SAE The Engineering Society For Advancing Mobility Land Sea Air and Space®
INTERNATIONAL

400 COMMONWEALTH DRIVE, WARRENDALE, PA 15096-0001 U.S.A.

SAE Technical Paper Series

900269

Clean Power - Lotus 2.2 Lt Chargecooled Engine

Simon P. Wood, John H. Bloomfield
Lotus Engineering

International Congress and Exposition
Detroit, Michigan
February 26 — March 2, 1990

SAE routinely stocks printed papers for a period of three years following date of publication. Direct your orders to SAE Customer Service Department.

To obtain quantity reprint rates, permission to reprint a technical paper or permission to use copyrighted SAE publications in other works, contact the SAE Publications Group.

ISSN 0148-7191

Printed in USA

900269

Clean Power - Lotus 2.2 Lt Chargecooled Engine

Simon P. Wood, John H. Bloomfield
Lotus Engineering

1 ABSTRACT

For 1989 introduction Lotus further developed its own 2.2 litre four-cylinder turbocharged engine to produce world-leading specific performance of 91 kw/litre (122 bhp/litre), for a production unit. This very high level of performance was achieved in compliance with current and proposed Federal and European emissions standards.

2 INTRODUCTION

Over the last decade increasingly stringent worldwide exhaust emission standards have slowed down development of higher specific engine performance.

Lotus have successfully tackled this technical challenge with innovative solutions for its 910 SE 2.2 litre chargecooled engine, associated exhaust emissions control systems and strategy. The engine is mounted in the Lotus Esprit SE, a hyper performance mid engined two seat car, utilising a composite body mounted on a steel back bone chassis.

1989, LOTUS ESPRIT TURBO SE

3 BACKGROUND

The heritage of this engine dates back to the early 1970's, it has been continuously refined and further developed since that time.

Over the production span of the engine considerable changes in emission legislation have occurred up to the present day, where European and Federal legislation for over 2.0 lt engines are now broadly similar. This enables production of a single specification power unit for all world markets. The list shown below indicates the principal engine specification changes that have occurred since its initial introduction in 1972. During this period Federal legislation has changed dramatically, this required major revisions, in particular to the exhaust emission control strategy.

Date	Performance
1972	104 kw N/A Carburettered
1974	119 kw N/A Carburettered
1980	157 kw Turbo Carburettered
1983	153 kw Turbo Carb + Catalyst
1984	134 kw N/A Carburettered
1985	160 kw Turbo MFI + Catalyst
1987	171 kw Turbo EFI + Catalyst
1989	197 kw Turbo SE EFI + Catalyst

(NB MFI - Mechanical Fuel Injection
EFI - Electronic Fuel Injection)

Legislation : Federal Test Limits (50 State)

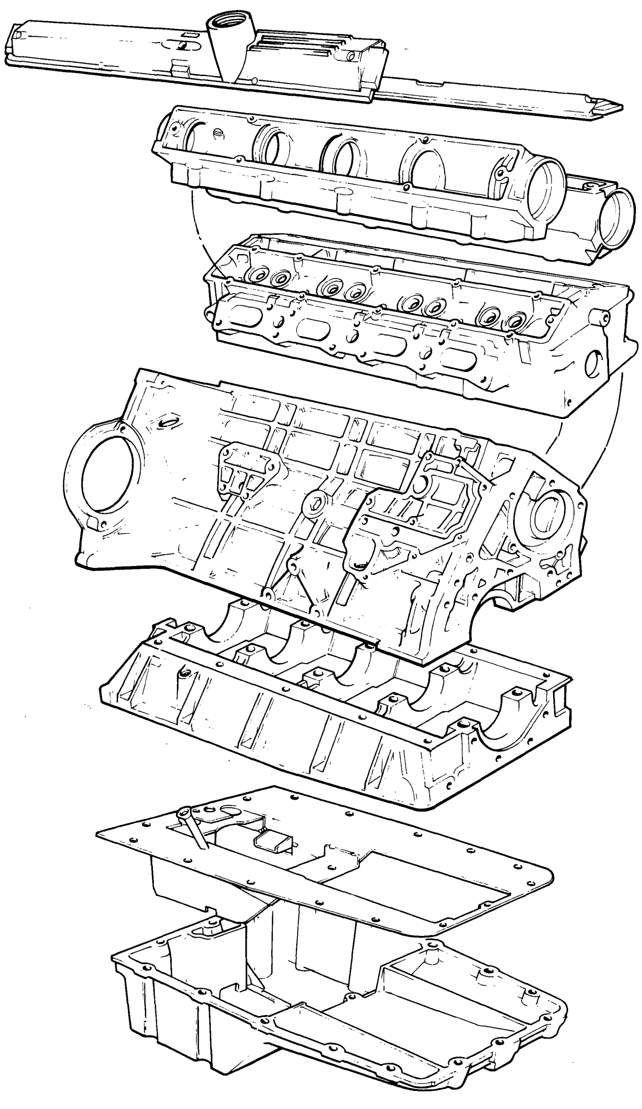
	HC	CO	NOx
1972	3.4	39.0	2.0
1989	0.41	3.4	0.4

(figures in g/mile)

4 MECHANICAL DESCRIPTION

4.1 STRUCTURE - The basic core of the engine is built around a structure of heat treated aluminium alloy castings, the cylinder centreline being inclined at an angle of 45°. The cylinder block is of open deck configuration with free standing Nikasil coated aluminium liners and incorporates a one piece ladder frame connecting all main bearings and a structural sump for maximum stiffness.

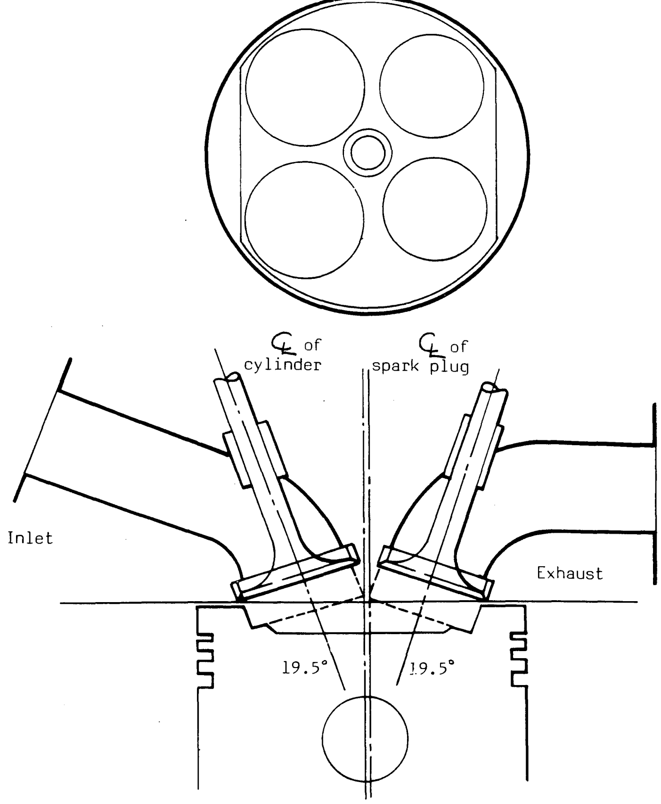
The crankshaft is manufactured in SG Iron and runs in copper/lead bearings. A steel flywheel is used to allow use of minimum inertias whilst maintaining burst strength at maximum engine speed of 7500 rpm.



4.2 PISTON & CYLINDERS - The forged aluminium Nikasil coated liners are bottom spigot located into the block and clamped into position by the cylinder head gasket. Obviously this is a critical joint face having to seal against peak gas pressures of up to 100 bar whilst minimising material distortion of the thin wall liner. Heat transfer properties of the liner are a major contribution to the performance of the engine. They have shown a reduction in the onset of combustion detonation characteristic of some 3° to 5° crank and allow continuous operation running in incipient detonation rather than the catastrophic failure typically experienced using conventional iron liners. During cold start running conditions the heat transfer to coolant is improved, this benefits rates of increase of coolant temperatures and hence heater performance but has also, and more importantly, been shown to increase the level of unburned HC emissions measured over the early stages of the Federal test cycle. Additional HC control systems are, therefore, necessary to achieve legislation demands if the combustion advantages of the aluminium liners are to be utilised.

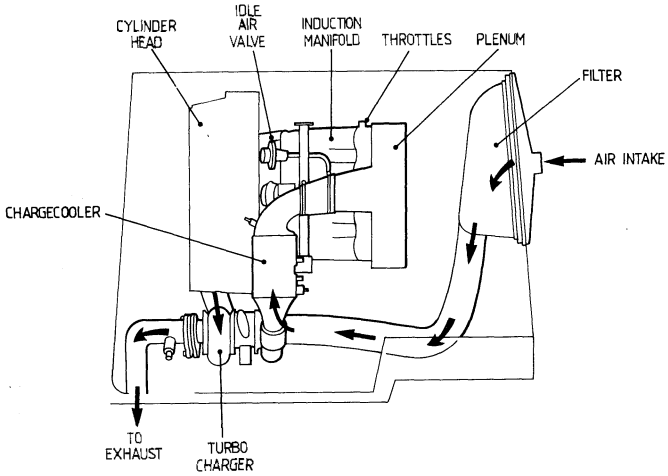
4.3 CYLINDER HEAD & COMBUSTION CHAMBER - The four valve head has combustion chamber, pentroof in shape, with a central 14 mm sparking plug of twin earth electrode design. This ensures improved earth electrode cooling due to the shorter heat transfer path and has been demonstrated to have greater ability to sustain combustion abuse or slight detonation for longer periods than the conventional single electrode component.

Squish areas are provided at opposite sides of the chamber to increase in cylinder gas movement. A nominal squish clearance of 2 mm has been arrived at through a development exercise considering both detonation limited performance and HC emissions. The squish faces are not parallel in section, but have an included angle of 5° as this was found to give the best compromise.



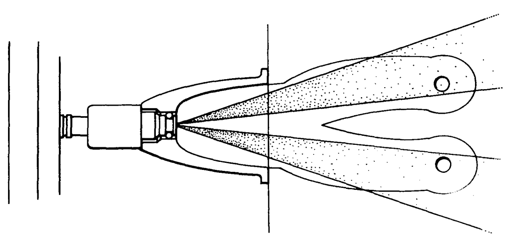
4.4 INDUCTION - The compressor draws clean air via the body mounted filter element. At peak power this imposes a restriction of 55 m.bar at compressor inlet.

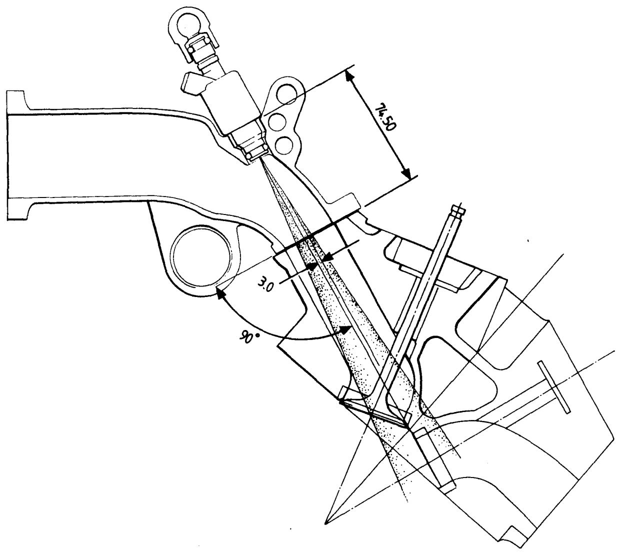
Gas from the compressor at temperatures and pressures of upto 150°C and 1.9 bar absolute is cooled by the chargecooler before passing the secondary injectors on entry to the plenum. Multiple throttles (ie one per cylinder) modulate the gas flow to each cylinder. At low throttle openings the 'blocking' reflective effect of the individual throttle plates reduce the back pulse from the inlet of one cylinder and hence reduces inlet charge exhaust dilution problems. Traditionally the absence of multiple throttles on engines with relatively long valve overlap periods, in this case 42° crank, can cause HC and feedback fuel flow control problems.



4.5 FUEL SYSTEM - One major problem with very high output per cylinder engines (50 kw/cylinder) is providing injectors that have the required linearity and fuel preparation characteristics at the light load emission range and a full flow requirement of greater than 6.0 gms/sec at full load. AC Rochester are currently working on new designs to fulfil these requirements but at the development stage of the 910 SE engine a 4.3 gm/sec injector was the highest flow available with the required linear control range. This then, required the fuelling strategy to change to four main injectors with additional high load fuel supply via two secondary power injectors.

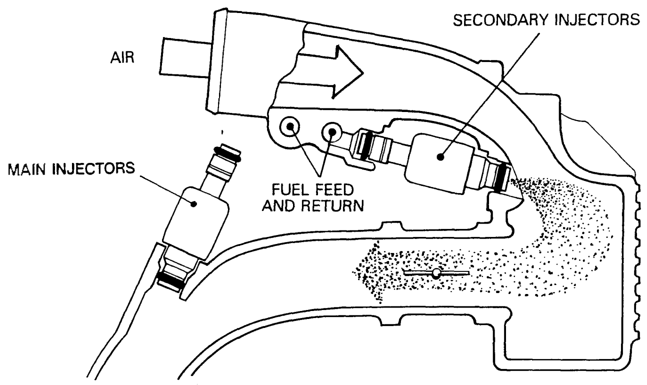
These main injectors are conventional single spray pencil stream units. Dual cone spray injectors were assessed, however no improvement was determined in idle stability or low speed emissions. It is thought this could be due to the not ideal match of spray and port angles, although some improvement was still expected.



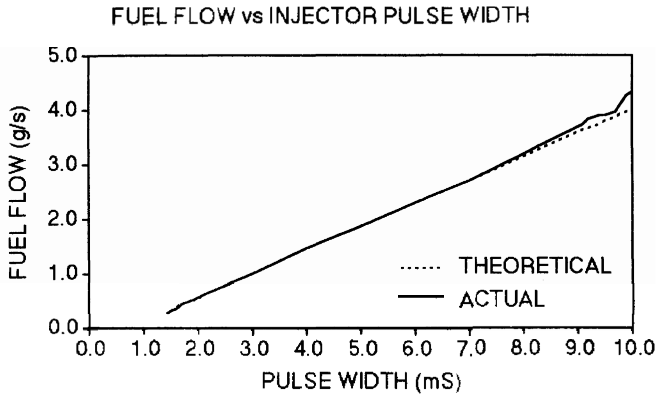


The secondary injectors are placed facing down stream at the entry to the plenum. There use is confined to high load operation only.

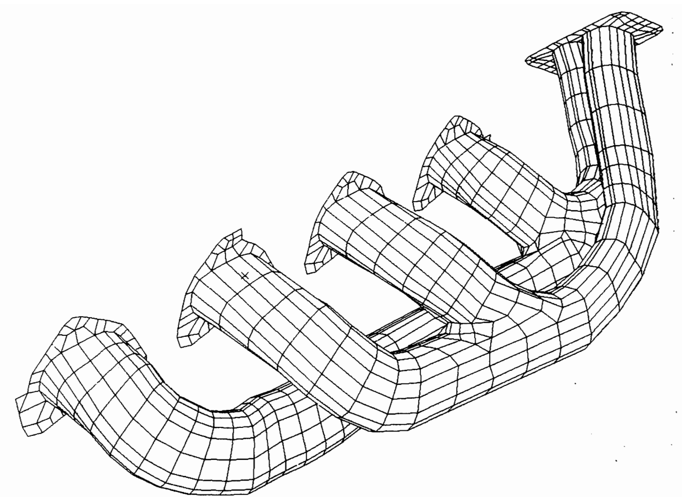
Various alternative locations were assessed within the physical constraints of packaging until the final compromise was achieved.



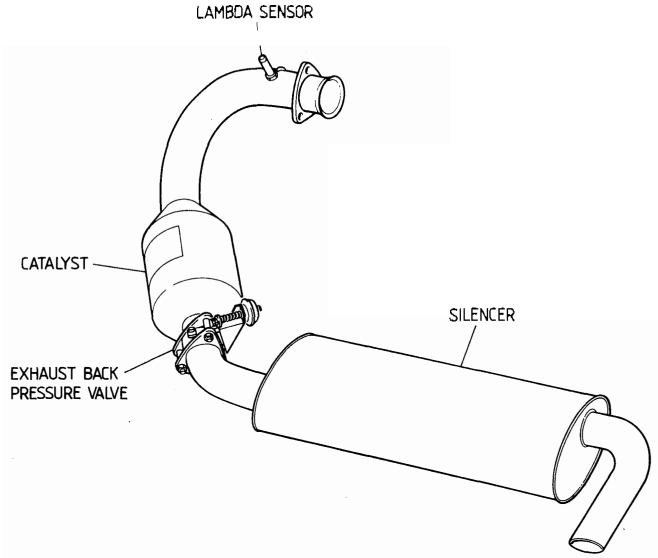
Placing the injectors either further up stream, or facing up stream, although expected to give performance improvements due to improved mixture preparation time and greater latent heat of evaporation, actually reduced performance by about 2 %. This was considered due to the weight of air displaced by the additional mass of vapourised fuel and the energy required to overcome the fuel momentum effects. There is little measured difference between the combined use of main and secondary injectors in their final position or the use of single, high flow main injectors only. The latter would obviously be the preferred route, however current technology prevents reliable manufacture of high flow injectors having a linear flow range of greater than about 9:1 or 10:1. The followimg diagram shows the linear characteristics of the main injectors.



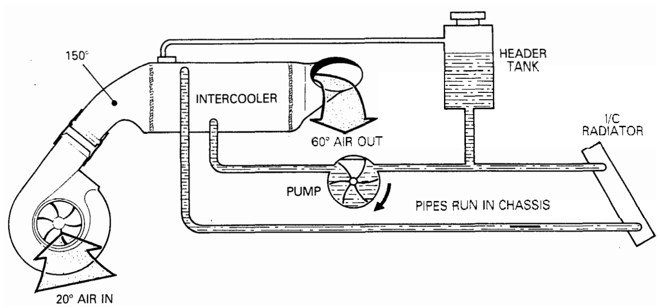
4.6 EXHAUST - The exhaust gas exits through a manifold designed to promote a directed pulse to the turbocharger, which is positioned above the transmission clutch housing. The manifold is manufactured in a high silicon-molybdenum nodular cast iron (SiMo) and is operated at turbine inlet temperatures of up to 980°C. Thermal image techniques have been used to confirm that bulk metal temperatures do not exceed the phase transition temperature of the material which occurs at around 840°C. Considerable CAD effort has been used to determine the final design of the manifold to enable use of SiMo as opposed to NiResist, the former having a lower coefficient of linear expansion which is considered desirable for minimum differential expansion effects.



The Garratt AiResearch TBO3 water cooled turbocharger exhausts into a single, diameter 73.5 mm, exhaust system consisting of catalyst, exhaust back pressure valve and single silencer box. The vehicle meets 75 dBA drive-by noise requirements.

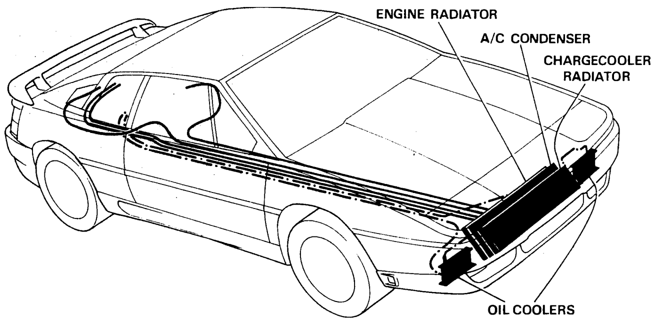


4.7 CHARGECOOLER - The chargecooler is mounted above the engine between the compressor exit and plenum intake. It performs the same function as a conventional turbocharger air/air intercooler except that the cooling fluid is liquid. This system has considerable advantages over an air/air system, especially for mid engine vehicles where packaging and availability of air flow at yaw angles can be a severe constraint.



Fluid is pumped around the system by a positive displacement engine driven pump. This provides a simple and efficient means of variable water flow with increasing heat rejection requirements. The system is sized at maximum vehicle speeds, when operated in a 20°C ambient, at which air exiting the chargecooler is reduced to 60°C. At lower vehicle speeds the exit temperature is further reduced since heat rejection into the system is also reduced. (NB The vehicle has no trailer towing capability).

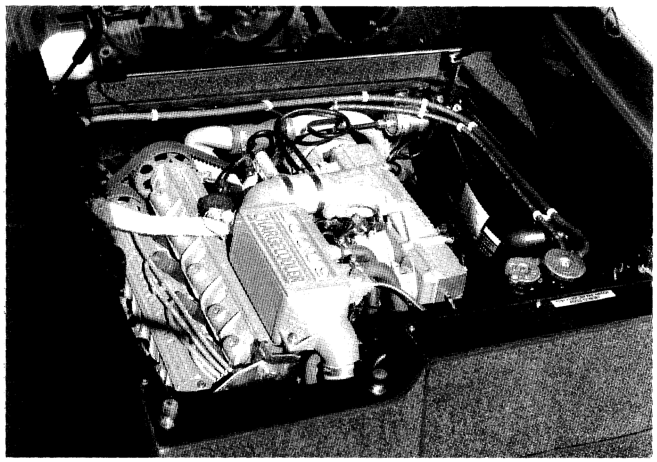
The hot coolant, at upto 70°C, exiting the chargecooler is cooled via a tube and fine type radiator at the front of the vehicle. This is, comparatively, a relatively large radiator for the heat rejection needed since the mean temperature difference between the air and coolant is lower than usually used in vehicle cooling systems.

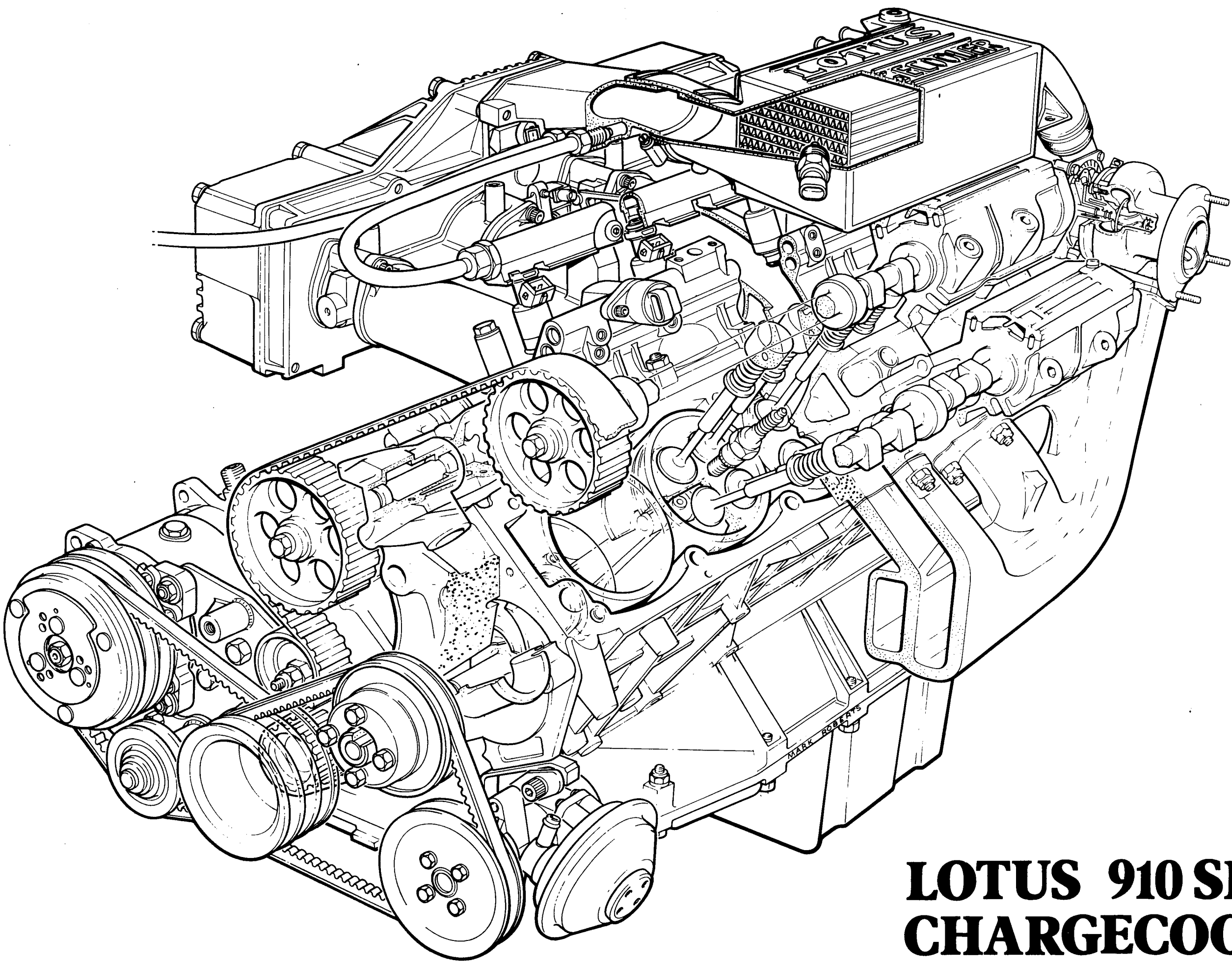


The advantages of this system for the Esprit over an air/air type can be summarised as follows:

- Minimum induction volume for maximum engine response.
- High thermal effectiveness, 69% at peak power
- Good package, very compact.
- Cooling ability modulated with engine speed.
- High thermal inertia.
- Minimum yaw angle influence.

The high thermal inertia of the system is a direct function of the specific heat capacity of the cooling fluids. In this case the cooling liquid has a Cp of 3.7 against Cp for air of 1.0 kJ/kg °K. Therefore for a similar heat absorption capacity the liquid cooled system can provide an instantaneous cooling ability 3.7 times longer than its equivalent air/air system. This allows higher than certified engine outputs to be achieved for perhaps 30-40 seconds due to the lower charge temperatures. In practice the 30 second installed performance is in the region of 210 kw (280 bhp). It should be remembered that certification performance tests require a stabilized reading to be held for one minute. Obviously this is not representative of dynamic vehicle sytems.





LOTUS 910 SE CHARGECOOLED

5.0 EMISSION CONTROL SYSTEMS

Raw engine out emissions, however low, generally require additional control systems to promote fast catalyst light off and NOx reduction, these are typically air injection and EGR.

The Lotus Esprit SE uses none of these and its only specific raw emission reduction system, other than a catalyst, is a post catalyst exhaust back pressure valve (EBPV). Principle items to be discussed here include the raw engine out emissions from the combustion chamber, catalyst design, engine management system and the exhaust back pressure valve. Other areas critical to overall emission performance (multiple throttles, combustion chamber etc) have already been discussed.

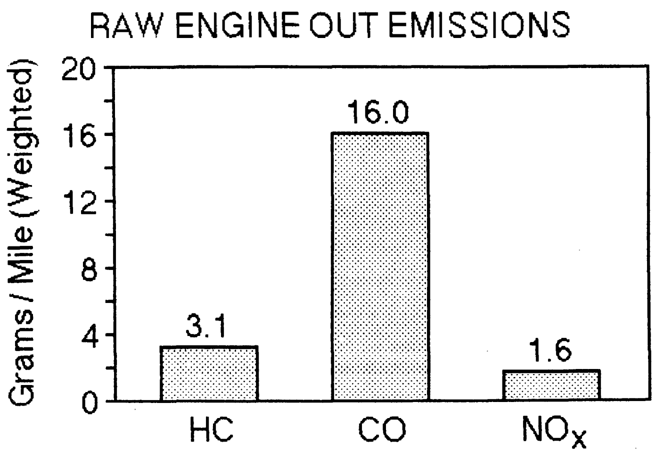
5.1 RAW ENGINE OUT EMISSIONS - The data presented below illustrates typical engine out raw emissions from production vehicles over a complete Federal test cycle. For comparison purposes, to achieve the current legislation targets of 0.41 HC, 3.4 CO and 0.4 NOx gm/mile at 50,000 miles with these raw levels, required catalyst conversion efficiencies of 87%, 79% and 75% respectively. With current technology this is achievable.

Potential future Federal 1994 legislation of 0.32 g/mile HC at 100,000 mile use, will require conversion efficiency of 81%, this suggests that some improvement in raw HC emission scatter will be required.

In the production environment every engine is hot tested, for one hour, and has to achieve the following raw emission targets for each cylinder before being passed to vehicle assembly.

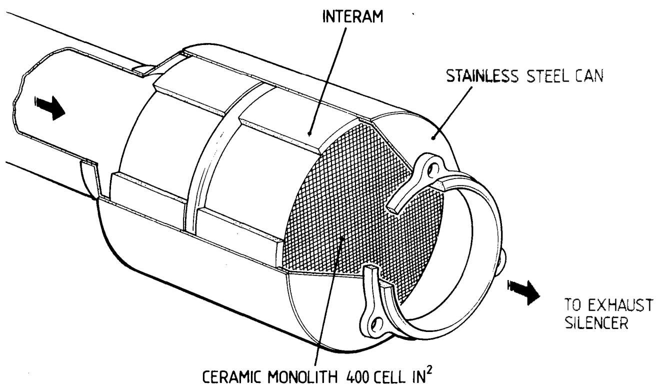
Engine Speed rpm	HC (ppm)	CO(%)
1000	less than 300	0.8 ± 0.3
2000	less than 300	0.8 ± 0.3
3000	less than 200	0.8 ± 0.3

NOx emission is not checked as this is generally well within emission test audit limits due to the cool combustion chamber design. It is also the exhaust gas least effected by build tolerance or component faults ie, injector leak, valve timing etc.



5.2 CATALYST - The catalyst design employed on the Lotus Esprit SE is a split brick design based around a 5.66 inch diameter extruded ceramic substrate. The bricks have an exceptionally low length to diameter ratio of 0.42 and 0.51 for the front and rear bricks respectively. They are mounted in a stainless steel can using Interam as the constraining and insulation medium following considerable longitudinal and radial substrate expansion testing. The bricks are mechanically constrained in the longitudinal direction using steel spacers.

The short brick design can be utilised in this application due to the action of the turbine wheel removing the severe exhaust pulse which could otherwise cause premature failure. In addition the relative large face area and CFD/FLIPS modelling of entry and exit conditions ensure that the pressure drop across each brick is kept to a minimum.



The split brick design was established after extensive testing to provide optimum light off characteristics and gas conversion efficiency, allowing differential loadings if required. The design shows an improvement in light-off time over a solid matrix. This is thought to be due to both the lower thermal inertia and heat rejection ability of the first brick, over an equivalent volume of solid brick, and the additional exit/entry turbulence caused by the gap between the bricks.

The coating itself follows conventional three way catalyst practice using nominal metal ratios of 5:1:1. The front and rear substrates carry different loadings to provide suitable light-off and conversion efficiency against precious metal concentration, and hence cost.

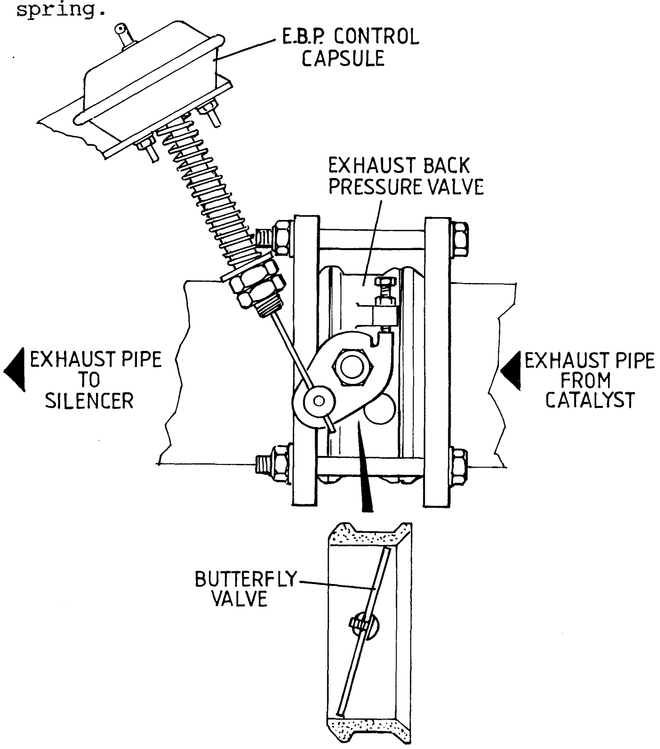
5.3 ENGINE MANAGEMENT SYSTEM - The Delco Electronics P4, semi-sequential eight bit microprocessor is used to control the engine management system. Software is based around that which already existed for another application, but has been specifically developed by Lotus for the unique boost control and exhaust back pressure valve systems.

The use of a mass air flow measuring system was considered, but later rejected due to the potential problems of attempting to measure air flow over a linear range with minimum pressure drop from idle to full load flow requirements of 600 m^3/hr. Consequently a speed density system has been utilised. This offered zero measurement induction pressure restriction, minimum packaging difficulties and potentially better reliability than mass air measurement. The speed density system proved a difficult challenge to calibrate on an engine using multiple throttles, short induction length, swept volume to downstream throttle ratio of only 0.8 and valve overlap of 42° crank. The problem was compounded by the turbocharged application since a wide range of manifold air pressure (MAP) measurement is possible at any single throttle angle, and speed, due to the variable boost pressure. The MAP signal was eventually measured through a series of orifices connecting each induction tract, and filtering the resultant signal both pneumatically and electronically.

Engine to engine and ambient air condition variations are accounted for by the adaptive fuel control system which continuously updates and modifies the basic programmed values. A barometric sensor is used for altitude compensation, and detonation sensing is used to control the iginition characteristics.

5.4 EXHAUST BACK PRESSURE VALVE (EBPV) - The EBPV comprises a SiMo casting, clamped between the catalyst and silencer, which carries an offset stainless steel throttle plate. This is sprung shut in the closed position under certain cold start or static conditions using a normal compression spring acting on a lever. This gives more desirable characteristics than a radial spring and is more easily insulated from radiated exhaust heat.

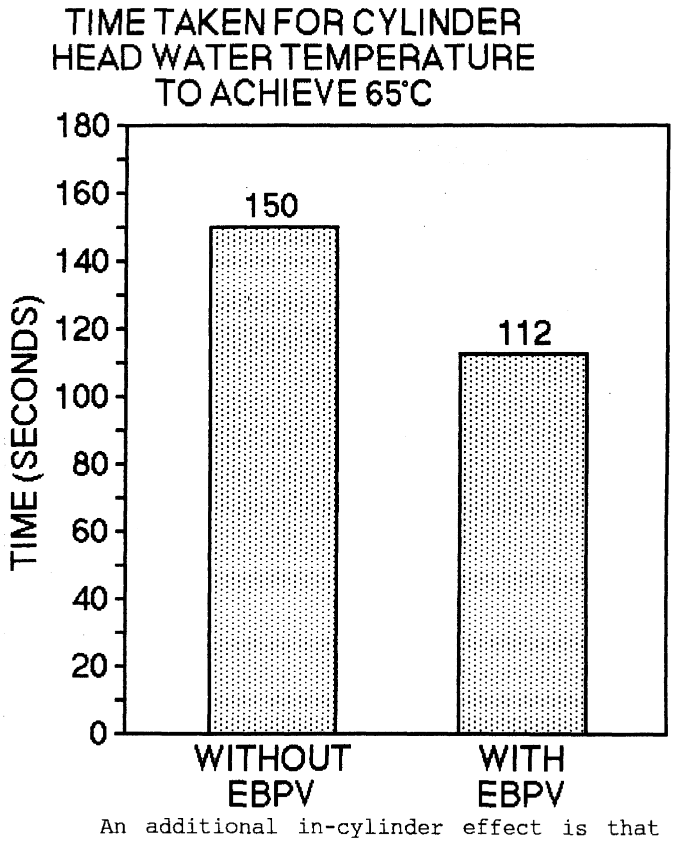
With the engine running the differential pressures acting on the offset throttle blade self modulates its position with engine load against resistance applied by the compression spring.



This provides an adjustable, and controllable, exhaust back pressure at idle conditions and a gently increasing characteristic as engine load and speed is increased. In this way drivability is not adversely affected to any great extent.

The increase in back pressure during engine warm up has been shown to decrease the measured exhaust emissions. The back pressure has several effects which combine to increase the catalysts overall performance and reduce exhaust pollutants, these are described.

The back pressure increases engine pumping work, and consequently increases engine load, and hence exhaust gas temperature and mass thoughput for the same idle or engine load/speed conditions. This also has the effect of increased in-cylinder heat rejection to coolant, and is illustrated below showing a comparison of time taken for the cylinder head water temperature to increase from a 25°C ambient start to 65°C during a Federal cold start emission test.



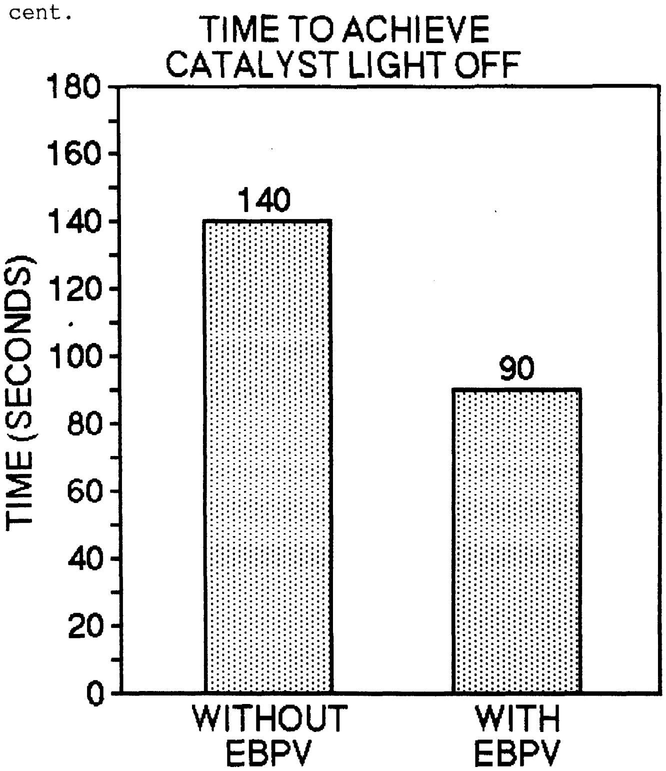
An additional in-cylinder effect is that of creating poor cylinder purging, and hence increasing the proportion or residual exhaust gas remaining causing dilution of the fresh incoming charge. This is the same effect as an external EGR system.

Since the increased back pressure results in a faster rise in exhaust gas temperature than with an ambient pressure system, the heating effect of the gas on the catalyst will be correspondingly faster with a more rapid increase in catalyst surface temperature, and hence the reaction rate, prior to the catalyst lighting off. This in turn will lead to a reduced time to catalyst light-off as a greater quantity of heat will be generated by the exothermic reactions taking place over the catalyst.

The increased pressure leads to a longer residence time of the gas over the catalyst. This may increase conversion by reducing any diffusional constraints imposed by the catalyst washcoat porosity. In addition, the longer residence time would lead to improved heat transfer between the gas phase and the catalyst surface prior to catalyst light-off.

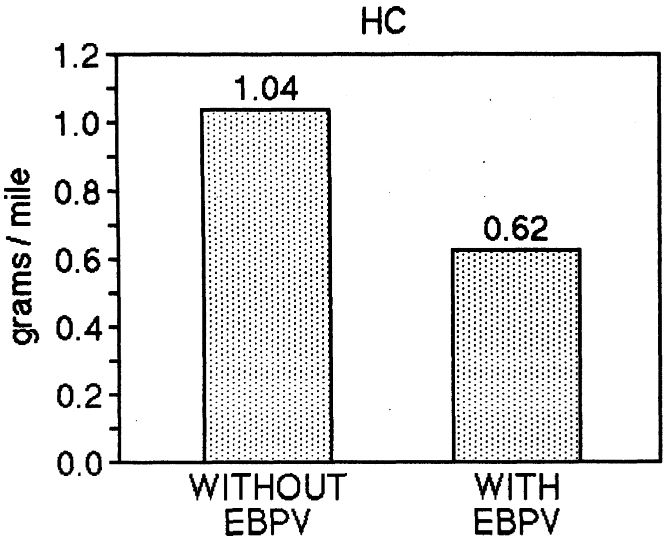
Once a region of the catalyst has reached the temperature where the heat generated by reaction raises the surface temperature above that of the gas phase, ie. the reaction becomes autothermal, the slower gas velocity will remove less heat due to an increased boundary layer effect, despite the thermal capacity of the gas stream being the same as at normal operating pressure. This enables the exotherm to spread more rapidly across the entire catalyst surface.

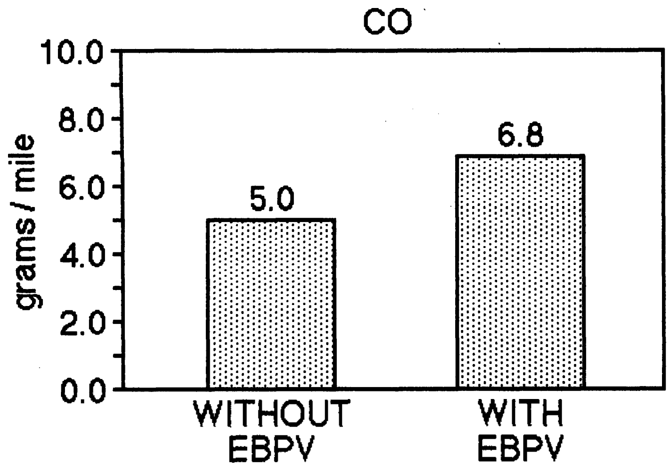
The reduction in light-off time is significant and has been shown to reduce the time taken to achieve 50 per cent conversion efficiency, considered light-off, by 35 per cent.

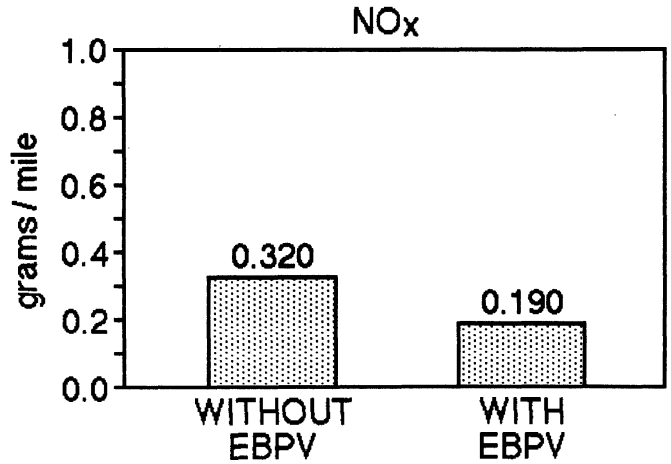


Reduction and oxidation of pollutants could also occur by homogeneous reaction in the gas phase. These reactions would occur at a significant rate at temperatures in excess of 700°C and the increased residence time in the hot parts of the exhaust system may increase the degree of pollutant conversion by this mechanism.

The subject is a complex, one and its mechanism not easily understood or confirmed. However the results achieved, and shown below, as measured during a cold Federal Test bag, can be repeated with high success.







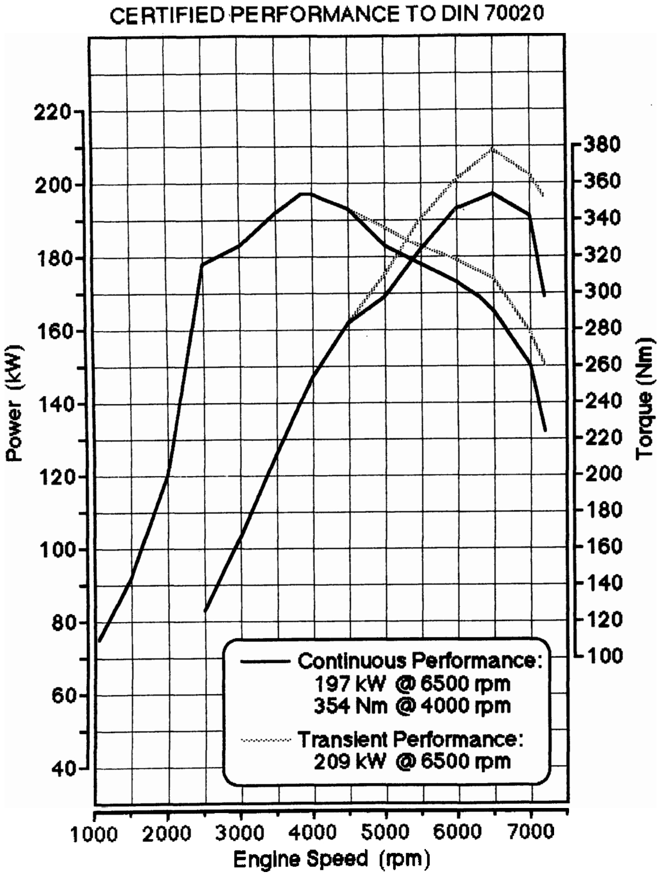
As shown, the negative effect is that CO is increased, which in some applications may cause additional problems. Surprisingly no increase in fuel consumption can be measured although it should be said that the EBPV is only in operation for 120 seconds, or until coolant temperature reaches 65°C. Once these conditions are met the valve is mechanically opened and then, because of its size, imposes no restriction on the exhaust system.

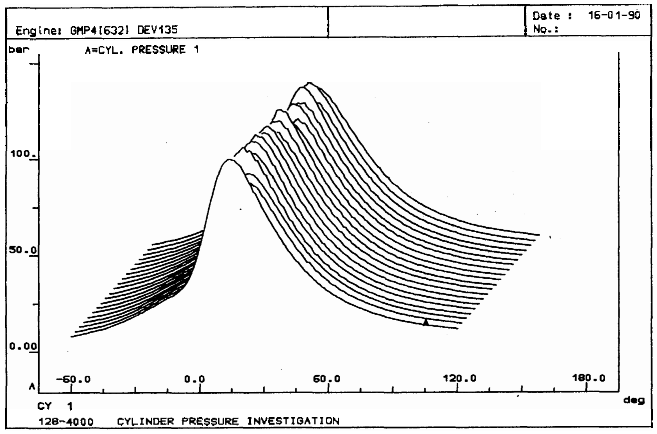
6 ACHIEVEMENTS

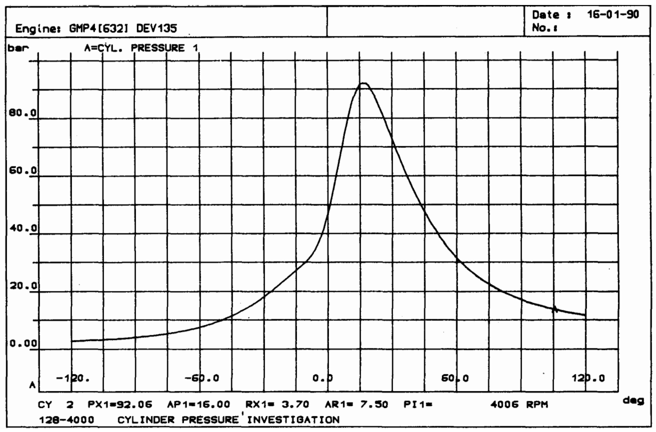
It is intended to discuss achievements in three distinct sections:
6.1 Engine Performance
6.2 Emission Performance
6.3 Vehicle Performance

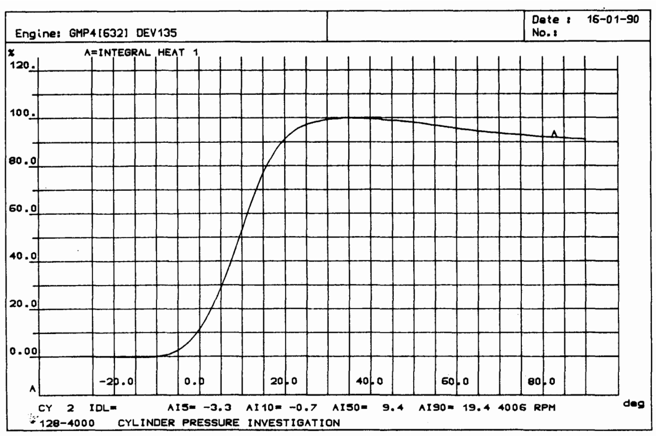
6.1 ENGINE PERFORMANCE - The certified performance, to DIN70020, of 197 kw (264 bhp) is, to our knowledge, both the highest performance four-cylinder engine and the highest specific performance output of any engine meeting Federal and European emission legislation. Peak torque is achieved at the relatively low speed of 4000 rpm, with power peaking 900 rpm before maximum engine rpm at 6500 rpm.

LOTUS ESPRIT TURBO
TYPE 910S CHARGECOOLED
CERTIFIED PERFORMANCE TO DIN 70020







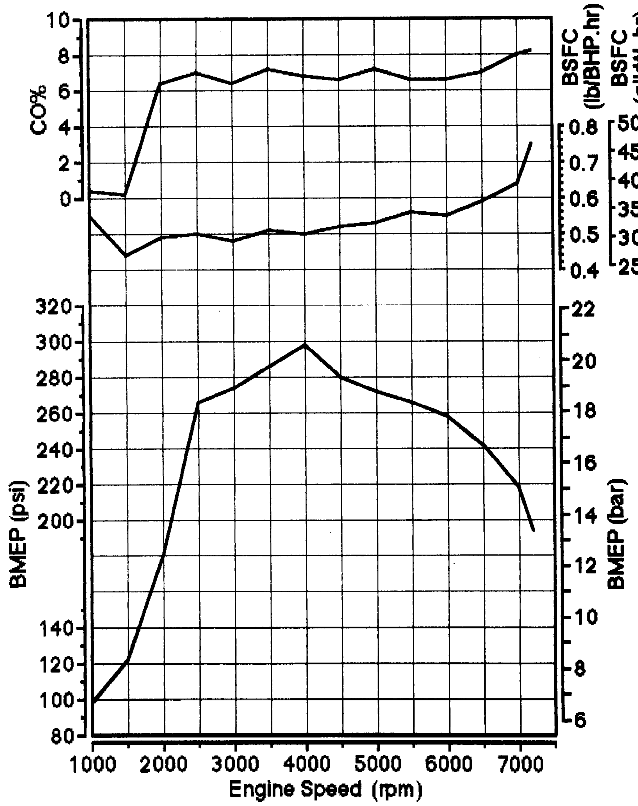


Above data measured at 4000 rpm, full load.

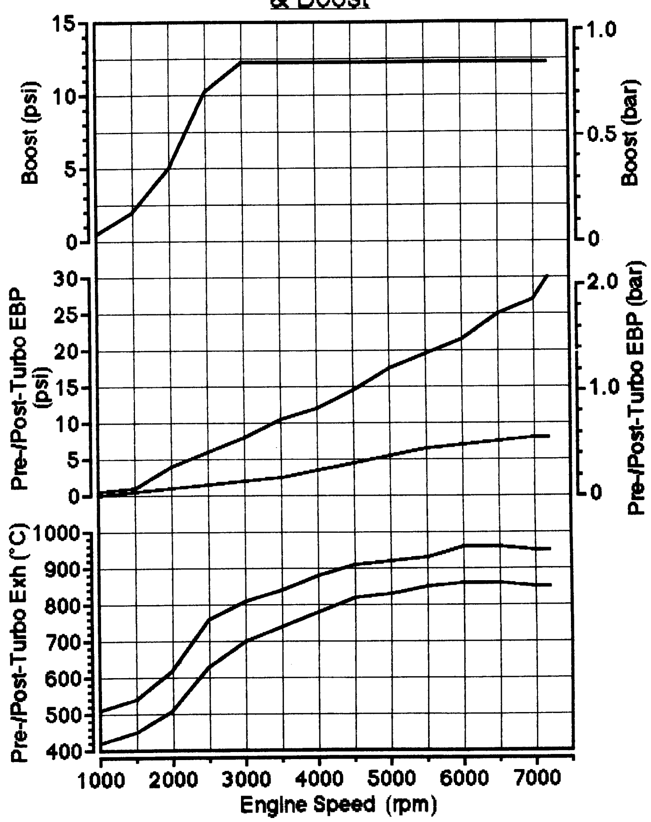
Obviously these outputs result in considerable mechanical and thermal loadings. The peak cylinder pressure is typically in the range of 90-100 bar and cyclic irregularity is well controlled. This is demonstrated in the waterfall plot showing 20 consecutive cylinder events. The high pressure is achieved without severe rates of pressure rise, as may be seen from the pressure diagram, and mass fraction burnt curve. Peak pressure is recorded at 16-18° after TDC and 90% mass burnt by 20° ATDC.

BMEP peaks at 20.6 bar (4000 rpm), where a BSFC of 300 gm/kw hr is recorded. At higher engine speeds a gradually increasing richer mixture is used to control exhaust gas temperature to a peak of 980°C. This can be seen by the change in slope of the exhaust temperature curves, and the consequential increase in BSFC.

BSFC, BMEP & CO%

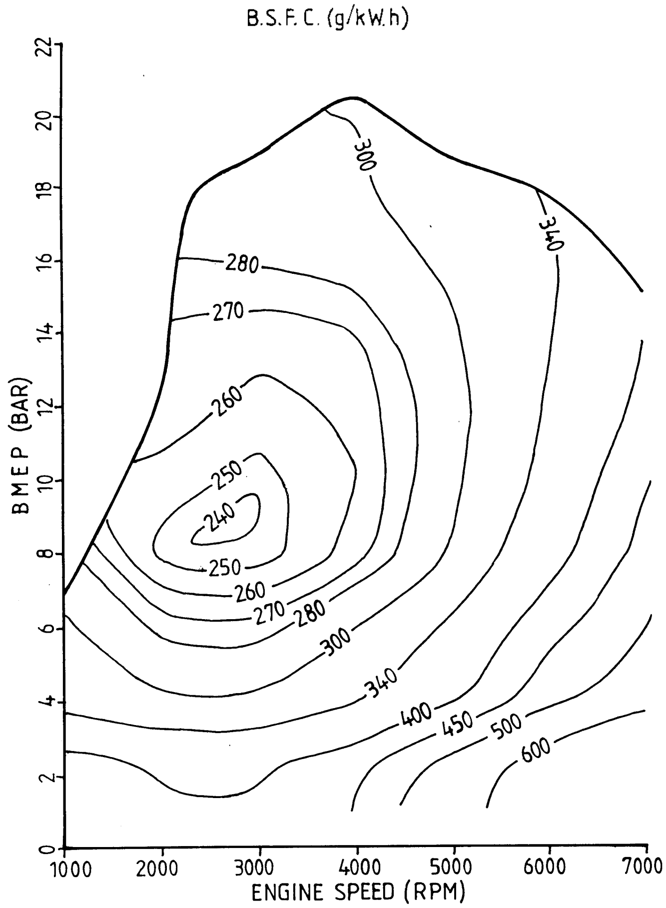


Exhaust Temperatures & Back Pressures & Boost



At part load conditions a minimum BSFC of 240 gm/kw hr is achieved through careful turbine and compressor matching whilst still running the over rich stoichiometric air/fuel ratio, currently necessary for feedback control systems, at which absolute minimum BSFC's cannot be obtained.

It must be remembered when comparing this figure with other engines that the geometric compression ratio is 8.0:1, and that it has been achieved with a valve overlap of 42°.



6.2 EMISSION PERFORMANCE - As previously stated, the required emission legislation for Federal and European markets is now very similar for the greater than 2.0 lt class vehicles. The targets during the development were therefore set at a level which would ensure achievement of Federal (49 states and CARB) and European certification, with a common engine management calibration. The table shows the actual achieved results.

	HC	**CO**	**NOx**
Federal Legislation	.41	3.4	.4
With DF's	.31	2.8	.36
Development Target	.2	2.0	.2
Certification level	.14	1.0	.27

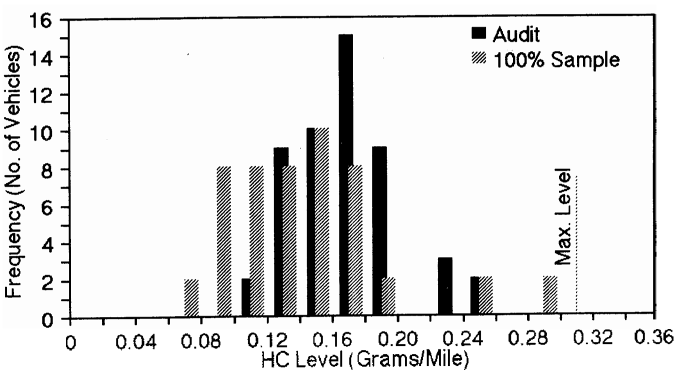
(Figures in gm/mile)

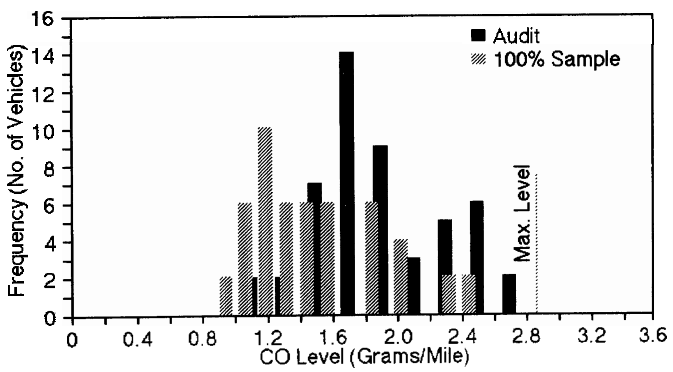
To confirm compliance of production vehicles a policy of audit monitoring, following 100% sampling of the first 50 vehicles has been adopted. The audit frequency of 10% is comparatively high, based on a total production volume of 550 vehicles in 1989.

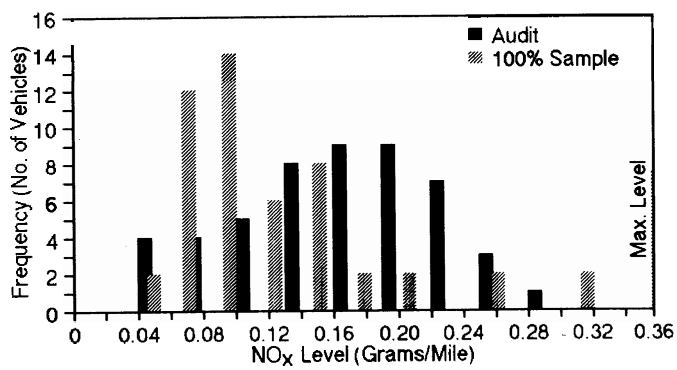
Results from these audit tests are displayed in the form of histograms. Each shows the comparison of the early production 100% sample rate (recorded in mid 1988), and the results from the latest audit tests recorded over one year later. Tabulation of the results for comparison gives:

	HC	CO	NOx
Targets with DF's	.31	2.8	.36
Mean 100% sample	.14	1.5	.12
Mean audit sample	.17	1.9	.16
3σ 100% sample	.29	2.7	.31
3σ audit sample	.26	2.8	.34

(Figures in gm/mile)





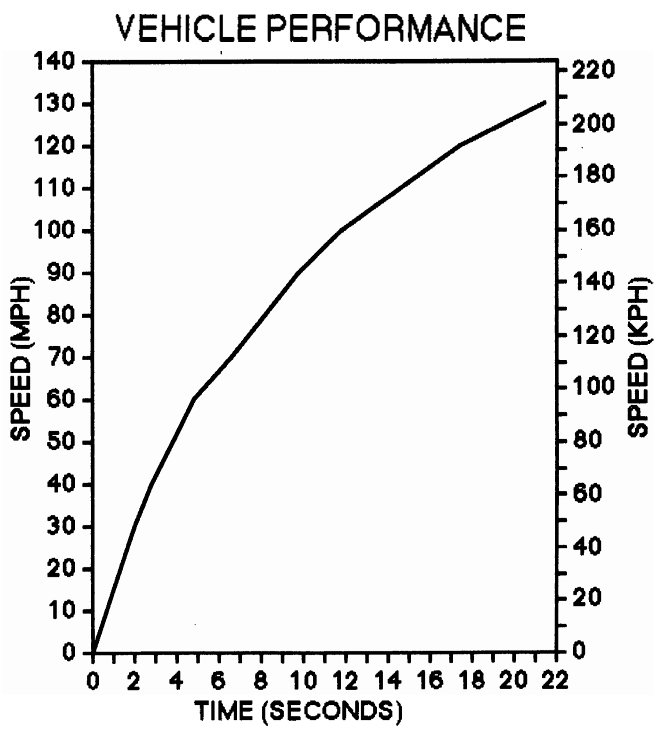


The results show that the mean gaseous emission levels are well under control, and compare favourably with the certification levels. It is thought that the lower NOx, for production engines, is because these engines have no carbon build up and therefore are not stabilised. The higher levels of CO could be due to similar reasons and new tyre losses. The 3σ level indicates the estimated capability of the quality control system. It represents the limits within which 99.8% of all values can be expected to be recorded, based upon the distribution of previous results. In this instance it may be seen that the CO concentration falls close to the maximum allowed levels with deterioration factors taken into account although this is still within the 3σ level.

This is a highly acceptable result for vehicles needing to comply with European 88/76 and Federal 50 state requirements. These statistical capability levels have proved to be of immense use in setting, and monitoring production control systems.

6.3 VEHICLE PERFORMANCE - Finally it is obviously the complete vehicle performance which is important. Running on regular 95 RON unleaded fuel typical performance figures are:

0- 60 mph	4.7 seconds
0-100 mph	11.9 seconds
Maximum speed	163 mph (262 kph)



Gear performance and engine response is even more impressive, as an example:

Fourth Gear:	50 - 70 mph	3.8 seconds
	70 - 90 mph	4.0 seconds
Fifth Gear:	70 - 90 mph	5.3 seconds
	90 - 110 mph	6.1 seconds

These levels of performance place the vehicle among the top of the "supercar" class of vehicle although few meet such stringent exhaust and environmental controls.

The engine drives through a five speed transaxle to Goodyear Eagle 245/50 ZR 16 rear tyres. Gear ratios are:

Gear	Ratio	Mph/1000 rpm
5th	0.82:1	23.1
4th	1.03:1	18.4
3rd	1.38:1	13.7
2nd	2.05:1	9.3
1st	3.36:1	5.6

Final Drive 3.889:1

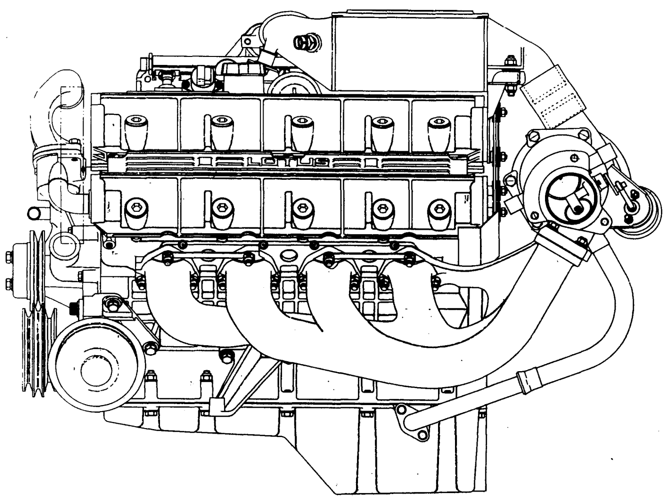
Kerb Weight 1305 kg

7 SUMMARY

Lotus set out to develop and produce an exceptionally high performance engine complying with worldwide legislation. This has been achieved in a light weight and highly efficient power unit, the main features of which have already been described in detail and include:

Forged Aluminium Liners
Optimised Combustion Chambers
Chargecooling
Catalyst Design
Exhaust Back Pressure Valve
Engine Management System
Quality Control Systems

In conclusion, this project clearly signals the rebirth of higher engine efficiencies in harmony with the environment and gives real world credence to the Lotus motto of "The Power of Innovation".



8 APPENDIX

Engine Specification

* Four-cylinders in line
* Displacement - 2174 cc
* Bore x stroke - 95.3 x 76.2
* Four valves per cylinder (two intake, two exhaust)
* Dual cam shafts
* Direct acting mechanical inverted bucket tappets
* Toothed belt timing drive
* Aluminium cylinder head, block, bearing ladder, frame and sump
* Open deck cylinder block
* Deep seated aluminium liners with "Nikasil" coated bores
* Cast SG iron crankshaft
* Forged steel connecting rods
* Forged aluminium pistons
* Semi-sequential fuel injection system
* Garratt TB03 turbocharger
* Weight 180 kg complete with anciliaries and clutch

9 ACKNOWLEDGEMENTS

The authors would like to thank the following organisations for their assistance and enthusiasm in supporting this project:

Johnson Matthey
TI Cheswick
NGK
AC Rochester/Delco Electronics
AES/GM Tech Centre
Behr
Mahle

Printed in U.S.A.