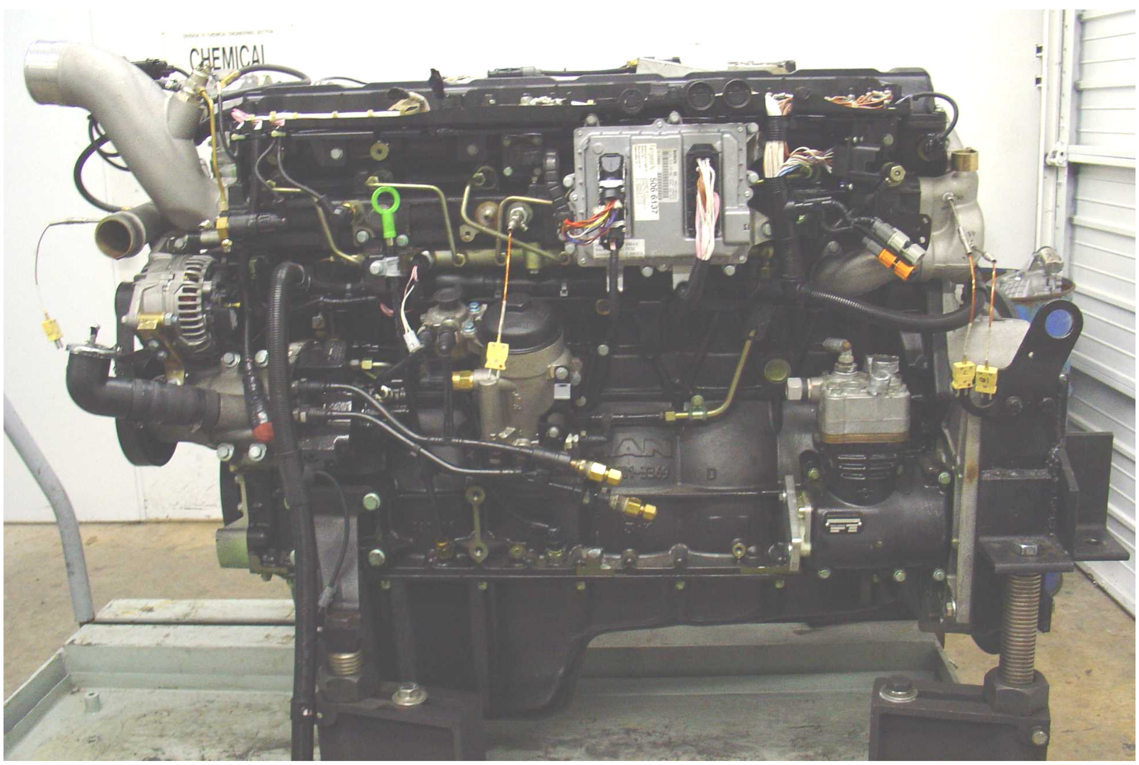

Figure 2. MAN D20 Engine (left view)

Figure 3. MAN D20 Engine (left front view)

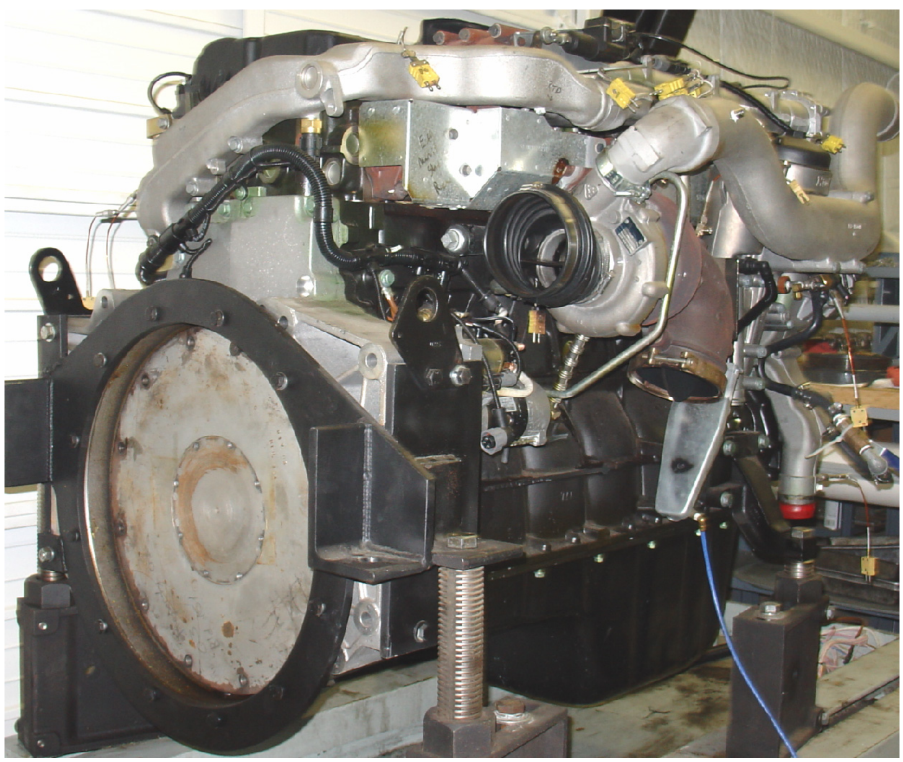

Figure 4. MAN D20 Engine (right rear view)

Figures 1-4 (previous pages) show views of the overall engine as received for teardown following performance testing. Note that most accessories were previously removed or not originally included, and some test instrumentation is still attached. Information will be presented primarily in the order of disassembly and related systems.

3.0 AIR HANDLING SYSTEMS

3.1 EGR System

The Exhaust Gas Recirculation (EGR) system on the MAN D20 engine is a pulsed system. Most high-pressure EGR systems vary the turbocharger turbine nozzle area to produce higher average pressure in the exhaust manifold than in the intake manifold to drive the EGR. On an inline-6 engine, the exhaust pulse amplitude in a low volume 3-cylinder manifold is much higher than the average pressure, and thus at the peak of the pulse, it is higher than the intake manifold pressure, although the average pressure is usually lower. Most of the pulsed EGR system is thus divided into two parallel paths, one for each 3-cylinder bank, with reed valves at the ends of the parallel paths to allow EGR flow at the peaks of the exhaust pulses.

The EGR system starts with the two exit flanges from the divided exhaust manifold (see Section 3.3). A valve housing sits above the exhaust manifold at the rear of the engine (see Figure 5), and is connected to the exhaust manifold boss from cylinders 4-6 (see Figure 6, mating boss to manifold is on lower left corner). A flexible tube also connects from another boss on the exhaust manifold from cylinders 1-3 to this valve housing (see Figure 18, upper left of picture). The valve housing contains two butterfly valves that control the rate of exhaust gas flow through the EGR system (see Figure 7).

A solenoid operated air cylinder controls the butterfly valves (see Figure 5, right center). The outlet of the valve housing feeds the EGR cooler, mounted above of the exhaust manifold on the right side of the engine. The two exhaust flows are kept separate through the valve

Figure 5. EGR Valve Housing, Air Cylinder, Cooler Entrance and Coolant Crossover Tube

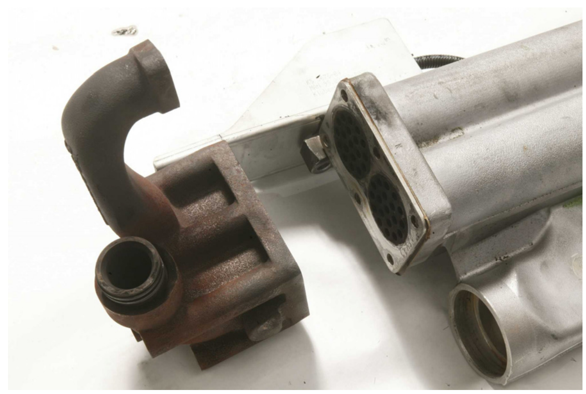

Figure 6. EGR Valve Housing (bottom view)

Figure 7. EGR Valves (butterfly)

housing and the cooler. The EGR cooler is cast aluminum with stainless steel tubes, made by Modine (see Figures 8-10). A cast aluminum crossover tube connecting to the rear, left side of both the block and the cylinder head flows coolant into the EGR cooler (see Figure 4, top left and Figure 5). Coolant exits the cooler at the front of the engine into the coolant manifold/pump assembly.

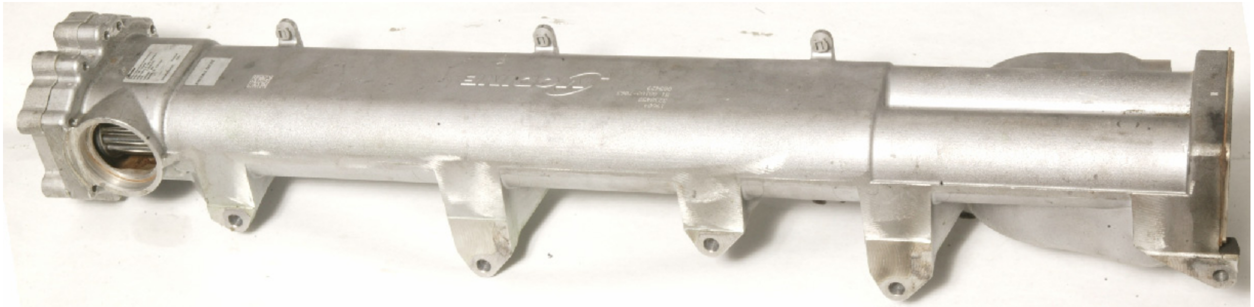

Figure 8. EGR Cooler (left side)

Figure 9. EGR Cooler-Stainless Steel Tubes

Exhaust gas exits the cooler into a cast aluminum housing containing the reed check valves and joins into a single stream after the valves (see Figures 10 and 11). From this housing the flow crosses through a stainless steel flex tube to the intake system on the left front of the engine (see Figures 11-13). The intake pipe where the exhaust gas is introduced does not appear to have any features that would promote mixing of the exhaust gas with incoming fresh air (see Section 3.4). Table 2 (next page) summarizes the EGR system components.

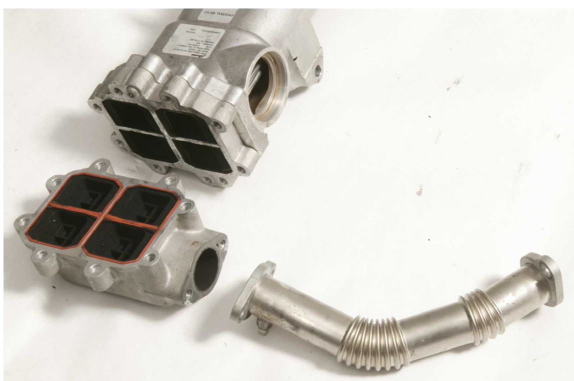

Figure 10. Reed Valves and Crossover Tube

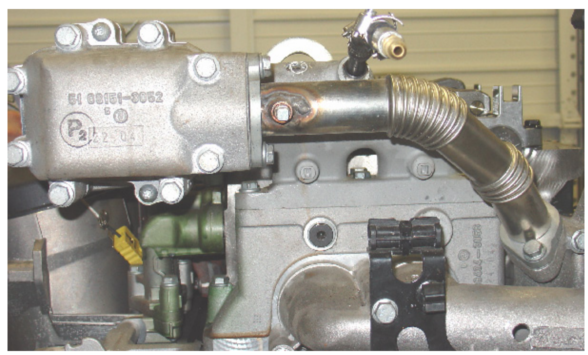

Figure 12. Reed Valve Housing and Crossover Tube (installed, front view)

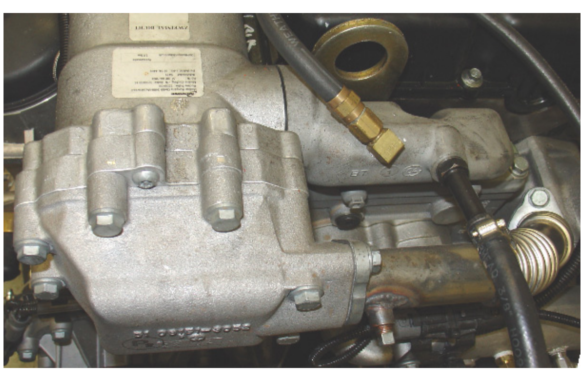

Figure 11. Reed Valve Housing (installed, top)

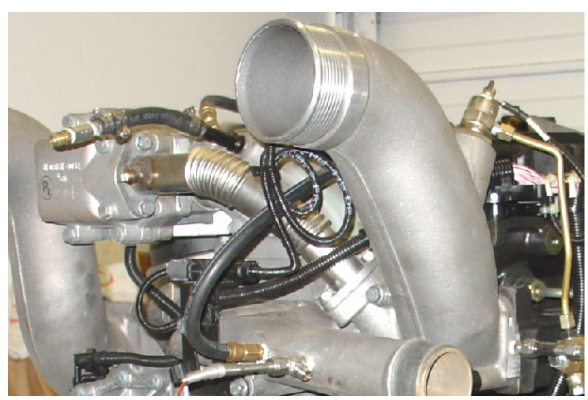

Figure 13. EGR Mixer / Intake Pipe Installed

TABLE 2. EGR COMPONENT SUMMARY AND DIMENSIONS

Component	Description / Dimensions
Inlet Flanges	one vertical inlet off rear manifold bank, one horizontal inlet off front manifold bank, 28 mm ID outlets x 25 mm L
Hot Side Tubes	Front: one stainless steel flex tube, 27 mm ID inlet and outlet x 110 mm L to cast iron section with 28 mm ID inlet, two 90 deg bends x 215 mm L Rear: Cast iron connecting sleeve 30 mm ID x 37 mm L to cast iron section with 28 mm ID inlet and one 90 deg bend x 75 mm L
EGR Inlet Valves	two 40 mm OD butterfly valves, two 40 mm ID outlets x 35 mm L
Cooler	Core: 70 mm H x 115 mm W x 850 mm L – 38 tubes 5.6 mm ID Gas: two 40 mm ID inlets, two 87 mm H x 35 mm W outlets Coolant: 48 mm ID inlet, 52 mm ID outlet; parallel flow
Reed Valves	four 34 mm H x 35 mm W inlets converging to four 25mm H x 25 mm W valve entrances, 90 deg bend converging to 35 mm ID outlet
Crossover Tube	34 mm ID inlet and outlet x 270 mm L
EGR / Intake Air Mixer	37 mm ID EGR inlet at 30 deg bend junction with inlet air tube x 80 L 84 mm ID intake air inlet x 350 mm L, 80 mm L to 72 mm H x 83 mm W outlet

Figure 14. Turbocharger with Inlet Air Connector / CCV Mixer, and Exhaust Brake

3.2 Turbocharger, Exhaust Brake

The MAN D20 uses a KKK turbocharger, usually referred to as "3K" in the US (see Figures 14-16). It contains a divided, fixed geometry turbine, and no wastegate. The turbine housing is made of iron and the compressor housing is made of aluminum. The two housings are joined by a steel bearing housing, with oil feed to the bearings off the block oil gallery. The return oil to the block is through a flex tube.

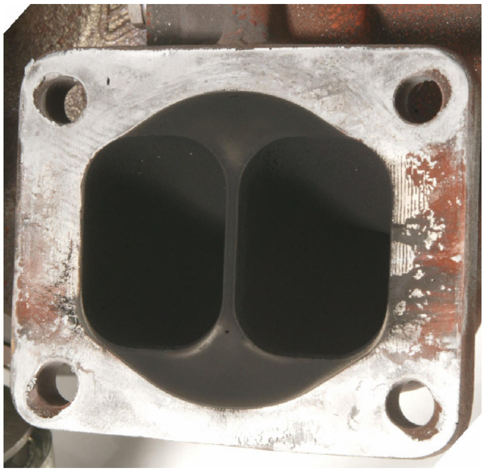

Figure 15. Turbine Inlet

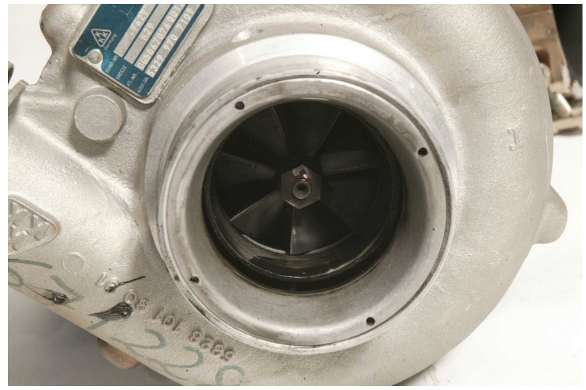

Figure 16. Turbocharger (compressor view)

The wheels appear to be made of standard materials, with aluminum compressor wheel and steel turbine wheel. There is not a wheel speed sensor. Inlet and exit dimensions are summarized in Table 3.

TABLE 3. TURBOCHARGER DIMENSIONS

Feature	Dimension
Compressor inlet ID	80 mm
Compressor discharge ID	48 mm
Turbine inlet H x W	52H x 37W x R10 mm (x 2)
Turbine inlet area	3676 mm^2
Turbine Outlet ID	71 mm

There is also an exhaust brake on the outlet of the turbo housing (see Figures 14 and 17). The brake is a butterfly valve, operated by an air cylinder. The exhaust brake works to activate the engine braking system as described in Section 4.5, Valvetrain and Engine Brake.

Figure 17. Exhaust Brake

3.3 Exhaust Manifold

The MAN D20 exhaust manifold is a 3-piece cast iron manifold located on the right side of the engine, with slip joints between cylinders 2 to 3 and 4 to 5 (see Figure 18, with cylinder 1 on the right, and Figure 19, with cylinder 1 on the left). The flows from front and rear 3-cylinder banks are separated up to and including the turbine inlet flange.

Figure 18. Exhaust Manifold (right bottom view)

Figure 19. Exhaust Manifold (top view)

The interior cross sections of the manifold are rectangular at the head flanges, and quickly transition into circular sections on the main manifold, then back to rectangular at the turbo flange. There are six individual manifold gaskets, which are single layer steel (SLS).

There are two exit ports off the manifold that feed to the EGR system. Flow from cylinders 1, 2, and 3 are taken off near the turbo flange, and fed through a stainless steel flex tube mounted to the manifold (see top left of Figure 18). Flow from cylinders 4-6 are taken off a circular boss between cylinders 5 and 6 (see right side of Figure 19).

The three sections of the manifold are connected together with slip joints, which are sealed by two sets of four flat expansion rings in slots on the ends of each of the end sections (see Figure 20). The rear bank EGR boss is also connected to the EGR valve housing with a cast iron sleeve containing two sets of four flat expansion rings in slots on each end (see Figure 20, left). Table 4 contains a summary of major dimensions.

TABLE 4. EXHAUST MANIFOLD DIMENSIONS

Feature	Dimensions
Inlet dimensions	43 x 43 x R8 mm
Turbine flange inner H x W	50 x 36 (x 2) mm
Exhaust flange thickness	12.5 mm
Runner lengths	35 mm
Log ID	39 mm

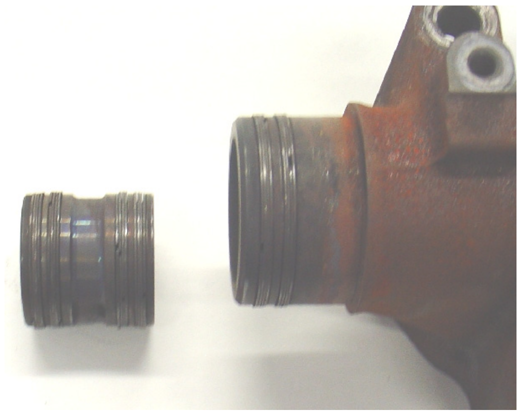

Figure 20. Exhaust Manifold Junction and EGR Connector Sealing Rings

3.4 Intake System

The D20 intake system starts with the cast aluminum intake pipe mounted on the left front of engine (see Figures 21 and 22). EGR flow is introduced into this pipe at an angle to the air flow (bottom of Figure 21). The pipe also contains the intake air flame heater system components: fuel control valve, glow plug, and temperature sensor.

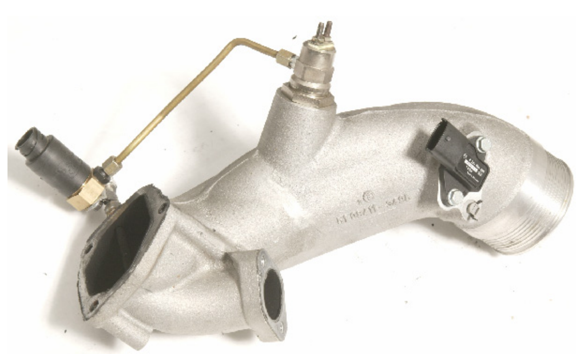

Figure 21. Intake Pipe / EGR Mixer / Inlet Air Flame Heater

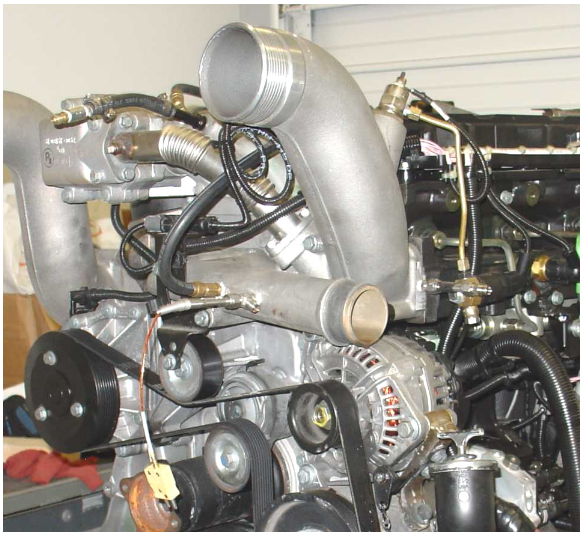

Figure 22. Intake Pipe, Mounted to Engine

The intake pipe mounts directly to the cylinder head, which has a cast-in intake manifold. The manifold runs the length of the cylinder head under the cam shaft bearing saddles in the head (see Figure 24 and top of Figure 27). The shape of the manifold cross section is rectangular, with the two lower and one upper corners chamfered (see Figure 23). There are six branches off of the manifold, each one supplying the two intake valves in each cylinder. Section 4 further details cylinder head and the shape of intake ports. Table 5 contains a summary of the intake pipe and manifold dimensions.

Figure 23. Cylinder Head Intake Manifold Entrance (pipe mount face)

TABLE 5. INTAKE PIPE AND MANIFOLD DIMENSIONS

Feature	Dimensions
Intake Pipe Entrance ID	84 mm
Intake Pipe Exit H x W	72 x 83 mm
Intake Manifold H x W x L	70 x 85 x 855 mm

4.0 CYLINDER HEAD, VALVE TRAIN AND HEAD GASKET

The MAN D20 has a single slab cast iron cylinder head (see Figures 24-28). The head is bolted to the block with a six bolt per cylinder pattern. The casting includes the intake manifold, as mentioned above. The camshaft is located in the head, just above the intake manifold.

Figure 24. Cylinder Head with Cast-In Intake Manifold (left view)

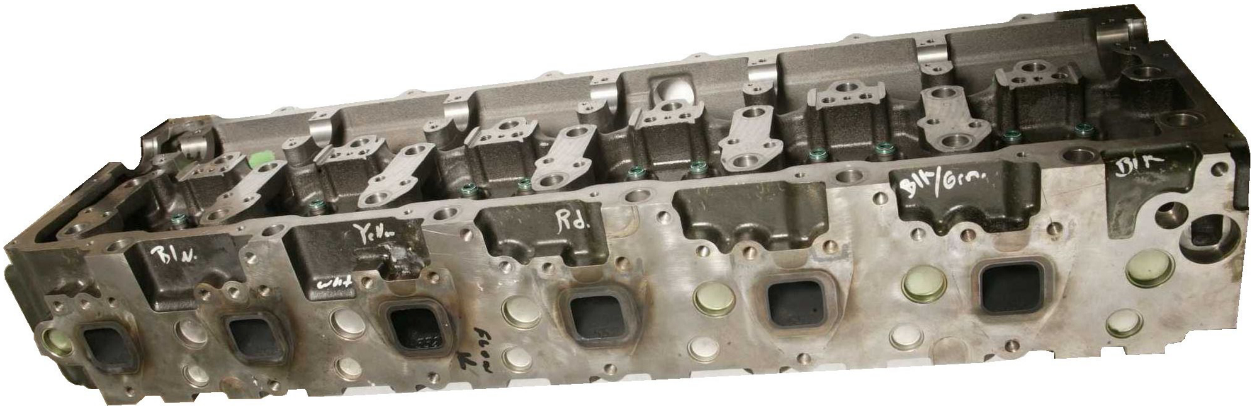

Figure 25. Cylinder Head (exhaust side view)

Figure 26. Cylinder Head (top view)

Figure 27. Cylinder Head with Cast-In Intake Manifold (firedeck view)

4.1 Valve and Port Arrangements

There is a four-valve arrangement on the D20, two intake valves and two exhaust valves. In Figures 27 and 28, intake ports are on the left, with each set perpendicular to the sides of the cylinder head in the "Far Square" arrangement. The intake valves are slightly larger than the exhaust valves. Note the chamfers cut into the valve pockets. All intake and exhaust pocket chamfers are concentric to the valves.

Figure 28. Cylinder Head - Four Valve Arrangement (bottom view)

Silicon rubber (RTV) molds were made of the D20 intake and exhaust ports by SwRI. There are six port branches off of the main volume of the cast-in intake manifold. Figures 29 and 30 show the intake port molds for cylinder 4. The branches have rounded rectangular cross sections at the base that quickly taper moving towards the intake ports, and tangentially intersect the valve pockets to promote swirl.

The exhaust ports sweep upward from the valve pockets into a fairly constant rectangular cross-section (see Figures 31 and 32) to the exit. Table 6 (next page) contains a summary of the port dimensions.

Figure 29. Intake Port Mold (iso view)

Figure 30. Intake Port Mold (top view)

Figure 31. Exhaust Port Mold (iso view)

Figure 32. Exhaust Port Mold (top view)

TABLE 6. INTAKE AND EXHAUST PORT DIMENSIONS

Feature	Dimension
Intake Ports Inlet H x W (where branches off main manifold)	42 x 64 mm
Intake Port Length (CL of valve to inlet of port)	92 mm 142 mm
Intake Valve Seat ID	32.2 mm
Exhaust Valve Seat ID	32.9 mm
Exhaust Port Length (CL of valve to exit port)	83 mm 136 mm
Exhaust Port Exit H x W	39 x 39 mm

4.2 Intake and Exhaust Valves

An intake and exhaust valve, along with springs, retainers and keepers are shown in Figure 33. All valves had one spring of constant pitch, made from round wire. Close ups of the valve seating surfaces are shown in Figures 34 and 35. Valves appeared to have even contact. There are no valve rotators.

Figure 33. Intake & Exhaust Valves, Springs, Retainers and Keepers

Figure 34. Intake Valve Seating Surface

Figure 35. Exhaust Valve Seating Surface

Table 7 lists major valve dimensions. Please see Appendix B for further details of valve and spring dimensions.

TABLE 7. VALVE MAJOR DIMENSIONS

Feature	Dimension
Intake Valve Head OD	40.1 mm
Intake Valve Stem OD	8.95 mm
Intake Valve Cold Lash	0.5 mm
Exhaust Valve Head OD	37.98 mm
Exhaust Valve Stem OD	8.95 mm
Exhaust Valve Cold Lash	0.6 mm

After engine disassembly, SwRI performed cylinder head flow bench testing of the D20 intake and exhaust valves and ports. See Appendix A for a copy of the flowbench report.

4.3 Valve Lift Measurements

Prior to disassembly of the valve overhead train, intake and exhaust valve lifts vs. crank angle were measured by SwRI, with valve cold lash set to specifications (see Figure 36).

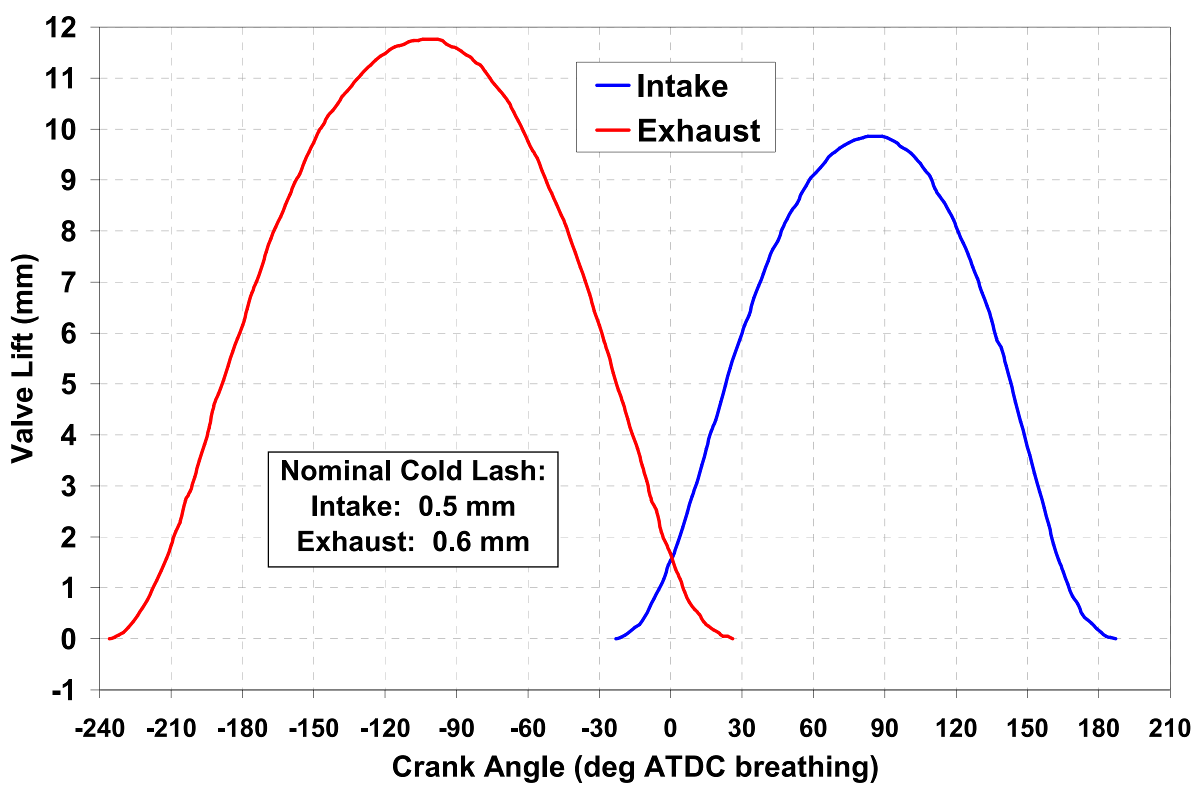

Figure 36. Valve Lift with Cold Lash

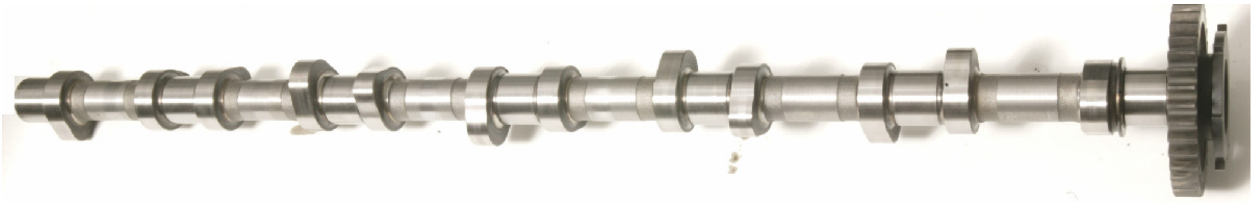

Figure 37. Camshaft

4.4 Camshaft

The MAN D20 has a single camshaft (see Figures 37 & 38) mounted on the intake side of the cylinder head with seven journal bearings. The forged steel gear on the rear of the shaft has a camshaft position wheel mounted behind it with 6+1 teeth, held by three bolts (see Figure 39), for the cam position sensor mounted in the head.

The camshaft is manufactured from a forged steel blank, with lobes induction-hardened. Intake and exhaust lobes have nearly the same widths. Although all journals displayed negligible wear, many of the lobes showed distinctive wear patterns with some light scoring and staining (see Figure 38).

The upper cam bearing cap and bearings are shown in Figure 40. The cap appears to be made from aluminum, and also serves as a cradle for the injector wiring harness. It is aligned to the cam saddle with two dowel pins. Each cam bearing half has two holes for oil flow, such that no alignment is required with the oil hole in the saddle. See Figure 26 for cam bearing saddles in the cylinder head. See Appendix B for measurements of journals and lobes.

Figure 38. Camshaft Lobes and Journal

Figure 39. Camshaft Gear and Position Wheel

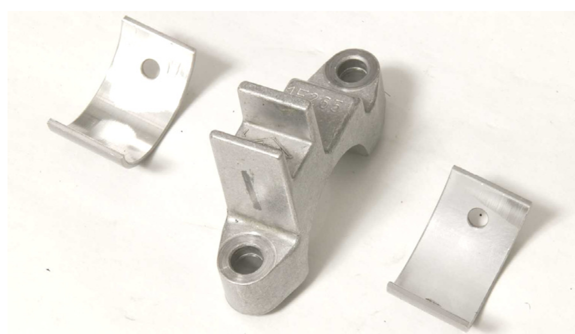

Figure 40. Cam Bearings & Cap

Figure 41. Camshaft and Valvetrain (installed, left rear view)

4.5 Valve Train and Engine Brake

The MAN D20 valve train uses rocker arms mounted on six separate shafts, with the shafts mounted in the cylinder head (see Figure 41). Each rocker pivot shaft is mounted in a pedestal which is bolted to the head with two socket head cap screws (see Figures 42 and 43). The intake and exhaust rocker arms appear to be mirror image identical designs.

Each rocker arm has a roller made of steel with a bronze alloy pin (see Figure 44). The valve end contains an elephant's foot joint for swiveling contact with the crosshead. Each foot is threaded with a locknut for adjusting clearance with the valve crossheads. An oil gallery in the head feeds through each pedestal into the hollow rocker shaft. The shaft then has holes that lubricate the bushings of the rocker arm. The bushings have holes that mate to cross drillings on both sides of both arms to lubricate the rollers and elephant's feet.

Figure 42. Rocker Assembly (top view)

The valve crossheads are shown in Figure 45 (exhaust crosshead is on the top). The exhaust crosshead has a piston on one side, which is part of the (MAN patented) engine brake system. Oil is fed to the crosshead through the exhaust rocker elephant's foot (see Figure 43, exhaust rocker on left.) The oil is then fed through the crosshead to pressurize the area behind the piston in the crosshead. On the top side of the crosshead, just above the piston, is a bleed hole as well. When the bleed hole is covered, pressure builds behind the piston and pushes it downward. When the hole is uncovered, the piston moves freely.

When assembled in the head, just above the exhaust crosshead is a counter-holder with a screw that can cover the crosshead bleed hole (see Figure 46). The counter-holder screw is adjustable and has a locknut, and is adjusted to provide a gap above the crosshead with exhaust valve closed. In normal operation, the bleed hole is not covered, and the exhaust valve opens and closes normally.

When engine braking is desired, the exhaust brake butterfly valve (see Figures 14 and 17) closes creating backpressure waves in the exhaust manifold, which cause the exhaust valves to flutter open immediately after they normally close. When the exhaust valve flutters open, the oil pressure moves the piston down, and as the valve then tries to close, it pushes the crosshead up against the holder screw, closing the bleed hole. This keeps the piston extended to hold the exhaust valve in the open position, creating engine braking by allowing highly restricted flow through the valve during compression and expansion strokes.

Table 8 lists rocker ratios.

TABLE 8. ROCKER RATIOS

Feature	Value
Intake Rocker Ratio	1.10
Exhaust Rocker Ratio	1.10

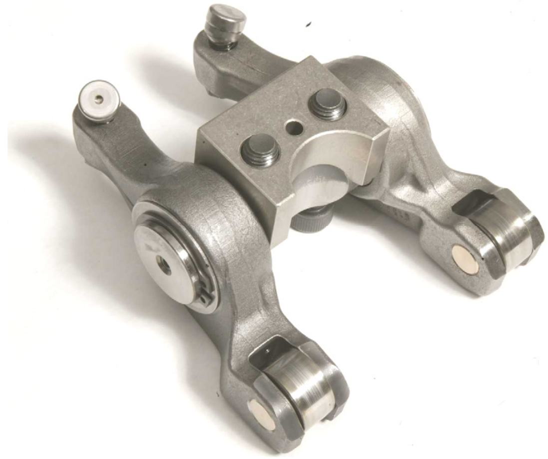

Figure 43. Rocker Assembly (bottom view)

Figure 44. Rocker Arm (bearing view)

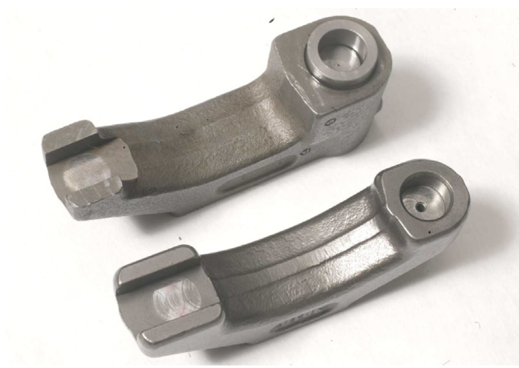

Figure 45. Valve Cross Heads

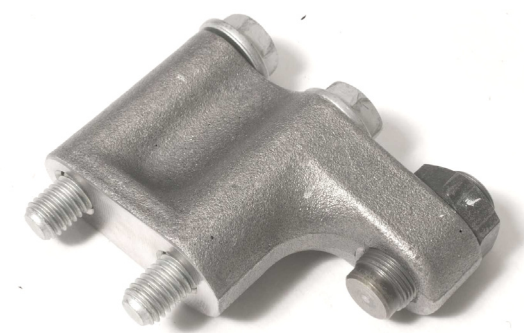

Figure 46. Engine Brake Counter-Holder

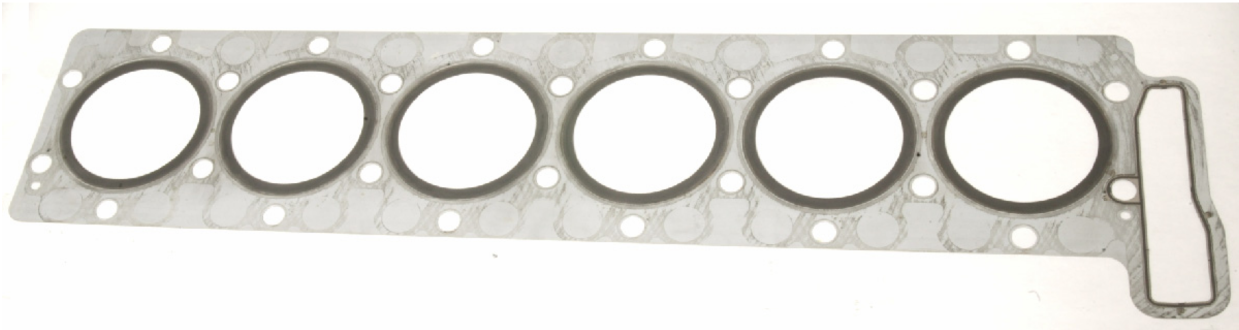

Figure 47. Cylinder Head Gasket (top view)

4.6 Cylinder Head Gasket

The D20 has a single layer steel (SLS) cylinder head gasket with an embossed rubber seal around the slot for the gear train (see Figure 47, cylinder 1 on the left, intake side on the bottom, gear train slot on the right). Note that there are no holes or cutouts for oil or coolant flow through the head gasket, only two small holes for locating dowel pins (see bottom left and bottom right). This is a feature of this engine, to provide capability for very high peak cylinder pressures. No extra gasket layers are used for the combustion seals. Instead, concentric ridges on the top of each cylinder liner (see Section 5.4) coin concentric grooves into the bottom gasket surface to provide a high pressure seal.

4.7 Cylinder Head Cooling

The cylinder head has no coolant mid-deck, and the water jacket in each cylinder cools three of the four valve bridges (not inlet-inlet bridge). The inlet to the head is from the coolant distribution manifold/water pump assembly mounted on the front of the engine, into a head passage on the exhaust side of the engine, near the firedeck. The passage runs to the rear of the head, with machined drillings off the passage that pass water into the jackets just to the exhaust side of the injector sleeve. Coolant flows up and to the left through the jacket, and along connecting cast passages on the top of the intake side of the head to the rear of the head.

There are two coolant exits from the head. The main exit is in the rear left side of the head, which flows into a crossover pipe feeding the EGR cooler. A second exit is in the front of the cylinder head into the thermostat housing portion of the coolant distribution manifold. The front exit, however, is restricted by the connector, which contains an orifice of about 11 mm diameter (see Figure 48). Thus it is probably used for vapor or stagnant flow relief for the front corner of the head. See Section 11 for more details on the cooling system.

Figure 48. Coolant Connector with Orifice

4.8 Cylinder Head Lubrication

The oil to the valvetrain is fed into the head externally, on the rear left side of the engine (near the cam position sensor). An oil rifle runs the length of the head, just under the rocker pedestals. Drillings connect the cam bearing saddles and rocker pedestals to the rifle. Oil return to the sump appears to mostly be over the rear gear train through the rear cavity of the head. There is also a return at the front exhaust side of the head that runs through the filter bypass cavity of the oil module, and then into the pan.

5.0 POWER CYLINDER

5.1 Piston and Wrist Pin

The MAN D20 engine utilizes an aluminum alloy piston made by Nural (see Figures 49-51), a Federal Mogul company, formerly Alcan Nural. Cast-in pockets are present in the skirts on both sides of the pin bores (see Figure 49). The sides of the skirt contain trapezoid-shaped areas coated with what appears to be a carbon-based low-friction material (see Figure 50). There are four valve pockets in the crown (see Figure 51)

Oil cooling is provided by piston cooling jets (see Figure 52) that spray oil to a cast-in gallery. The single spray jets are connected to the oil rifle on the exhaust side of the block. There are two gallery entrances in the bottom of the piston, one on each side of the pin. In this engine size range, most pistons are gallery-cooled due to increasingly higher cylinder pressures and stricter emissions requirements. There are also drain holes through the side wall of the piston, near the gallery ports, to feed the oil ring.

The pin is hollowed-out and has beveled end faces (see Figure 53). It is free-floating and is located by snap rings in the bore of the skirt. The pin bore has no bushings.

Figure 49. Piston and Pin Snap Ring

Figure 50. Piston Skirt with Coating

Figure 51. Piston Crown and Valve Pockets

Figure 52. Piston Cooling Jet

Critical dimensions for the piston and wrist pin are listed in Table 9.

TABLE 9. PISTON AND PIN DIMENSIONS

Feature	Dimension
Compression Height	76.8 mm
Bowl Diameter	70.0 mm
Max Bowl Depth	21.1 mm
Pin Bore Diameter	52.00 mm
Pin Length	95.87 mm
Pin OD	51.94 mm
Pin ID	22.89 mm

The crown of the piston has a central axi-symmetric combustion bowl. A silicon rubber (RTV) mold was made of the piston bowl by SwRI, then sliced in half to photograph the bowl profile (see Figure 54). The center of the piston bowl is conical, with a flattened top. The edges of the cone drop to a large radius forming the bottom of the bowl, which ends tangent to vertical sides. The top of the bowl contains an outer step up to the crown.

5.2 Piston Rings

There are three piston rings, top ring, intermediate ring, and an oil control ring. The top ring is a barrel face, full keystone, chrome-plated ring. The second ring is rectangular, tapered face, chrome plated scraper. The third ring is a double railed oil control ring, with coil spring expander.

5.3 Connecting Rod and Rod Bearings

The connecting rod is a forged steel, angled split design with the cap secured by two bolts (see Figures 55 and 56). The big end of the rod is manufactured by the fractured split method. The big end of the rod has cut-outs for the bearing locating tabs (see Figures 57 and 58).

The shank has a typical I-beam cross-section. No oil drillings are located in the shank as cooling of the upper power assembly and lubrication of the small rod end and pin is done with piston cooling jet spray.

Figure 53. Piston Pin End

Figure 54. Piston Bowl Mold

Figure 55. Connecting Rod

Figure 56. Piston & Connecting Rod Assembly

The small end of the connecting rod has a pressed-in bronze-faced bushing and tapered end faces. The tapered end of the rod yields large piston pin bore-to-pin contact area.

Critical dimensions for the connecting rod are summarized in Table 10.

TABLE 10. CONNECTING ROD DIMENSIONS

Feature	Dimension
Overall Length	372.7 mm
Small End ID	52.00 mm
Big End ID	95.08 mm
Center-to-Center Length	256.0 mm
Bolt Diameter	M12

Figure 58 shows the bearings from the big end of the connecting rods. Both bearings have smooth surfaces with no oil grooves or oil holes. Material appears to be tri-metal lead / tin / copper on steel back bearings. Each bearing has one locating tab on the back of the shell.

5.4 Cylinder Liners

The MAN D20 engine utilizes a top stop liner design (see Figure 59). Two O-rings are located in the block to seal against the liner.

The top of the liner has concentric protruding ridges machined into it (see Figure 60). When the cylinder head clamping load is applied, the ridges coin grooves into the SLS cylinder head gasket (see Section 4.6), forming a high pressure combustion seal.

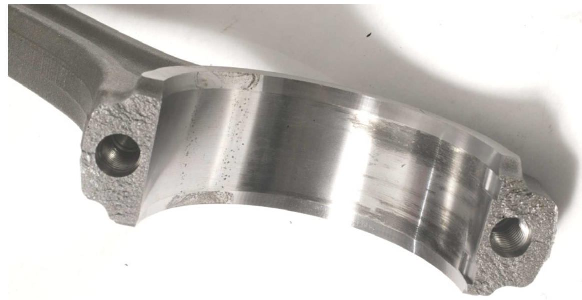

Figure 57. Connecting Rod Big End - Fractured Split

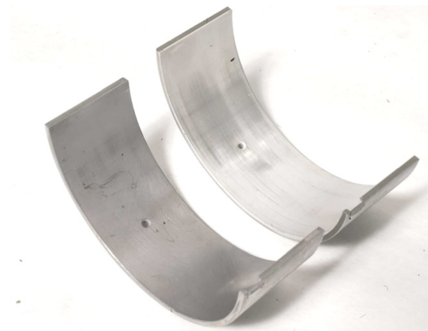

Figure 58. Connecting Rod Bearings

Figure 59. Cylinder Liner

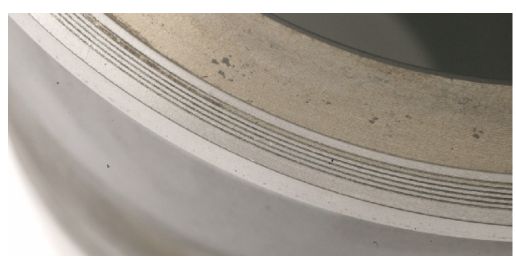

Figure 60. Cylinder Liner Top Ridges

6.0 ENGINE BLOCK AND OIL PAN

6.1 Engine Block, Cooling and Lubrication

The MAN D20 engine block, shown in Figures 61-65, is a deep-skirt design, cast from a high-strength compacted-graphite iron (CGI) alloy GJV-450, according to MAN press releases. Table 11 lists some of the critical dimensions.

TABLE 11. MAJOR BLOCK DIMENSIONS

Feature	Dimension
Bore Spacing	154.0 mm
Pan Rail Width	398 mm
Skirt Depth from Crank Center	100 mm
Top Deck to Main Saddle	354 mm

The D20 features front and rear gear sets (see Section 8). The block has a six-bolt pattern per cylinder for mounting the cylinder head, with two dowel pins for location (see Figure 63).

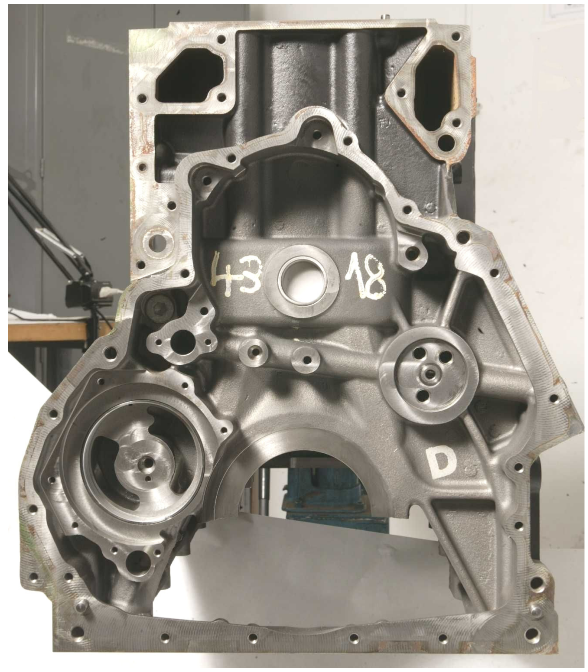

Figure 61. Engine Block (front view)

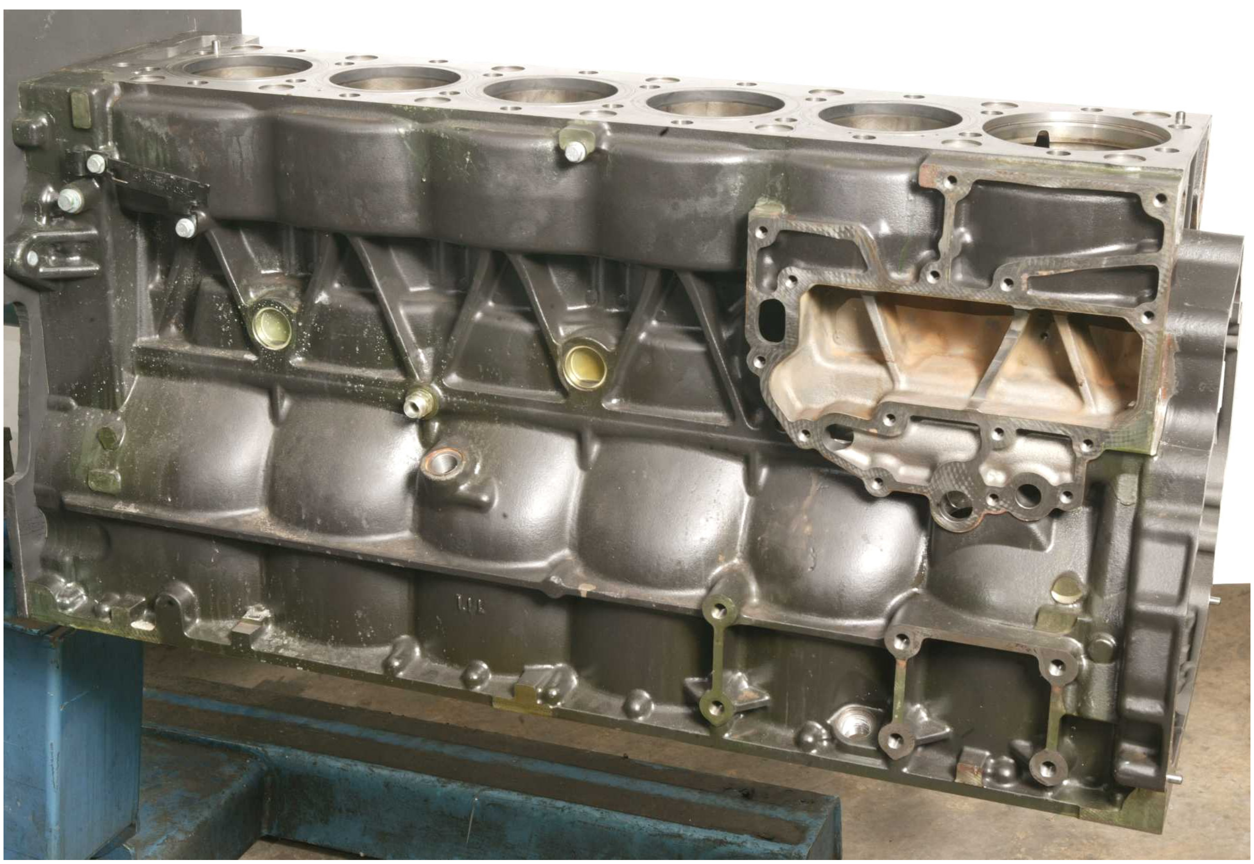

Figure 62. MAN D20 Engine Block (right side view)

Figure 63. MAN D20 Engine Block (top view)

Figure 64. MAN D20 Engine Block (left side view)

Note the width of the oil pan rails (see Figure 65). Also, as shown in Figures 62 and 64, the walls of the block and skirt feature a contoured shape with irregular surfaces and many cast-in ribs. These features add stiffness to the block and aid in noise reduction and, along with the CGI material, provide for high strength with low weight.

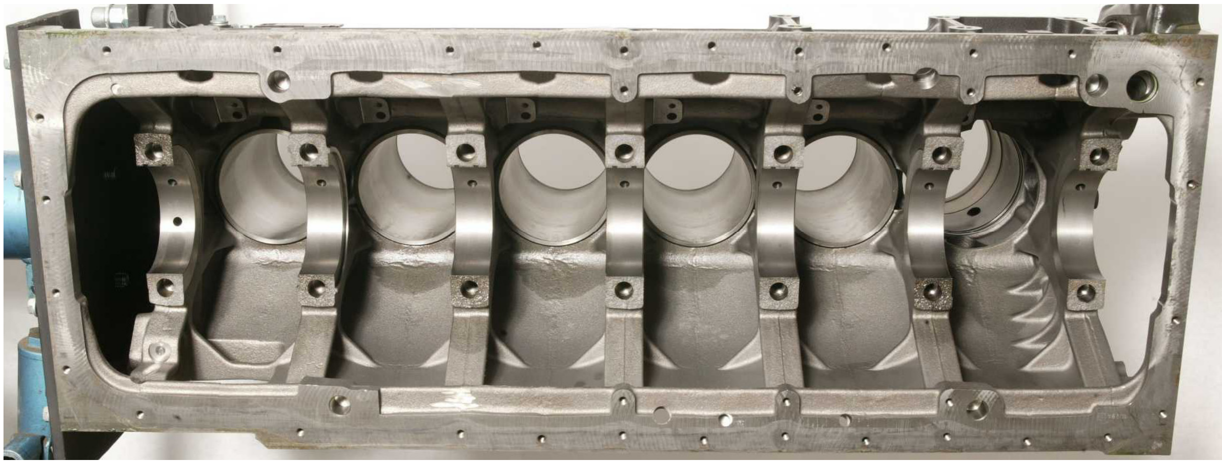

Figure 65. Engine Block (bottom view)

The main oil rifle is drilled into the right side of the block. The rifle is supplied from oil module on the right side of the engine, and provides oil to piston cooling jets, and (through diagonal cross-drillings) to crank bearings, idler gears and turbocharger bearings. Oil to the cylinder head is routed externally. Coolant flow through the block begins on the right front side of the engine where coolant enters from the externally mounted water distribution manifold into the block (see Figure 61, top left). A cavity runs from the front of the block to the rear on the right side of the engine (see top of Figure 62). Two holes connect this main cavity to each liner jacket. One hole is located higher than the other. There are also holes between each cylinder connecting the liner jackets. Coolant also flows into the oil cooler cavity at the front right side of the engine (see Figure 62, right center).

On the left side of each liner jacket are two exit holes that flow coolant to the return cavity in the left side of the block. The left side cavity has two exits from the block. The main exit is at the rear of the left side, into an elbow and crossover tube feeding the EGR cooler (see Figure 64, top right). There is also an exit in the front into the coolant distribution manifold (see Figure 61, top right). Coolant to the head is routed externally, not through the block.

Although there is a large opening in the front coolant exit, flow is highly restricted by the front plastic-coated metal gasket between the block and the coolant distribution housing, which contains only a small orifice hole at the top of the opening, most likely for vapor relief (see Figure 66 near top). Upon disassembly, this front gasket was found to be torn, with the tear extending around more than half of the outside of this front coolant exit, allowing much higher coolant flow than was intended (see Figure 67).

Figure 66. Torn Front Gasket

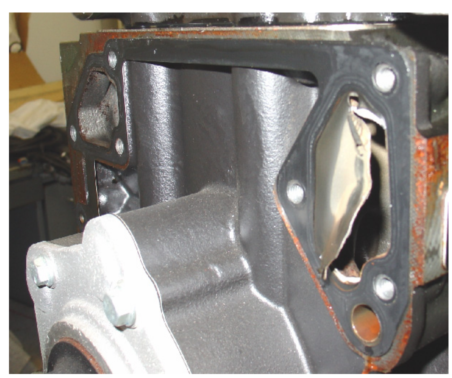

Figure 67. Torn Front Gasket on Block

6.2 Main Bearing Caps

The block features two-bolt main bearing caps that are manufactured as part of the block and then fractured-split from the main bearing saddles (see Figures 68-70). This is done to eliminate fretting of the main caps and maintain crankshaft bearing bore alignments, and no dowels or extra machined features are needed for alignment. There are also cut-outs on the bores for locating the main bearing shells.

Figure 68. Main Bearing Cap-Split Line

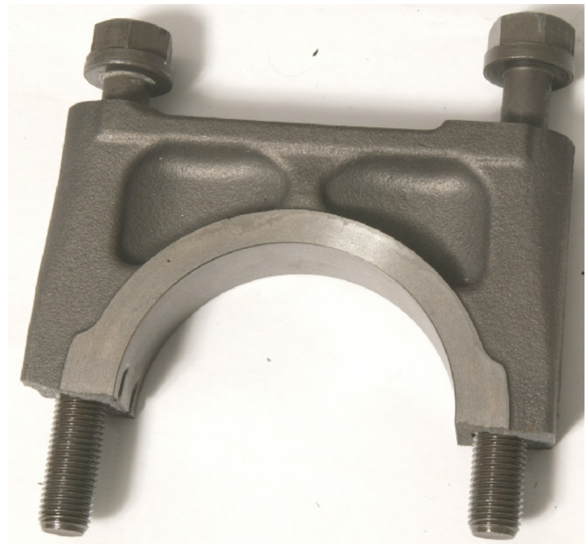

Figure 69. Main Bearing Cap

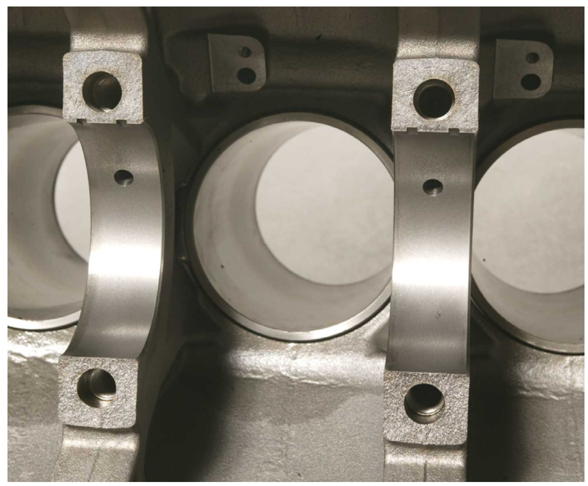

Figure 70. Fractured Split Main Bearing Saddles

6.3 Oil Pan

The D20 oil pan is made from two stamped steel pieces (see Figure 71). The two pieces are nested together and bonded, to form the oil pan. There is also an intermediate layer for noise abatement. Note the vertical and horizontal ribs to add further stiffness. The oil pan is shallow for the rear two-thirds of its length, while the front one-third carries the majority of the oil capacity.

Figure 71. Oil Pan

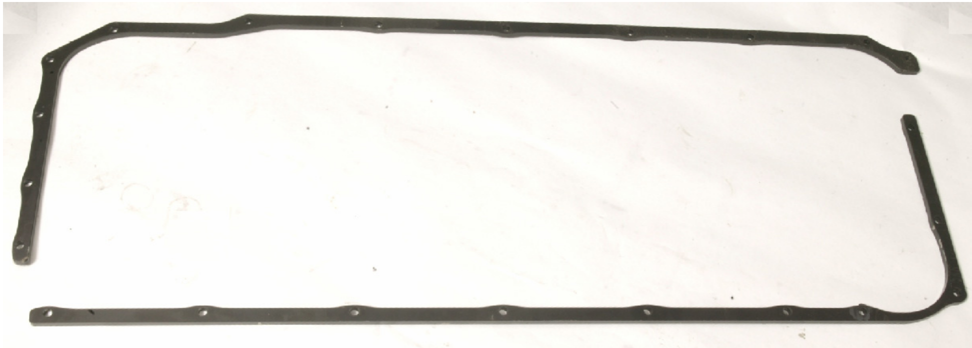

Figure 72. Oil Pan Clamping Rails

Figure 73. Crankshaft

The oil pan is fastened to the block with two forged steel rails for even clamping (see Figure 72), with 10 mm tall standoff sleeves between bolt heads and rails to maintain clamping load.

7.0 CRANKSHAFT, VIBRATION DAMPER, AND MAIN BEARINGS

7.1 Crankshaft

The MAN D20 crankshaft is made from forged steel and features induction-hardened journals and fillets, with no undercuts of the fillets (see Figure 73). It is an integrally balanced unit with counterweights drilled out or machined in some locations to achieve proper balance. The crankshaft is supported by seven main bearings, with the thrust bearing location at bearing six.

Oil for the main bearings is fed through holes from the main oil rifle into the upper main bearing saddle (see Section 6.1). The oil then passes through cross drillings in all of the main crank journals, except #6, to angled drillings to lubricate adjacent connecting rod bearings. All of the crank oil drillings are chamfered on the hole edges.

The crankshaft has gears on both ends. The rear gear and flywheel is secured to the crankshaft with 10 bolts. The front gear and vibration damper is secured with eight bolts.

Critical dimensions are listed in Table 12.

TABLE 12. CRANKSHAFT DIMENSIONS

Feature	Dimension
Main Journal Diameter	104.00 mm
Rod Journal Diameter	90.00 mm
Main Bearing Width	35.75 mm
Rod Bearing Width	36.01 mm
Thrust Bearing Thickness	3.35 mm

7.2 Vibration Damper

The vibration damper, as shown in Figure 74, is mounted to the drive-gear end of the crankshaft, on the front end of the engine. It is a viscous-type vibration damper mounted on an eight-bolt pattern to the crankshaft, through the crank gear.

Figure 74. Vibration Damper

7.3 Main Bearings

The main bearings feature a grooved upper shell drilled for oil supply, and a smooth lower shell with grooves only at the ends (see Figure 75). Each bearing shell has a tab on the backside for locating it within the main bore. Thrust bearings, located at bearing #6, are shown in Figure 76. Both top and bottom thrust bearings are used.

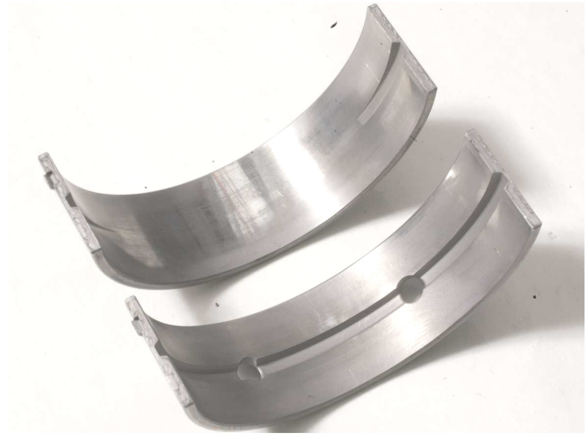

Figure 75. Main Bearing Shells

Figure 76. Thrust Bearings

8.0 GEAR TRAIN

The MAN D20 engine features front and rear gear trains. Both are contained in gear housing cavities cast into the block. The front gear train (see Figure 77) consists of the crank gear (bottom), idler gear (on right), oil pump gear (left bottom, not visible), and fan drive gear (top). The idler gear also drives another gear through a slot in the block housing (top right), which drives a shaft with the supply and high pressure fuel pumps on the rear (see Section 9) and the auxiliary belt drive pulley on the front (see Figure 1, bottom right). All of the gears are spur gears.

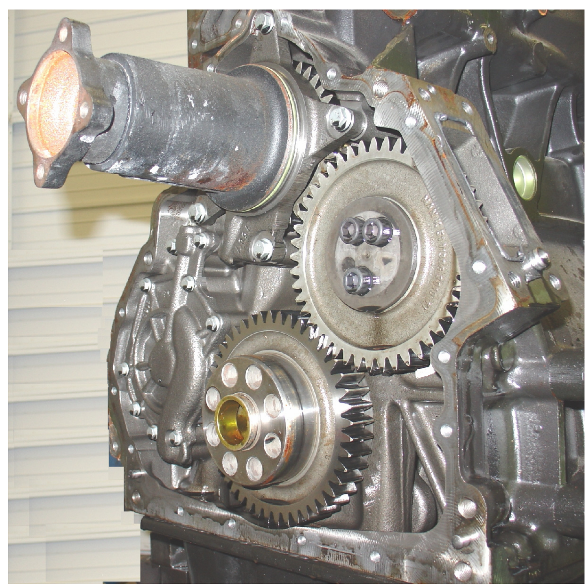

Figure 77. Front Gear Train

Figure 78. Front Gear Train Cover

A cast aluminum gear housing cover mounts over the gear train, to the front of the block (see Figures 78 and 79). The cover has a plastic material adhered to it, presumably for noise reduction. The cover contains a rubber oil seal (bottom of figures), which fits snugly around the nose of the crankshaft gear (bottom of Figure 77). An O-ring in a groove on the fan drive housing (Figure 77, top center, light green ring) seals the top of the front of the cover.

On the rear gear train (see Figure 80), the crank gear (bottom center) drives the large gear in a compound idler gear set (center). The small gear on the back of the compound set (see Figure 81) drives an idler gear at the top of the block (see Figure 80, top left), which connects to an idler in rear of the cylinder head through slots in the block and head to drive the camshaft gear (head gears not shown). Again, all gears are spur gears.

The crank gear also drives an idler gear (Figure 80 bottom left), which through a slot in the block, drives the air compressor, attached to the rear of the left side of the block (see Figure 2, bottom right). The air compressor idler gear is actually a pair of scissors gears (see Figure 82), to remove gear lash and suppress noise from the air compressor torque reversals. The rear gear train is enclosed by the flywheel housing (see Figure 83).

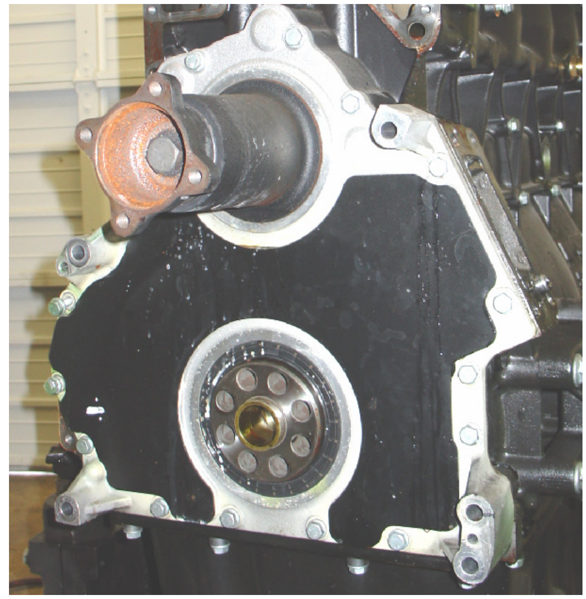

Figure 79. Front Gear Train Cover (installed)

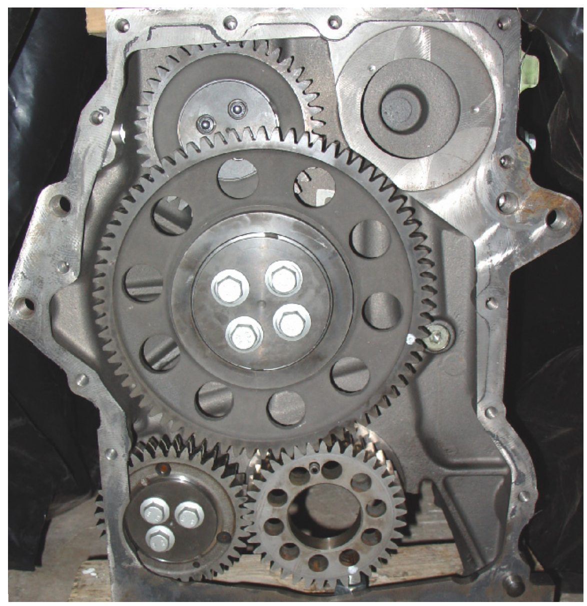

Figure 80. Rear Gear Train

Figure 81. Compound Idler Gear Set (back)

Figure 82. Air Compressor Idler (scissors) Gears and Hub

Although not fully machined in this model, features are cast into both the block (Figure 80, top right) and the flywheel housing (Figure 83, top center) for a rear engine power take-off (REPTO), which is apparently driven by the large compound idler gear.

9.0 FUEL SYSTEM

The fuel system for the MAN D20 is the Bosch second generation High Pressure Common Rail (HPCR), based upon a high pressure pump and a high pressure accumulator or "rail" common to all injectors.

9.1 Supply System

The fuel supply system begins with an inlet fuel filter screen and water separator in a visibly translucent plastic bowl, attached to the fuel filter housing (see Figure 84, top left). On top of the primary fuel filter is a hand priming pump.

9.2 Fuel Pump / Accessory Drive Pulley Assembly

From the filter, fuel is carried through tubing to the inlet of the supply pump, which is mounted on the rear of the fuel pump and accessory drive

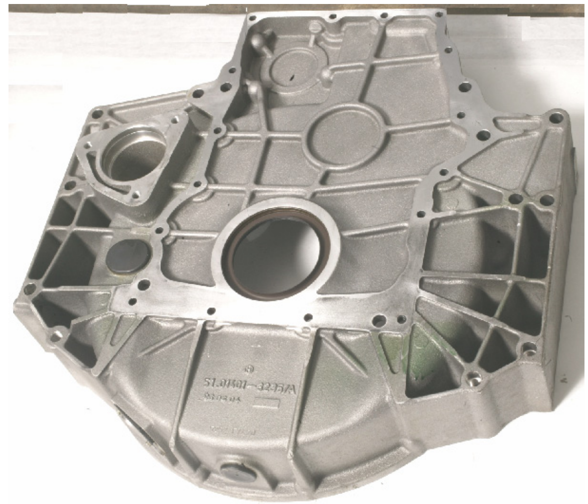

Figure 83. Flywheel Housing (engine side)

Figure 84. Fuel Filter Assembly

pulley assembly (see Figure 85, far left). The assembly is mounted onto on the left of the top of the front gear train. It is gear driven, with a gear protruding on the bottom of the assembly (see Figure 86) through a slot on the block gear housing to connect with the front gear train idler gear (see Section 8 and Figure 77, top right). The assembly contains two fuel pumps, a supply pump and a high pressure pump (see Figure 85, left of center), a fuel manifold and valve block (center), plus an accessory belt drive pulley (bottom right), all mounted on the same shaft, with a gear ratio of 5/3 to crankshaft speed. The assembly also contains the engine oil fill tube (top right).

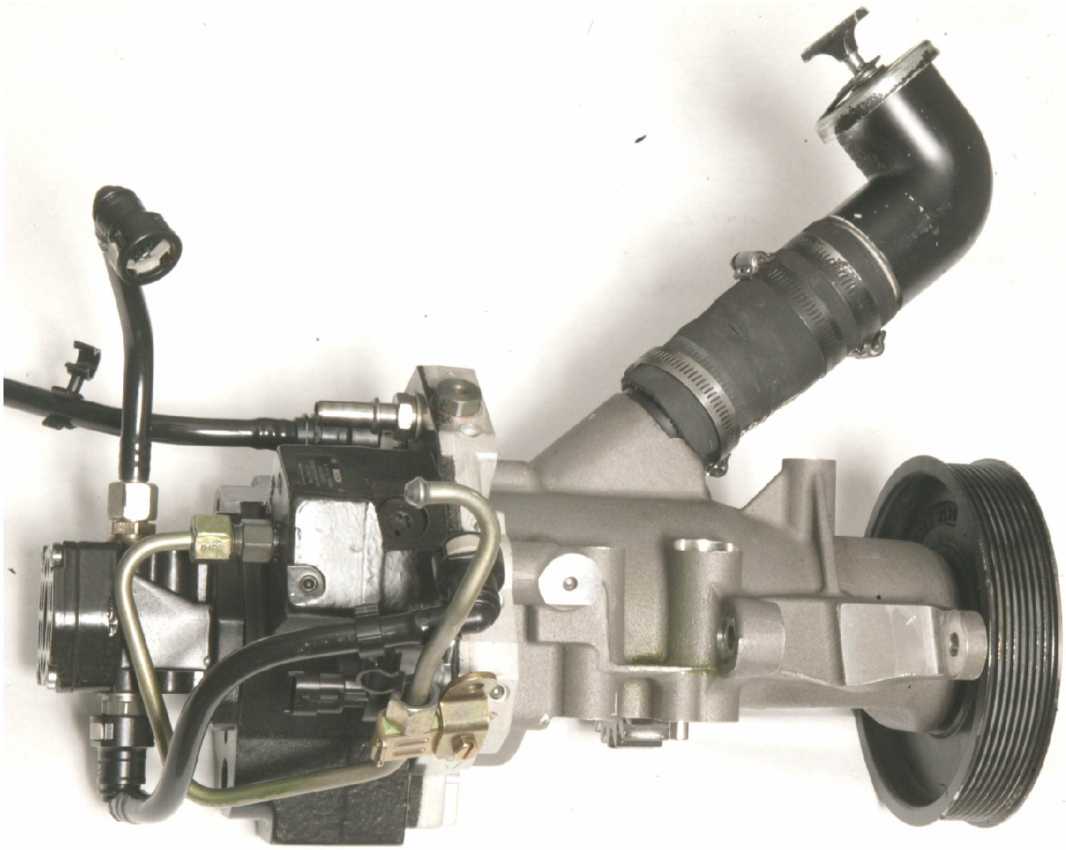

Figure 85. Fuel Supply and High Pressure Pumps, Fuel Manifold/Valve Block, Accessory Drive Pulley and Oil Fill

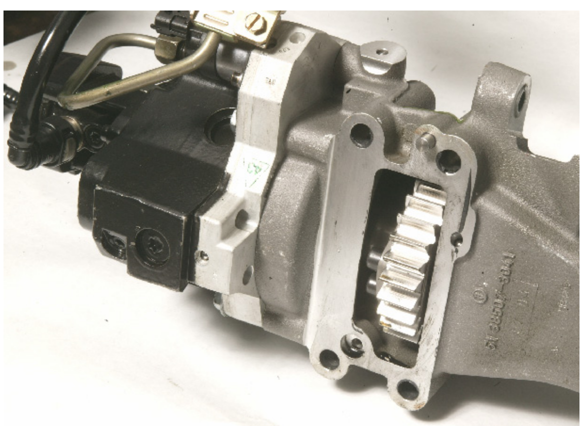

Figure 86. Fuel Pump and Accessory Drive Assembly (bottom view of drive gear)

9.3 Fuel Filter Assembly

From the supply pump, fuel flows through tubing to the fuel filter assembly (see Figure 84). It enters through a fitting (bottom left of center) which can optionally contain an added fuel heater sleeve, according to service literature (not present on this engine). Fuel then flows upward through a cast passage, past a supply fuel pressure sensor (left above center) and into the main fuel filter canister. After flowing through the main (cartridge) filter, it enters a manifold in the bottom of the assembly which has a banjo fitting exit (bottom center) to the inlet air flame heater (see Section 3.4 and Figure 21), and an entrance from the fuel rail overpressure valve (Figure 84, bottom right), in addition to the main fuel supply exit (bottom right of center). The manifold also has a plastic manual water drain fitting (bottom on right).

9.4 Fuel Manifold and Valve Block

From the fuel filter exit, fuel flows to the fuel manifold and valve block, attached to the high pressure fuel pump (see Figure 85, center), which contains internal drillings and two valves. The first valve controls the supply pressure to a constant 5.0 bar (72.5 psig). Fuel then flows to a fuel control actuator (FCA), which is a proportional valve controlled by the ECM, regulating how much fuel goes to the inlet of the high pressure pumping chambers (called "inlet metering control"). Fuel not sent to the high pressure pump is sent by the pressure control valve and/or FCA back to a junction with the intake to the inlet fuel filter screen.

The high pressure pump is a Bosch CP3.4 pump. This pump is very similar to the CP3.3 pump used on smaller midrange engines (such as the Cummins ISB and GM/Isuzu Duramax), except that it is larger for higher capacity. It is not yet in production in the U.S., but is manufactured exclusively for MAN in the Czech Republic. Besides being larger, its center chamber (cam and follower tappets) is also oil lubricated, rather than fuel lubricated like the CP3.3.

The pump contains three pumping plungers arranged radially at 120 degree intervals. The central cam lobe of the pump is circular and eccentric to the pump shaft axis. Sliding on the outside of the lobe is a circular sleeve with three flats on the outside. The sleeve does not rotate. As the eccentric cam rotates, the center of the sleeve moves with the cam center, and the three sleeve flats press upon sliding flat tappets, each of which contains the inner end of one of the three injection plungers surrounded by a return spring.

At the outer ends of the plungers are the three high pressure pumping chambers. Each chamber contains two check valves, an inlet and an outlet. As the plunger moves inward, it draws fuel from the supply circuit through the inlet check valve. As the plunger moves outward, the inlet check valve closes, the pumping chamber pressure increases until it exceeds the pressure in the high pressure circuit, which opens the outlet check valve and pumps fuel into the high pressure circuit.

9.5 High Pressure Fuel Rail and Connectors

From the high pressure pump, fuel is carried through a double-walled composite steel transfer tube to the high pressure accumulator or "common rail" (see Figure 87, inlet on left end). The rail is a cylindrical steel alloy forging, mounted on the bottom of the intake manifold cast into the cylinder head. From the rail, six double-walled composite steel tubes of equal total length carry the high pressure fuel to the injector high pressure connectors, mounted horizontally above the intake manifold in the cylinder head. Each injector line contains at least two bends, to allow for pressure expansion.

The rail also contains a fuel pressure sensor (on left, between lines for cylinders 1 and 2), and an overpressure valve (on right end). The overpressure valve does not normally open, but is a safety device in the event of pressure sensor or controls malfunction, and outputs fuel to the fuel supply circuit. The high pressure injection lines and transfer line from the high pressure pump to the rail are fastened to the rail, pump and injector connectors with swaged tapered tip fittings.

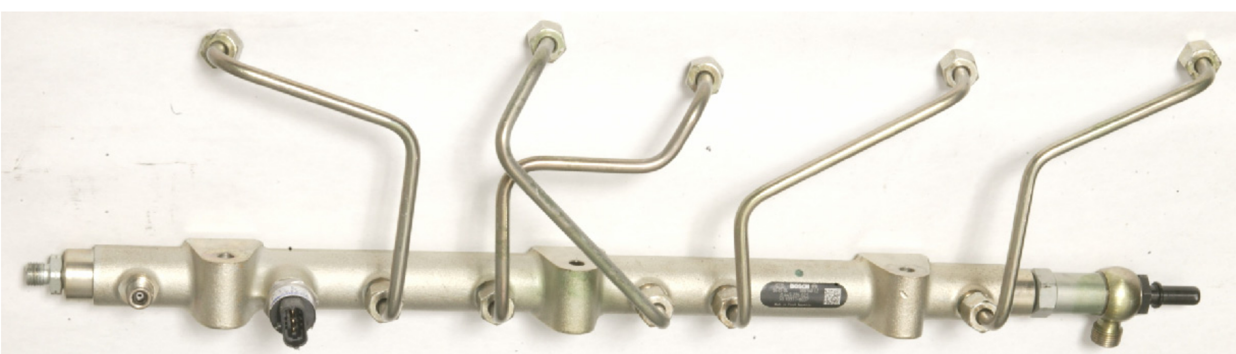

Figure 87. High Pressure Common Rail and Injector Lines (note: one injector line is missing)

The high pressure injector connectors (see Figure 88) are tapered steel, thick-walled tubes that are connected to the injectors with a spherical tip inserted into a seat in the side of the injector. They are fastened into the cylinder head with externally threaded sleeve nuts, with O-ring seals to contain any fuel leakage within the injector drain circuit.

The total fuel volume of accumulator (rail), transfer line, injection lines and high pressure connectors is enough that the fuel, due to its compressibility, stays at relatively constant pressure. The ECM regulates the fuel control actuator (FCA) in the injection pump assembly (see Section 9.4) to achieve the target rail pressure, with feedback from the fuel pressure sensor on the rail. The system is capable of rail pressures from 300 to 1600 bar (4350-23,200 psi), with the overpressure valve on the rail set to open at 1800 bar (26,100 psi). These pressures are achievable throughout most of the engine speed range, independent of the engine speed. This independent pressure capability, especially high pressures at low speeds, is a major asset for achieving combustion and emissions targets.

9.6 Fuel Injectors and Drain Rail

The MAN D20 fuel injectors are direct needle-control injectors by Bosch (see Figure 89). The injectors mount vertically in the cylinder head, held down by single bolt yoke clamps (see top of Figure 88), with tips protruding into the centers of the cylinder bores. A flat copper washer around the injector tip seals the injector bore from the combustion chamber. An O-ring seals the top of the injector bore. The high pressure fuel inlet is the spherical seat in the side of the injector for the high pressure connector (see Figure 89, left center). Leakage fuel and control valve bypass flow exits the injector through a small hole in the side (on left near bottom) into the annulus around the injector between the O-ring and copper washer. A drain drilling runs the length of the cylinder head and intersects the injector bores tangentially and the high pressure connector bores, to carry leakage and bypass fuel to the drain circuit and back to the fuel tank.

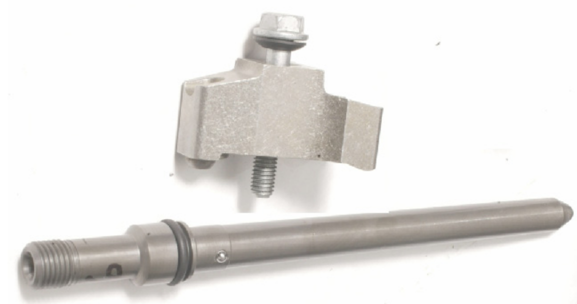

Figure 88. Fuel Injector Clamp and High Pressure Connector

Figure 89. Fuel Injector

As part of the common rail system, the chambers in the injector from the high pressure connector inlet to the needle chamber remain at high pressure constantly during engine operation.

The tip of the injector contains a needle with a return spring similar to other closed nozzle injectors, in that fuel pressure acts to lift the needle and allow flow to the spray holes, and the spring acts to close the needle. However, extra direct control is provided by a control plunger in the center of the injector, contacting the top of the needle. Above the control plunger is a control chamber with two orifices, a feed or inlet orifice, and a bleed or outlet orifice. The feed orifice connects horizontally to the injector high pressure fuel inlet. The bleed orifice leads upward to a ball valve controlled by the solenoid on top of the injector.

Prior to injection, the solenoid return spring holds the ball valve down, closing the bleed orifice path and pressurizing the control chamber above the control plunger. This provides force downward on the injector needle which, along with the needle return spring, is greater than the pressure force in the needle chamber, holding the needle down to close the path to the nozzle spray holes.

To start injection, the solenoid is energized, which lifts the ball valve off its seat and allows flow through the bleed orifice out of the control chamber, and out of the injector to the drain circuit. Due to the feed orifice at the control chamber inlet, the control chamber pressure then drops, reducing the force holding down the control plunger and injector needle. The pressure below the needle lifts it, allowing flow to the spray holes to begin injection.

To end injection, current to the solenoid is cut off, and the solenoid return spring moves the ball valve downward, closing the bleed orifice path. The control chamber pressure rises to the rail pressure immediately from flow through the feed orifice, providing force downward on the control plunger and needle. Along with the needle return spring force, this overcomes the pressure force below the needle, which returns to its seat in the nozzle, halts flow to the spray holes and ends injection.

Due to the fast response and direct needle control, the injector is capable of multiple injections during each combustion event, providing pilot and post injection capability. Some rate shaping is also possible with optimization of the relative sizes of feed and bleed orifices, and the rate of solenoid current change.

10.0 LUBRICATION SYSTEM

10.1 Oil Pump

The D20 oil pump is a gerotor pump, with the outer stator being driven by the crankshaft gear, rather than the inside rotor, as on most gerotor pumps (see Figures 77 and 90). This design helps to reduce the thickness of the assembly. The pump cover (see Figure 90) mounts directly to the block. The suction line tube (see Figure 91) bolts to the bottom and inside of the block and passes oil to the pump cavity in the front of the block.

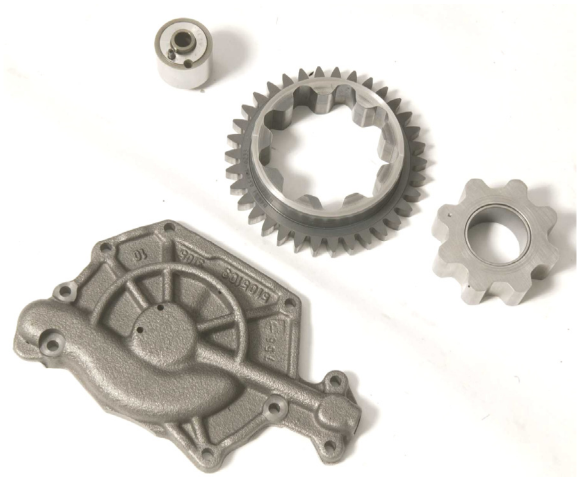

Figure 90. Oil Pump

Figure 91. Oil Suction Line

10.2 Oil Module and CCV System

A large oil module is mounted on the front of the exhaust manifold (right) side of the block (see Figure 92). This module contains the oil filter cartridge (on right), oil pressure control valve, oil pressure sensor and bypass valves for both the filter and oil cooler for high pressure drops (mostly used for cold starts). As part of the closed crankcase ventilation (CCV) system, it also contains the oil mist separator (on left), and routes oil to the cylinder head. It also routes return and CCV separated oil back to the sump. The oil cooler mounts to the back side of the module, and is embedded in coolant in a cavity in the block (see Figure 93, top center). The module is made mostly of cast aluminum.

The top of the oil mist separator (See Figure 92, top left) feeds the crankcase air to the inlet air connector / CCV mixer at the turbo compressor inlet (see Figure 14).

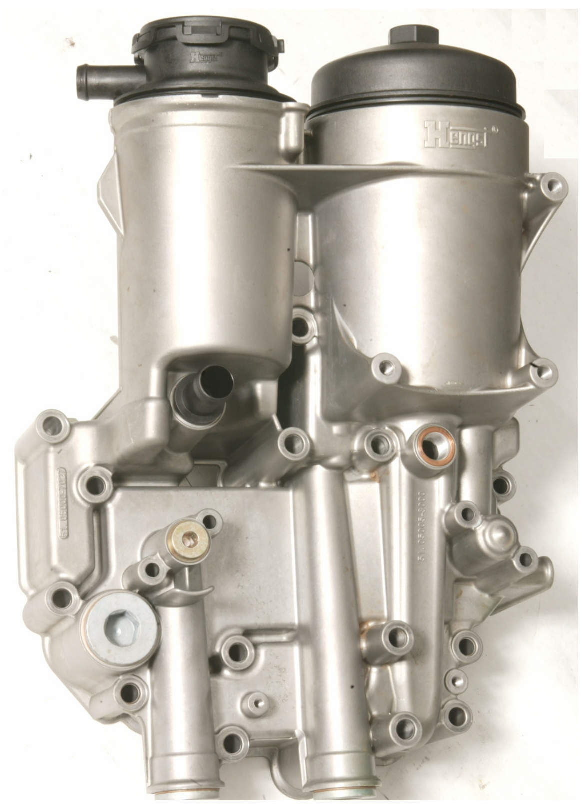

Figure 92. Oil Filter Module

Figure 93. Oil Cooler Cavity

10.3 Oil Cooler

The oil cooler is a typical plate and fin cooler with 10 plates (see Figure 94). Major dimensions of the cooler are shown in Table 13.

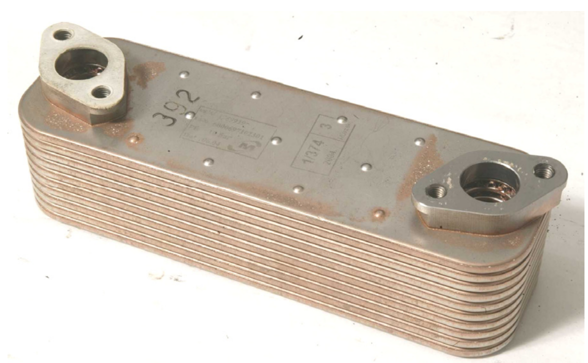

Figure 94. Oil Cooler Core

TABLE 13. OIL COOLER DIMENSIONS

Feature	Value
Core length	250 mm
Core width	78 mm
Core height	68 mm
Flow type	Cross flow

10.4 Oil Rifle and Feeds

After the filter, the oil flows from the filter base into the block main oil gallery. See Section 6 for discussion of oil paths through the block, Section 4 for valve train lubrication.

11.0 COOLING SYSTEM

11.1 Coolant Pump and Flows

The coolant pump is a pulley-driven centrifugal pump mounted in a coolant distribution manifold on the front of the engine (see Figure 95 and center of Figure 1). The distribution manifold is made up of four aluminum castings assembled together (see Figure 96). The first is a large piece that bolts to the front of the block (see Figures 97 and 98). It houses the pump (top left, Figure 97) and water inlet from the radiator (bottom left), feeds coolant into the top of the block (see Figure 61, top left) and receives coolant bleed flow from the block (see Figure 61, top right and Figure 67).

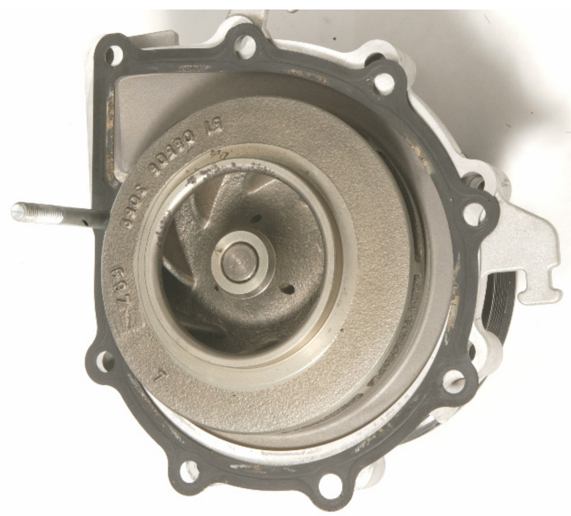

Figure 95. Coolant Pump

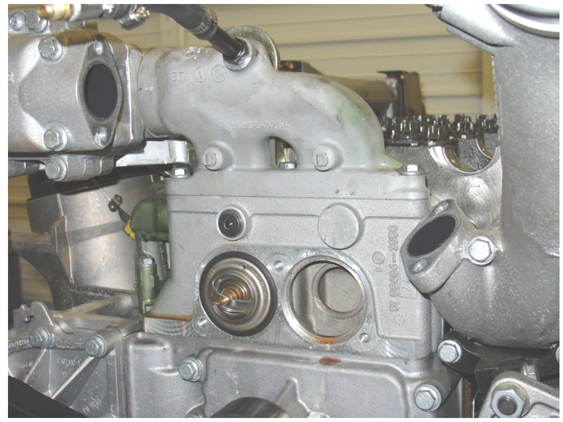

Figure 96. Top of Distribution Manifold w/ Thermostat Cover Removed

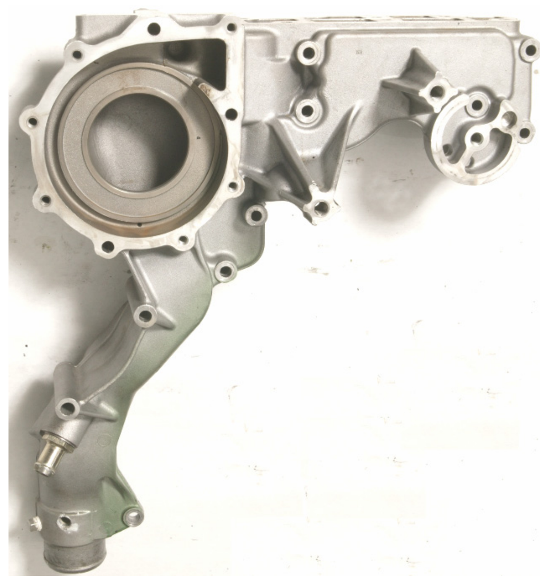

Figure 97. Distribution Manifold-Main Piece

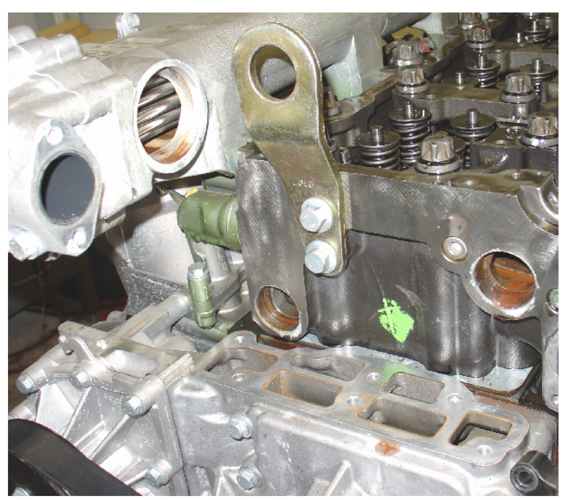

Figure 98. Distribution Manifold Main Piece (thermostat housing and EGR return removed)

The second is a thermostat housing that sits on top of the first main piece (see Figure 99). It feeds coolant into the front of the cylinder head coolant manifold (see Figure 98, center round hole) and receives restricted coolant flow from the cylinder head return passage (see Figure 98, right center hole and Figure 48). The third piece is a return elbow from the EGR cooler (see Figure 100), which sits on top of the thermostat housing. The final piece is the thermostat cover (see Figure 101) that directs water to the radiator. It is mounted on the front of the thermostat housing.

Figure 99. Thermostat Housing (top rear view)

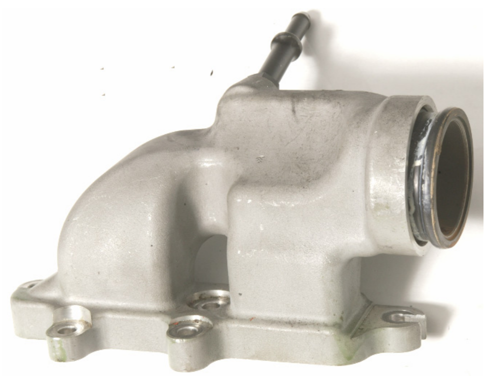

Figure 100. EGR Coolant Return Elbow (rear view)

Figure 101. Thermostat Cover (top rear view)

Coolant flow through the block and cylinder head is mostly diagonal, from front right to left rear. The flow exits the rear of the left of the block into a return elbow (see Figure 102). The coolant also exits the left of the rear of the head and the block return elbow into the coolant crossover tube (see Figure 103), which carries the flow across the back of the head and up to the inlet at the rear of the EGR cooler (see Section 3.1 and Figure 5).

Rather than using standard O-ring connections, many of the coolant connectors are made from straight stainless steel tubing covered by a molded rubber jacket with molded flanges at both ends (see Figures 99, 100 and 104). Besides appearing quite sturdy, the connectors allow for component tolerances and slight misalignment.

See Section 6.1 for further information on flows through the block and around the cylinder liners, and Section 4.7 for further detail on coolant flows through the cylinder head.

11.2 Thermostats and Coolant Bypass

The thermostat housing holds two interchangeable thermostats (see Figures 96 and 105). According to service literature the thermostats open at 83°C (181°F).

Figure 102. Block Coolant Return Elbow

Figure 103. Coolant Crossover Tube

Figure 104. Crossover Tube Inlet Connectors

Figure 105. Thermostat

With the thermostat fully open, coolant flow exits the front of the thermostat housing through the thermostat cover to the radiator. With the thermostat fully closed, coolant flows downward through the backside of the thermostat housing and main manifold to the pump inlet.

12.0 ELECTRONIC CONTROLS, SENSORS AND ACTUATORS

The following are the production sensors and actuators for the MAN D20 engine:

On-engine sensors:

- Intake manifold air temperature
- Boost pressure
- Coolant temperature
- Fuel supply pressure
- Fuel rail pressure
- Oil pressure
- Oil temperature
- Camshaft speed and position sensor
- Crankshaft speed and position sensor

Actuators:

- Injector actuators (one each)
- Fuel (rail pressure) Control Actuator (FCA)
- Exhaust gas recirculation (EGR) valve actuator
- Exhaust brake actuator

The camshaft speed and position sensor is mounted in the rear of the cylinder head to sense the 6+1 tooth wheel bolted to the camshaft gear (see Figure 39). The crankshaft speed and position sensor is mounted in the top right of the flywheel housing to sense the 60-2 holes drilled into the flywheel.

The MAN D20 electronic control module mounts on the top center of the left side of the block with shock isolation mounts (see Figure 2). The mounting plate is not fuel cooled.

13.0 ACKNOWLEDGEMENTS

The authors would like to thank SwRI Design Section staff W. Robert Schultz, student intern Anthony Megel, and SwRI Engine Lab Technicians James Sczepanik, Steven Schneider and Denny Zaske for their contributions to this report and the enclosed appendix data. We also thank HD Benchmarking Program Managers Michael Ross and Robert Burrahm for their reviews and suggestions for report modifications.

Also valuable data and information included in the report was obtained from the MAN D20 press releases, service manuals and service bulletins.

14.0 GLOSSARY

Table 14 contains a glossary of abbreviations used in this report.

TABLE 14. GLOSSARY OF ABBREVIATIONS

Abbreviation	Definition
CCV	Closed Crankcase Ventilation
CGI	Compacted Graphite Iron
CL	Center Line
Ctr	Center
Cyl	Cylinder
D20	MAN D2066 (10.5L) engine
ECM	Electronic Control Module
EGR	Exhaust Gas Recirculation
ECE	European Council of Environment
FCA	Fuel (rail pressure) Control Actuator
H x W	Height x Width
HD	Heavy-Duty
HPCR	High Pressure Common Rail
ID	Inner Diameter
MAN	MAN Engine Co.
MAN D20	MAN D2066 (10.5L) engine
OD	Outer Diameter
REPTO	Rear Engine Power Take-Off
RTV	Room Temperature Vulcanizing (silicon based sealant)
SLS	Single Layer Steel (gasket)
SwRI	Southwest Research Institute
TDC	Top Dead Center

APPENDIX A

MAN D20 Flowbench Report

SwRI Engine Benchmarking Program: Flowbench Testing of the MAN D20 Cylinder Head

by

Ford A. Phillips
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September 9, 2005

SwRI Engine Benchmarking Program: Flowbench Testing of the MAN D20 Cylinder Head

Ford A. Phillips
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Standard flow and swirl tests were conducted on the intake and exhaust ports for one cylinder of the MAN D20 cylinder head at the SwRI flow bench facility (see Figures 1 and 2). Tests were conducted on cylinder three using the manifold for the intake and a flow adapter for the exhaust ports. Ports were cleaned of existing deposits from previous testing before flow testing was performed. All tests were performed with a pressure drop across the ports of 20 in-H_2O (4.98 kPa). Steady-state tests were performed in 1 mm increments of valve lift. Figures 1 and 2 illustrate the engine components used in the test set-up. The engine parameters used to analyze the flow data are listed in Table 1 (next page).

Figure 1. MAN D20 Cylinder Head used for Flowbench Testing (top view)

Figure 2. MAN D20 Cylinder Head used for Flowbench Testing (bottom view)

TABLE 1. ENGINE PARAMETERS

Engine Parameter	Quantity
Serial Number	5050767228B2C1
Bore	120 mm
Stroke	155 mm
Connecting Rod Length (Center to Center)	256.0 mm
Compression Ratio	19.0:1
Inner Valve Seat Diameter (intake)	32.3 mm
Maximum Tested Valve Lift (intake)	12.0 mm
Inner Valve Seat Diameter (exhaust)	32.9 mm
Maximum Tested Valve Lift (exhaust)	14.0 mm

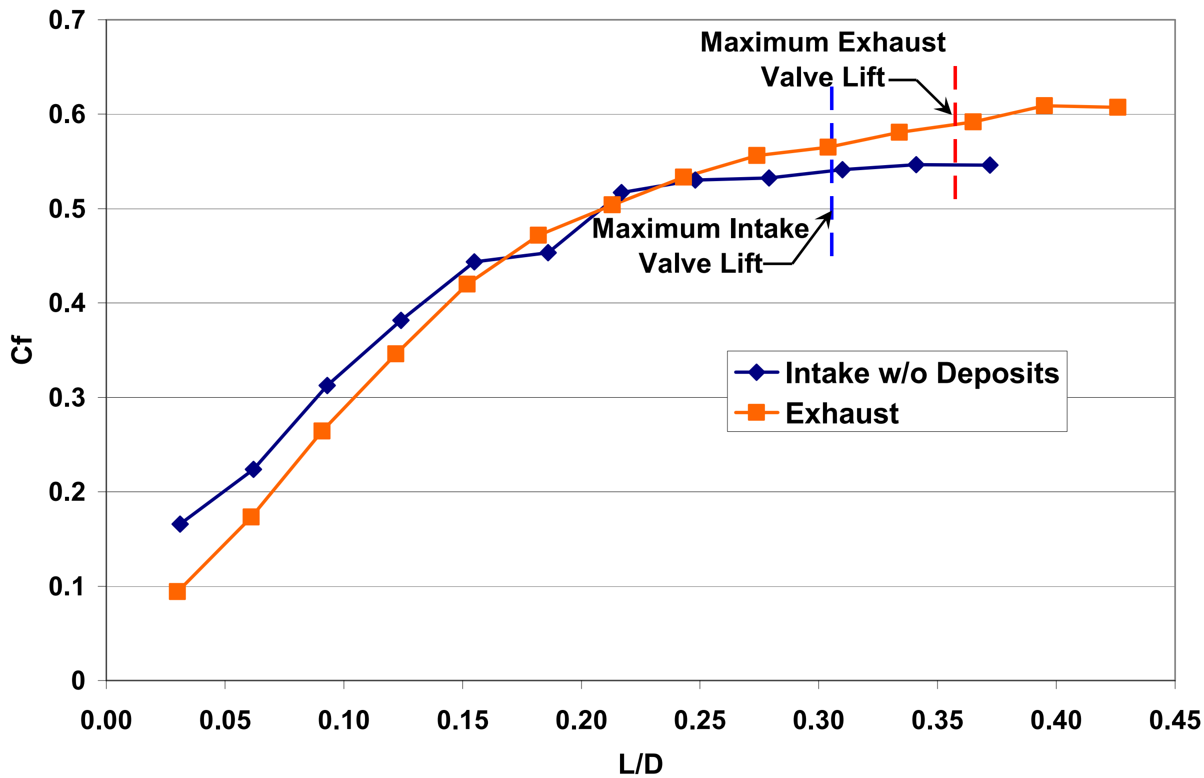


Figure 3. Comparison of Flow Coefficients

Figure 3 compares the valve and port flow coefficients for the intake and exhaust ports. The tested valves can be seen in Figures 4 and 5.

Figure 6 shows the non-dimensional swirl values for the intake ports. Swirl measurements were conducted using the SwRI impulse swirl meter.

The highest (negative) swirl occurs at the higher valve lifts, nearly leveling off around 0.28 L/D. Over the valve lift range, Nr is quite high, leading to the high swirl ratio shown in Table 2. Negative values of N_r indicate that the direction of swirl generation was clockwise looking down the cylinder bore.

Figure 4. Intake Valve

Figure 5. Exhaust Valve

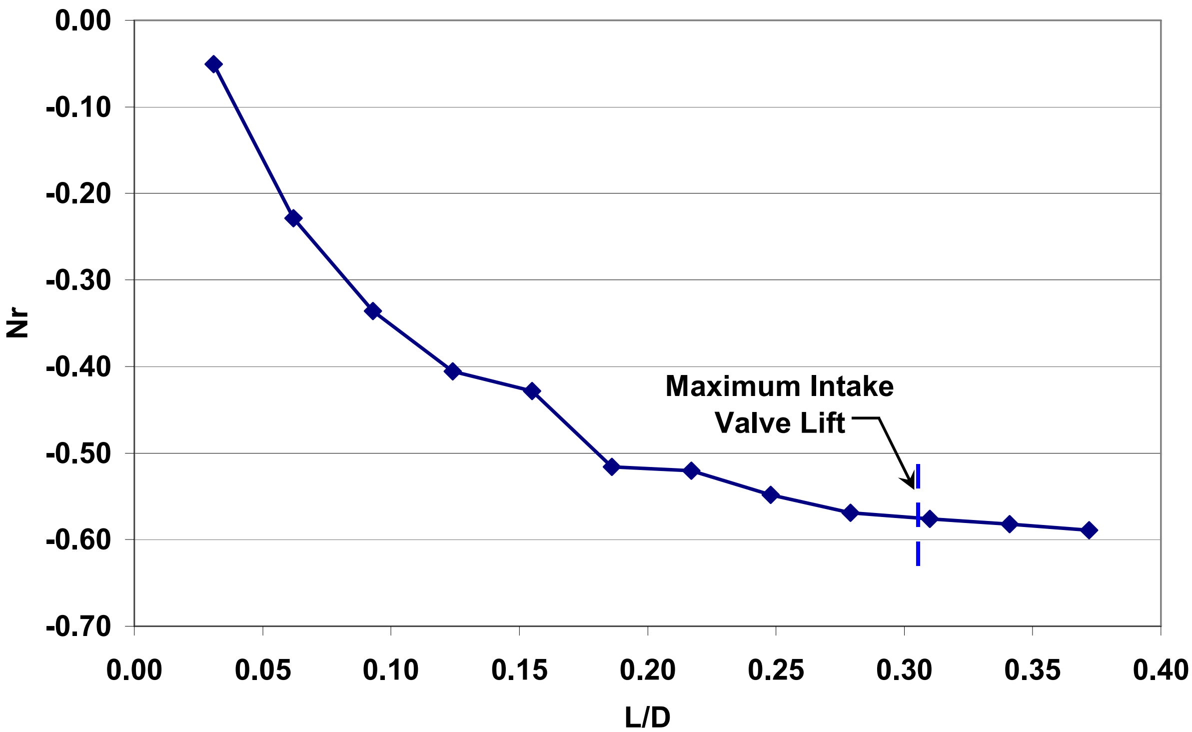


Figure 6. Intake Valve Non-Dimensional Swirl

TABLE 2. SWIRL RATIO AND MEAN PRESSURE LOSS RESULTS MEAN PISTON SPEED OF 11.2 M/S

Engine Parameter	Value
Swirl Ratio	-3.464
Mean Pressure Loss	19.14 kPa

Table 2 lists swirl ratio and mean pressure loss. These values have been normalized to an engine speed corresponding to a mean piston speed of 11.2 m/s so that they can be compared against other engines of similar design. This design has a relatively low amount of pressure loss for such a high swirl ratio as seen in Figure 7.

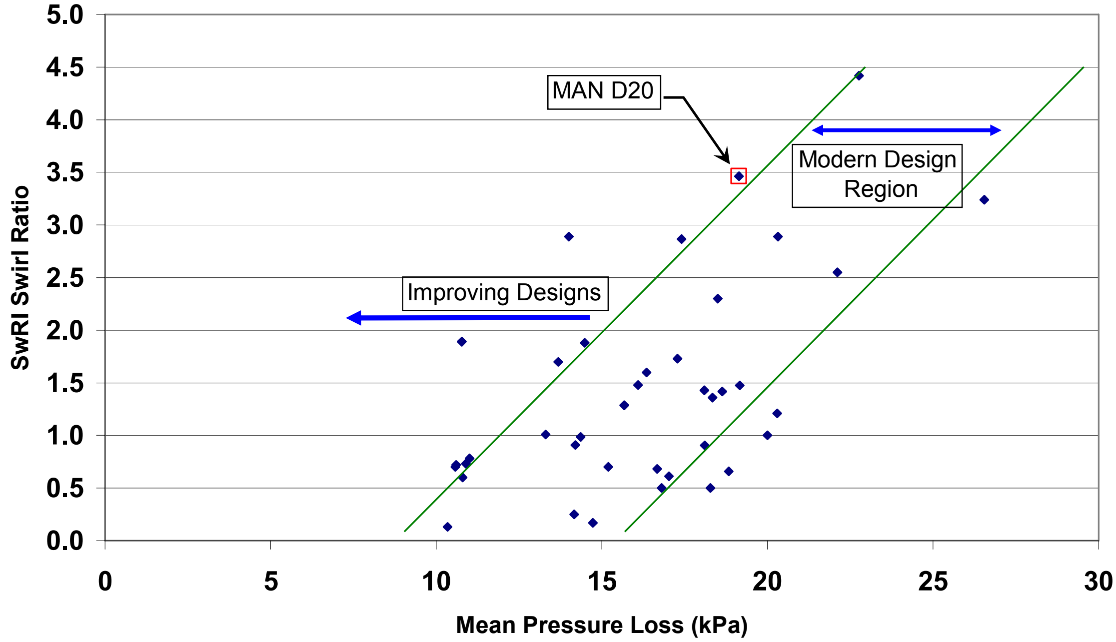


Figure 7. Comparison of Similar Diesel and CNG Engines at 11.2 m/s Mean Piston Speed

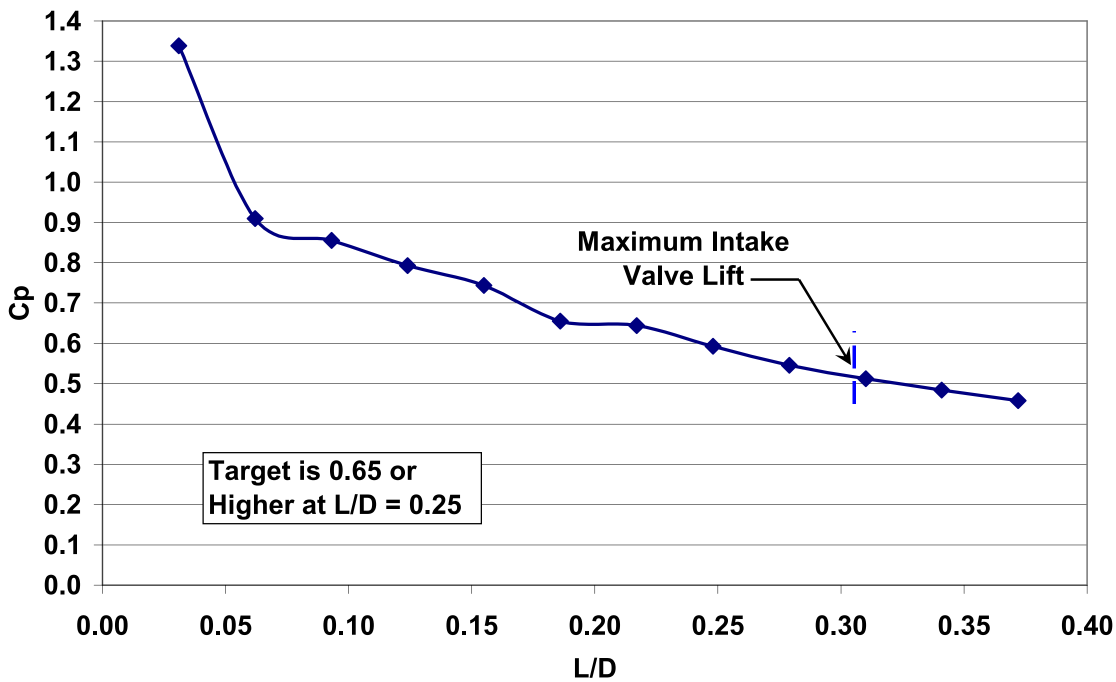


Figure 8. Intake Valve Coefficient of Performance

Figure 8 shows the coefficient of performance for the intake ports. Coefficient of performance (C_p) is a useful parameter for evaluating the trade-off effects of flow and swirl and for assessing the overall efficiency of the intake ports. SwRI typically sees C_p values of 0.65 or higher at L/D ratios of 0.25 for intake ports on this type of engine. The intake ports with intake manifold have a C_p of around 0.59 at L/D = 0.25. This suggests that these ports have not been fully optimized.

Calculations

Flow coefficients (Cf) are calculated using the following equation:

$$C_f = \frac{Q}{nAV_0}$$

where:

- Q = volumetric flowrate (m^3/s)
- n = number of valves open
- A = valve seat area (m^2)
- V_0 = reference isentropic velocity (m/s)

Reference velocity V_0 is the velocity which would be produced at the exit of an isentropic converging nozzle with the same pressure drop as the valve/port tested exiting into a plenum. V_0 is defined by the compressible equation:

$$V_0 = \sqrt{\left(\frac{2\gamma}{\gamma - 1}\right) \times \left(\frac{P_0}{\rho_0}\right) \times \left[1 - \left(\frac{P}{P_0}\right)^{\frac{\gamma - 1}{\gamma}}\right]}$$

where:

- γ = air specific heat ratio
- P = cylinder static pressure (Pa abs)
- P_0 = inlet stagnation pressure (Pa abs)
- ρ_0 = inlet stagnation air density (kg/m3)

Non-dimensional swirl (N_r) is calculated using the following equation:

$$N_r = \frac{8G}{mBV_0}$$

where:

- G = reaction torque measured with impulse swirl meter (N-m)
- m = total mass flow through ports (kg/s)
- B = bore diameter (m)
- V_0 = reference isentropic velocity (m/s)

Coefficient of performance is calculated using the following equation:

$$C_p = \sqrt{\left[\frac{BN_r}{4Dn}\right]^2 + \left[\frac{DC_f}{4L}\right]^2}$$

where:

- B = bore (m)
- N_r = non-dimensional swirl
- D = inner valve seat diameter (m)
- n = number of valves open
- C_f = flow coefficient
- L = valve lift (m)

Swirl ratio RS is the ratio of swirl speed at the end of induction (terminal swirl) to engine speed, defined by the equation:

$$R_S = \frac{\omega_F}{\omega_E}$$

where:

- ω_F = terminal swirl velocity (rad/sec)
- ω_E = engine speed (rad/sec)

As the flows in the engine are fully turbulent, swirl ratio does not change very much with engine speed. Terminal swirl velocity is calculated by integrating the instantaneous angular momentum flux ($\dot{I}\omega$) throughout the induction period, and dividing by the final induced charge air mass inertia:

$$\omega_F = \frac{1}{I_{final}} \int_{TDC}^{IVC} \dot{I}\omega \cdot dt$$

where:

- I_{final} = mass moment of inertia at the end of the induction stroke(kg-m^2)
- $\dot{I}$ = instantaneous mass moment of inertia flux (kg-m^2/sec)
- ω = instantaneous swirl velocity (rad/sec)

The instantaneous angular momentum flux is calculated by the SwRI method which is based upon a filling and emptying model of the cylinder, assuming an initial pressure in the cylinder and port of 1 bar, no heat transfer, and compressible flow equations (using the derived valve/port flow and swirl coefficients) throughout the intake stroke.

Figure 9 shows the measured D20 intake valve lift vs. crank angle, which was used to calculate the mean pressure loss and swirl ratio.

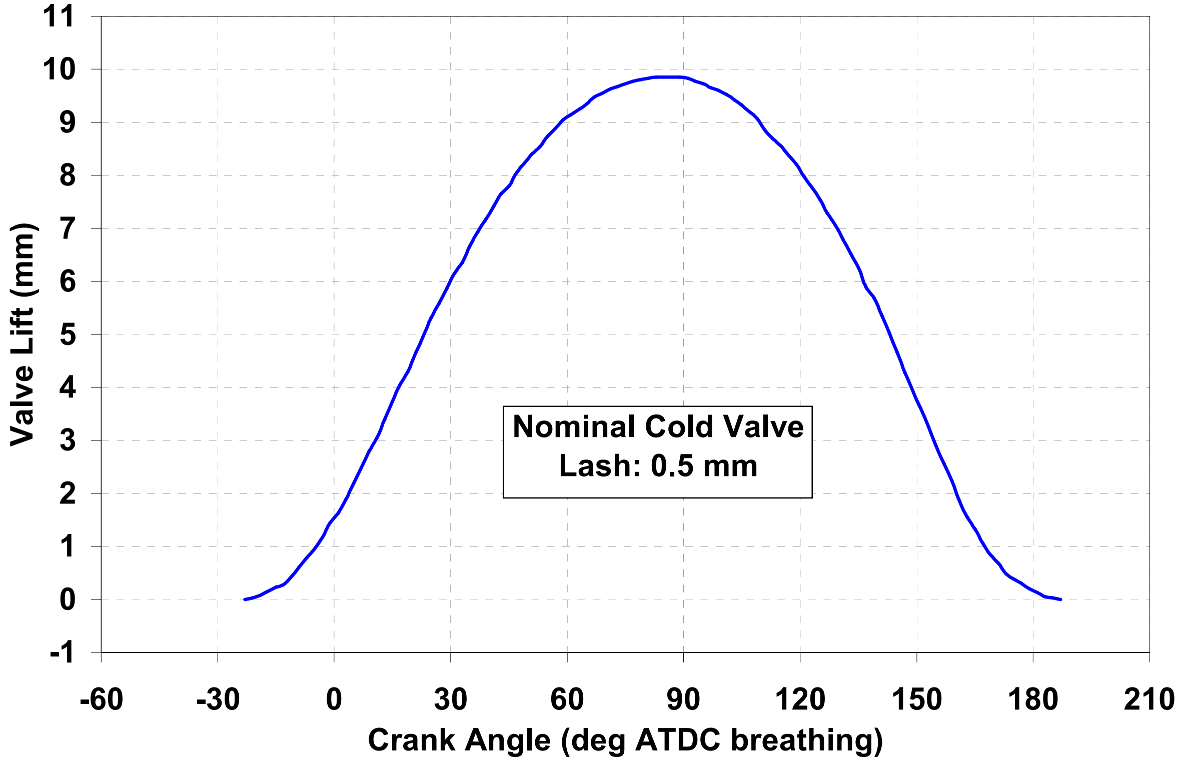


Figure 9. Cold Intake Valve Lift

APPENDIX B
MAN D20 Engine Critical Engine Parameters

Critical Engine Parameters
MAN D20 Engine

Engine:		MAN D20
General Information		
Displacement (L)		10.518
Configuration		Inline
# Cylinders		6
Bore (mm)		120
Stroke (mm)		155
Rated Power (kW) at Speed (rpm)		316 @ 1900
Peak Torque (N-m) at Speed (rpm)		2100 @ 1000-1400
Rated Power (hp) at Speed (rpm)		424 @ 1900
Peak Torque (lb-ft) at Speed (rpm)		1549 @ 1000-1400
Fueling at Rated Power (mm^3/stroke)		215.2
Fueling at Peak Torque (mm^3/stroke)		276.1 (@ 1400 RPM)
Idle Speed (rpm)		550
Compression Ratio		19.0 : 1
Oil Capacity (L)		n/a
Engine Weight (dry w/ flywheel, flywheel hsg, A/C, starter) (kg/lb)		988.8 kg / 2180 Lb
Component		
EGR valve	Type	Butterfly
	Vendor	n/a
	Valve flapper diameter (mm)	40.0
	Inlet diameter (mm)	28.0
	Outlet diameter (mm)	40.0 x 2
EGR cooler	Type	Tube
	Vendor	Modine
	Inlet diameter (mm)	40.0 x 2
	Outlet dimensions (mm)	87 H x 35 W
	Case dimensions (mm)	70 H x 120 W x 870 L
	Core dimensions (mm)	70 H x 115 W x 850 L
	Tube ID (mm)	5.6
EGR mixer	Type	Pipe junction
	Air inlet ID (mm)	84
	Air outlet dimensions (mm)	72 H x 83 W
	EGR inlet ID (mm)	37
Turbocharger	Vendor	KKK
	Compressor inlet diameter (mm)	80
	Compressor discharge diameter (mm)	48
	Turbine inlet dimensions (H, W, corner rad)	52 x 37 x R10 (x 2)
	Turbine inlet area (mm^2)	3676
	Turbine outlet diameter (mm)	71
	Water Cooled Bearing Housing (Y/N)	N
	Turbine flange thickness (mm)	12
Intake manifold	Inlet diameter (mm)	84
	Intake port inlet area (mm^2)	2667
	Manifold outlet H x W x Corner (mm)	42 H x 64 W x R5
	Runner length	n/a
	Exterior Plenum Out Dimensions	72 H x 83 W

Exhaust manifold	Exhaust inlet area (mm^2)	1794
	Exhaust inlet dimensions (mm)	43 x 43 x R8
	Runner length	35
	Manifold ID (mm)	39
	Exhaust flange thickness (mm)	12.5
Injectors	Hole Diameter	0.241
	# of Holes	6
	Included angle of holes	3 @ 148 deg, 3 @ 154 deg
Head gasket	Type	Single Layer Steel
	Body thickness (mm)	1.25
	Combustion seal thickness (mm)	1.25
	Combustion seal width (mm)	3.8
Head bolt	Bolt Type - Dia x Pitch x Length	M18 X 2.0 X 245
	Hex	24 Torx
	Number of Bolts	26
	Torque (N-m)	300 + 270 deg
	Small head bolts	n/a
Main cap	Type	2 bolt Fracture split
	Width (mm)	177
	Height (mm)	104.2
	Thickness (mm)	38.33
	Main bore ID (mm)	111.14
Main bolt	Bolt Type - Dia x Pitch x Length	M18 x 2.0 x 160
	Hex	27 Torx
	Torque (N-m)	300 + 90 deg
Block	Bore Spacing	154.0
	Pan Rail Width	398
	Skirt Depth	100
	Top deck to main saddle (mm)	354
Liner	Type (Top Stop, Parent Bore, Mid Stop)	Top Stop
	Overall height (mm)	260
	TRR Thickness (mm)	8.44
	Mid stroke thickness (mm)	10.0
	BRR thickness (mm)	10.0
	Top/mid stop OD (mm)	150.0
	Top stop thickness (mm)	8.0
	Average liner protrusion (mm)	0.2
Piston	Type	One Piece Aluminum
	Vendor	Nural
	Material	Aluminum Alloy
	Compression Height (mm)	76.8
	Top land height (mm)	10.58
	Bowl diameter (mm)	70.0
	Max bowl depth (mm)	21.1
	Oil cooling	Yes
	Pin bore diameter (mm)	52.00
	Mass (g)	1927.4
Piston pin	Length (mm)	95.87
	OD (mm)	51.94
	ID (mm)	22.89
	Mass (g)	1204.7

Connecting rod	Horizontal / angle split	Angle split
	Machine / Fracture Split	Fracture
	Oil drillings	No
	Overall length (mm)	372.7
	Distance between bore ID's (mm)	182.52
	Distance between bore centers (mm)	256.0
	Small end ID (mm)	52.00
	Big end ID (mm)	95.08
	Bolt Type - Dia x Pitch x Length	M12 x 1.5 x 64
	Hex	M16 Torx
	Number of Bolts	2
	Mass (g) w/ Cap & bolts	3536.8
Geartrain	Spur or helical	Spur
	Width of cam gear (mm)	18.0
Crankshaft	Main journal OD (mm)	104.00
	Main journal fillet radius (mm)	3.57
	Rod journal OD (mm)	90.00
	Rod journal fillet radius (mm)	3.175
	Web thickness	32.89
	Pin overlap	19.48
	Main bearing width (mm)	35.75
	Main bearing thickness (mm)	3.49
	Rod bearing width (mm)	36.01
	Rod bearing thickness (mm)	2.5
	Thrust bearing thickness (mm)	3.35
	Thrust bearing OD (mm)	138.0
	Thrust bearing ID (mm)	114.0
Vibration damper	Type (Viscous, Rubber)	Viscous
	Thickness (mm)	32.6
	OD (mm)	327
	Ring ID (mm)	183
	# bolts	8
	Bolt Type - Dia x Pitch x Length	M16 x 1.5 x 75
	Torque (N-m)	150 + 90 deg
	Mass (g)	13154.18
Flywheel	Bolt quantity	10
	Bolt Type - Dia x Pitch x Length	M16 x 1.5 x 80
	Torque (N-m)	100 + 180 deg
Camshaft	Min/Max intake lobe diameter (mm)	51.6 / 61.1
	Intake lobe width (mm)	18.0
	Min/Max exhaust lobe diameter (mm)	51.9 / 62.8
	Exhaust lobe width (mm)	18.0
	Min/Max injector lobe diameter(mm)	n/a
	Injector lobe width (mm)	n/a
	Min/Max braking lobe diameter (mm)	n/a
	Braking lobe width (mm)	n/a
	Bearing width (mm)	25.8
	Bearing thickness (mm)	2.00
	Bearing journal OD (mm)	39.80
	Exhaust rocker roller OD/length (mm)	25.96 / 14.0
	Intake rocker roller OD/length (mm)	25.96 / 14.0
	Injector rocker roller OD/length (mm)	n/a
	Rocker shaft OD (mm)	31.8

Cylinder head	Material	Cast iron
	Intake valve recession (mm)	0.029
	Exhaust valve recession (mm)	0.029
	Installed spring height (mm)	46.7
	Injector bore ID (lower) (mm)	21.3
	Injector bore ID (upper) (mm)	26
	Valve guide ID (mm)	8.02
	Valve guide OD (mm)	16.14
	Valve guide height (mm)	19.86
	Intake stem seal ID (mm)	8.68
	Exhaust stem seal ID (mm)	9.19
Intake valve	Head diameter (mm)	40.0
	Seating surface width (mm)	3.79
	Head thickness @ OD (mm)	2.54
	Head thickness @ stem (mm)	5.64
	Stem OD (mm)	8.95
	Stem height (mm)	148.49
	Overall height (mm)	160.42
	Mass (w & w/o deposits) (g)	119.7 / 119.3
	Peak lift (mm)	9.85
	Cold lash (mm)	0.5
Exhaust valve	Head diameter (mm)	38.0
	Seat width (mm)	3.51
	Head thickness @ OD (mm)	2.5
	Head thickness @ stem (mm)	8.45
	Stem OD (mm)	8.95
	Stem height (mm)	140.3
	Overall height (mm)	160.35
	Mass (w & w/o deposits) (g)	139.4 / 139.4
	Peak lift (mm)	11.76
	Cold lash (mm)	0.6
Intake valve seat	Aspect ratio	1.34
	Height (mm)	7.65
	Width (mm)	5.71
	Valve seat ID	32.3
	Seating surface width (mm)	2.96
	Seat angle (deg)	30
Exhaust valve seat	Aspect ratio	2.88
	Height (mm)	7.33
	Width (mm)	2.54
	Valve seat ID	32.9
	Seating surface width (mm)	2.93
	Seat angle (deg)	45
Retainer	Mass (g)	39.9
Valve spring	ID (mm)	24.1
	OD (mm)	31.8
	Intake spring wire OD (mm)	3.78
	Exhaust spring wire OD (mm)	3.78
	Intake spring mass (g)	60.5
	Exhaust spring mass (g)	60.5

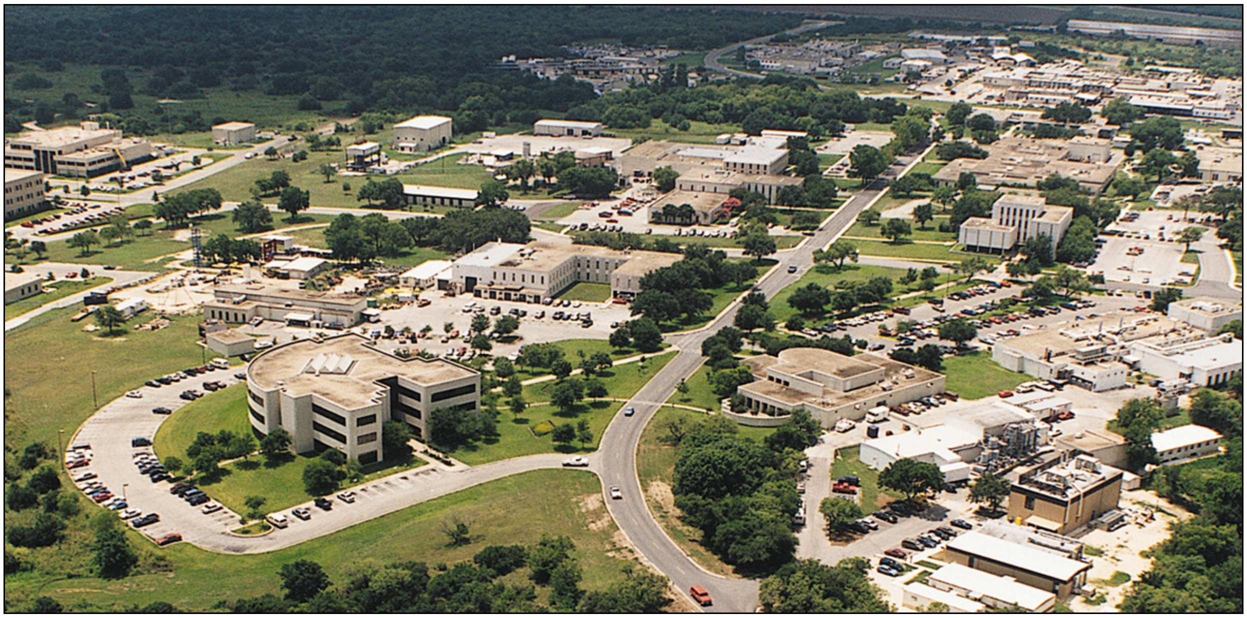
Bridge Measurements	Intake-Intake D-1 (mm)	2.49
	Intake-Intake D-2 (mm)	11.62
	Min Dist Inj. Bore (mm) Depth-1	9.87 - 11.07 chamfers differ
	Min Dist Inj. Bore (mm) Depth-2	14.72
	Exhaust-Exhaust D-1 (mm)	11.44
	Exhaust-Exhaust D-2 (mm)	17.58
	Min Dist Inj. Bore Depth-1(mm)	13.57
	Min Dist Inj. Bore Depth-2(mm)	16.68
	Intake-Exhaust 1 D-1 (mm)	12.7
	Intake-Exhaust 1 D-2 (mm)	20.79
	Intake-Exhaust 2 D-1 (mm)	9.63
	Intake-Exhaust 2 D-2 (mm)	16.13

MAN D20 Engine Component Weights

Component Description	Weight (lbs)	Weight (kg)	Remarks
Rocker Cover	2.8	6.2	with gasket and bolts
Oil Pan	13.6	30.0	
Connecting Rod	3.5	7.8	
Piston, Rings & Pin	3.2	7.1	
Oil Filter Block	8.9	19.6	
Flywheel Housing	27.2	60.0	
Crank Shaft	97.5	215.0	
Block, No Caps	227.2	501.0	
Main Cap with Bolts	3.1	6.9	fracture split
Liner	7.2	15.9	
Water Pump	5.1	11.2	
Front Support	5.0	11.1	X2 side mounts left and right
Breather Ass'y	n/a	n/a	built into oil filter block
Front Gear Cover	3.8	8.4	
Air Compressor	17.7	39.0	
Fuel Pump Assembly	20.0	44.0	with accessory pulley drive & oil fill tube
Injector	0.6	1.2	
Turbo	24.5	54.0	
Rocker Shaft Ass'y	2.2	4.7	
Air Inlet	2.6	5.6	
Damper	13.2	29.0	
Pulley	n/a	n/a	
Exhaust Manifold	15.9	35.0	
Lube Oil Pump Ass'y	4.3	9.5	with pickup tube
Cam and Gear	11.6	25.5	
ECM	1.6	3.6	
Front Cover Plate	3.8	8.4	
Valve Parts/ 1 cyl	0.9	2.0	
Oil Cooler	2.9	6.3	
Main Bearings/ 1 cyl	0.3	0.7	
Starter	9.1	20.0	
Flywheel	29.9	66.0	
Headbolt and Washer	0.5	1.1	no washer used
Cylinder Head	141.1	311.0	
Fuel Rail with Lines	5.4	11.9	
Injector Feed Tubes	0.2	0.4	high pressure connectors
Front Gears (crank & idler)	5.5	12.2	includes hub
Rear Gears (crank & idlers)	16.6	36.5	includes 4 idlers and hubs
Fan Drive Hub and Gear	6.4	14.1	
EGR Inlet Valve Ass'y	5.4	12.0	
EGR Cooler and Reed Valves	10.4	23.0	
Coolant Crossover Tube	3.4	7.5	includes block exit elbow
Thermostat Housing and Cover	3.9	8.5	includes thermostats and EGR return
Main Coolant Manifold	6.4	14.0	
Compressor Discharge Tube	4.1	9.0	
Alternator and Pulley	6.6	14.5	

MAN D20 Bolt Grades

Bolt Description	Grade
Fuel Pump Mount	10.9
Exhaust Manifold	n/a
Fuel Rail Mount	10.9
Air Compressor Mount	10.9
Vibration Damper	10.9
ECM	10.9
Cam Bearing Cap	10.9
Flywheel	10.9
Oil Cooler/Filter Housing	10.9
Main Coolant Manifold	10.9
Thermostat Housing	10.9
Coolant Pump	10.9
Oil Pan	10.9
Cylinder Head Bolt	10.9
Main Bearing Cap	10.9
Connecting Rod Cap	11.9



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Southwest Research Institute values your feedback.

For questions or comments about this report, please contact:

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