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NEW EMISSIONS REGULATIONS – IMPACT ON ENGINE DESIGN AND OIL FORMULATION

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Abstract: For the past eleven years changes in heavy-duty diesel engine emission limits have driven changes in engine design. In turn, these changes in engine design have made the service environment of the engine lubricant more severe and necessitated the development of increasingly higher quality heavy-duty oils. This paper will review the historical co-evolution of emissions limits, engines, and lubricants as a background to what may be the most dramatic change in emissions control technology yet considered.

This new technology is exhaust gas re-circulation (EGR), and although it offers the possibility of allowing diesel engines to reach significantly lower levels of exhaust emissions; it also brings with it an array of new concerns and potential problems. A new API performance category , which is currently known as PC-9, is being developed to meet the lubrication needs of these EGR-equipped engines. This paper will provide an overview of the early development status of this new category along with a description of the new engine tests being considered. Although none of these new tests are yet available for new product development, some very preliminary data points are available using CH-4 quality oils in the new tests. A quick review of these results will be contrasted against the known performance of these products in the current CH-4 tests.

By extrapolating these results from specific tests to general performance needs, this paper will finally predict the probable implications of these tests on the formulation requirements of PC-9 quality lubricants.

Background: For many years, in fact until 1988, diesel engine exhaust emissions were largely uncontrolled by the U.S. Environmental Protection Agency. Although there were some limitations on black smoke, the more conventional pollutants such as unburned hydrocarbons (HC), nitrogen oxides (NOx), and carbon monoxide (CO) were left uncontrolled for diesel engines long after they had been brought under strict control for passenger cars. To some extent this was a reasonable position, as diesel engines offer inherently low levels of HC and CO in their exhaust streams due to their operation with a dramatic excess of air compared to a spark-ignited engine as used in a passenger car.

In fact, a review of the EPA limits on HC and CO as shown in Table One reveals that the limits first imposed on these two pollutants in 1988 do not tighten as the years progress. It should also be noted that these limits are not really constraining for diesel engines as they can easily be met with no changes to the engine hardware. The battleground for the diesel engine designer lies in the trade-off between the other two controlled pollutants, NOx and particulate matter (PM). Although the details of the combustion chemistry are more complicated, it is useful to consider the control of both NOx and particulate matter as the two horns of a dilemma. Generally, things done to improve the combustion process i.e. to burn the fuel more completely will reduce the engine out particulate matter. Unfortunately, this good combustion leads to very high peak flame temperatures which also generates high levels of NOx. Conversely, anything which "messes up" the combustion event can bring down both the peak flame temperature and the generation of NOx, but at the same time it will directionally increase the particulate matter. Of course all of the trade-offs to control NOx and PM must be balanced to maintain the best possible fuel economy.

Some of the engine design changes to control diesel engine emissions were described in the 1995 NPRA paper by Fetterman and Shank. Generically, the control of PM is done with changes which improve the combustion of the fuel in the engine. These include such things as much higher injection pressures in order to form smaller fuel particles, increasing the rate of "swirl" of the air in the combustion chamber, reducing the amount of dead space in the combustion chamber, and even slowing down the rated engine speed to allow more time for the fuel to burn completely. During this time the control of NOx has been handled by retarding the timing of the injection of the fuel into the combustion chamber. By delaying the injection event until closer to top dead center, the combustion event is changed so that the peak flame temperature drops and NOx generation drops.

Unfortunately, this delay in injection timing means that the fuel injector is still firing after the piston passes through top dead center and begins to move back down the cylinder. This, combined with the extremely high fuel injection pressures involved can cause some of the fuel to spill over the top of the combustion chamber bowl. Some portion of this fuel is coked by the high temperature of the combustion zone, and it is converted to soot. In turn, some portion of this soot reaches the cylinder liner and becomes entrained in the lubricant film and transported into the bulk lubricant in the engine sump. Thus, one impact of the control of engine out NOx has been a significant increase in the soot loading of the engine oil.

Both of the last two API performance categories, CG-4 and CH-4, have had the control of oil entrained soot as key portions of their engine test requirements. Some tests, such as the Mack T-8 and T-8E look at an oil's ability to prevent excessive increases in viscosity when it is loaded with 4 to 6% soot. Other tests such as the Cummins M11 and the Roller-Follower Wear Test address the oil's ability to prevent excessive wear in the valve train with similar levels of soot loading, while the Mack T-9 looks at ring and liner wear with about 2% soot in the oil. Again, in all of these tests at least one of the key pass/fail parameters is a measure of how well the oil can cope with the increased soot loading which comes from retarded timing to control NOx.

If we look at the impact these engine changes have had on oil formulations, several trends evolve. First, the dramatic increase in soot loading from 1-2% in pre-emission controlled engines to 6+% in 1999 emissions compatible engines has required a significant increase in dispersant potency. At the same time, piston design changes combined with increased specific engine output (not an emission requirement, but a part of the real world none-the-less) have lead to the need for enhanced oxidation stability and piston cleanliness / detergency. Finally, the need to control engine wear in a high soot environment has lead to a careful balance of the dispersant and antiwear components in the oil. The good news for additive suppliers is that, generally, these new engines like to have more additives! The bad news for them is that the U.S. lubricant market is extremely competitive and cost sensitive, so these additives must be delivered in a well-optimized, cost effective package.

Up to this point, this background discussion has been historic...a review of what has happened to date. From here on, it will be looking forward to what is coming and that is a 50% reduction in the NOx limits in October of 2002. Although the engine manufacturers, the EPA, and the California Air Resources Board had mutually set this target level of performance several years ago, the original target timing was to be 2004. It was accelerated to 2002 as a part of several consent decrees signed in late 1998 between the various engine manufacturers in the U.S. and the EPA.

As discussed earlier, NOx reductions from the 1988 limits through 1999 have been met by retarding the injection timing. According to the engine design experts at all of the engine manufacturers, reducing NOx from today's limit of 4.0 g/bhp-h to the 2002 limit of 2.0 g/bhp-h is beyond the capability of additional retardation of timing. A new emission control technology is required to meet these NOx reductions. This new technology is known as exhaust gas recirculation (EGR). EGR reduces NOx by putting non-combustible components into the incoming air-fuel charge, once again reducing peak flame temperature and NOx generation. In addition to this simple dilution effect of EGR, even greater benefits can be seen if the exhaust gas is cooled before it is returned to the engine. One part of this advantage is the cooler intake charge allows better filling of the cylinder and thus better power generation. The other part of the advantage is that the EGR components have higher specific heat values than the incoming air and fuel, so they even further cool the combustion mixture and allow more power / better fuel economy at a fixed NOx generation level.

Developing API quality level PC-9: The anticipated lubricant needs of these new EGR-equipped diesel engines is the sole driving factor for the developing PC-9 quality level. Figure one shows a schematic diagram of a generic cooled EGR system. Exhaust gas is taken from the high pressure area upstream of the turbo-charger turbine and passed through a cooler. This cooled gas is mixed with fresh intake air as it exits from the intake charge-air cooler, and then the mixture of fresh air plus EGR is drawn into the engine. (N.B. the engineering effort required to make this happen is not insignificant, but it is well beyond the scope of this paper.)

One of the major concerns about the use of EGR with high-output diesel engines stems from the need to cool the exhaust gases before returning them to the engine intake. The problem with this is that diesel fuel contains sulfur. Even "low-sulfur" diesel fuel still contains 300 to 400 ppm as a typical level of sulfur. When the fuel is burned in the engine, this sulfur is converted to SOx. In addition, one of the main by-products of the combustion of a hydrocarbon fuel is water vapor, so the exhaust stream contains some level of NOx, SOx, and water vapor. In the past these have not been a problem, because the exhaust gases have been extremely hot which keeps these components in a dis-associated gaseous state. However, when the EGR stream is cooled before it is returned to the engine, the mixture drops below the dew point, and liquid water condenses out. This water reacts with the NOx and SOx components to form a mist of nitric and sulfuric acids in the EGR stream. This mixture is then fed back into the power assembly of the engine where it has been seen to cause catastrophic increases in ring and liner wear. In addition, the use of EGR with no change in injection timing will also cause an increase in soot generation. The little bit of good news coming with EGR is that it is so efficient in controlling NOx that engine designers expect to be able to advance injection timing which will both reduce soot and improve fuel economy.

The engine manufacturers concern over the impact of EGR is so great that they have proposed and started development of three new EGR-equipped engine tests for PC-9. These tests are the Mack T-10, the Cummins M11-EGR, and the Caterpillar 1Q. It is anticipated that each of these tests will measure similar performance attributes to their CH-4 counter-parts, the T-9, M11, and 1P, except they will evaluate these parameters in an engine equipped with EGR.

To re-cap their expected duties, both the T-9 and T-10 will look at ring and liner wear as well as bearing corrosion protection. The M11 and M11-EGR will address sliding valve train wear, filter plugging, and sludge control; and both the 1P and 1Q will evaluate the oils ability to control piston deposits. As this paper is being written, none of these tests is yet available to industry, so much of what is said is based on plans and predictions. With that disclaimer, what follows is a discussion of each new test.

Mack T-10: The Mack T-10 is a new test using an in-line six cylinder, turbo-charged and after-cooled diesel engine which has been modified to use EGR. An ASTM Task Force reporting to the HDEOCP has been formed to develop this test for PC-9. Several shake-down tests have been run in the Mack test laboratory in Hagerstown, MD. By the end of October, 1999, Mack plans to have seven engines distributed to industry labs as well as a preliminary draft of a test procedure. It is anticipated that this test will run for 300 hr. with two phases...similar to the T-9 test. The first phase will run for 100 hr. with retarded timing to pre-condition the oil with soot, and the second phase will run 200 hr. at low speed and extremely high firing pressure to generate ring and liner wear. Again, both of these operating conditions are similar to the T-9, but the use of EGR in the T-10 is expected to dramatically increase the wear rates compared to the CH-4 test. The current development plan calls for a discrimination mini-matrix to start in late 1999 and for the test to be ready for the ASTM precision and BOI matrix testing in the Spring of 2000.

Cummins M11-EGR: The Cummins M11-EGR is also a new test using an in-line six cylinder, turbo-charged and after-cooled diesel engine which has been modified to use EGR. The test is at roughly the same level of development as the T-10 with some testing done in Cummins engine laboratory in Columbus, IN. and ten engines expected to be distributed to industry by October, 1999. An ASTM Task Force has also been formed to develop the M11-EGR test. The test procedure is expected to vary somewhat from the M11 test, in that it will use a 100 hr. pre-sooting phase (similar to the T-10), followed by a 250 hr. cycling phase with variations in engine speed, load, EGR rate and cooling. The original expectation was that the M11-EGR test might generate 10-12% soot in the oil, but more recent data suggests the level will be more like 8-10%. Still, this represents a dramatic increase in soot loading compared to the 5-7% soot required for CH-4 / Mack EO-M PLUS / Cummins CES20076 test requirements. Based simply on the test length, EGR cycling, and soot loading, it would appear that the M11-EGR test could be the defining test for PC-9.

Caterpillar 1Q: The Caterpillar 1Q test is also a new test for PC-9, but in this case it is a single-cylinder laboratory test engine which has been modified to use EGR. The test engine assembly which Cat identifies as the 1Y3700 Single Cylinder Oil Test Engine (SCOTE) uses the same block and head as the 1P test. However, for the 1Q test it uses a new piston design as well as EGR. Since all engine labs have 1Y3700 SCOTE installations and the new piston is readily available, the power-producing portion of the 1Q can be run today. In fact, Caterpillar have released a test procedure for a test which they call the pre-Q. It uses the proposed 1Q operating conditions but without EGR, and both Caterpillar and the other industry labs have experience running this test. However, the availability of EGR-conversion kits for the 1Y3700 engines is somewhat behind the other two new tests. Cat's original design used a variable venturi to help draw EGR into the intake air stream, and this design proved to be plagued with deposit problems. A new EGR system has been designed using increased back-pressure to drive the EGR stream, similar to both the T-10 and M11-EGR tests.

Industry status: As indicated earlier, the industry need is to have API licensed oils meeting the needs of EGR-equipped engines available no later than October of 2002 when the new EPA emissions limits become effective. However, many engine manufacturers would like to have oils available even earlier, as they can accrue credits for early introduction of lower NOx engines. To support this desire, ASTM is targeting January 2002 as the desired first allowable use date. Working back from January 2002, the API typically requires a minimum of one year development time for a new category to insure that all parties have sufficient time for reformulation testing. This means that all ASTM test development work and limit setting must be complete by January 2001. Figure two shows the official HDEOCP timeline as of September 1999, and based on this plan it is possible that PC-9 could be developed in time. However, a review of the early timeline plans for both API CG-4 and CH-4 would show that both categories slipped by one year. Considering the dramatic increase in engine severity expected with EGR-equipped tests combined with the fact that none of the new tests are available as of the September 1999 timeframe, it requires a very optimistic outlook to predict an on-time delivery for PC-9. Still, all parties are working diligently to develop PC-9 as quickly as possible since the EPA emissions timing is non-negotiable, and these new oils will be required to protect EGR-equipped engines.

While the new test hardware is slightly behind the OEM's desired schedule, progress has been made on many of the development supporting activities. Potential test matrix designs have been developed, and agreement in principle has been reached on the matrix funding. Final selection of the basestocks to be used in the matrix is expected at the November API lubes committee meeting, and a task force has been working on defining the matrix test oils. At this time, it would seem that on-time delivery of PC-9 is still a possibility, but it will require a full share of good luck combined with continued hard work by all shareholders to maintain the aggressive schedule for on-time delivery of the new tests.

In addition to the three new EGR-equipped engine tests being developed for PC-9 there are a significant number of other tests which will define PC-9. Eight of the CH-4 engine and bench tests are planned to be carried forward either at the CH-4 performance level or, perhaps, with tightened limits for pass/fail. These carry-forward tests are:

The 6.5 liter Roller Follower Wear Test

The Engine Oil Aeration Test

The Caterpillar 1N Aluminum Piston Deposit Test

The Mack T-8E

The Cummins High Temperature Corrosion Bench Test

ASTM D892 Foaming Test

ASTM D6278-98 Shear Stability Test

ASTM D5800 Volatility Test

The original PC-9 request from EMA also contained a number of tests which have been formally dropped from the category definition. Still, there remain several requested performance parameters which have not been dropped, but final agreement has not been reached on the test which will be used to measure that parameter. First among these is an oxidation test. The EMA requested the John Deere JDQ-78A oxidation test as part of their original category definition. This test has not been well received by the oil and additive company members of the HDEOCP. Although the EMA members have indicated early support for the test, they have also indicated a willingness to consider other options to measure an oil's oxidation protection. At the September 99 HDEOCP meeting a Task Force was formed to look at meeting the oxidation test requirements of PC-9.

In addition to all of the above tests there are two new bench tests which are also being considered for PC-9. The first is a seal compatibility test similar in intent to the CARS test developed for passenger car lubricants. In concept, this test will identify reference oils which show aggression towards seals in glassware tests, but which have shown acceptable field performance. These reference oils will be used by seal suppliers to develop new seal compounds, and oil suppliers will screen their new products against the performance of these reference oils to insure that more aggressive products are not brought to the market. The final bench test will look at the low temperature performance of heavily-sooted used engine oils. Data is being collected on drain oils from the Mack T-8E to assess these low temperature performance concerns.

Cost considerations: The development of both the new PC-9 category tests and new oils to meet the required performance level will be expensive propositions. The planned budget for the "funded" portion of the test precision and BOI matrix is approximately $2,000,000. However, the "funded" portion of the testing represents only a fraction of the actual matrix cost as the test labs must fund that portion of the cost which would be required for test stand calibration. Of course, even though the labs provide the up front funding, these costs are eventually passed back to the oil and additive companies which conduct tests for oil approvals. The entire cost of the development matrix, including the "funded" tests as well as the calibration tests is projected to approach $7,000,000 depending on which matrix design is finally selected.

Once the development testing is complete, oil formulators still face an impressive bill to qualify a finished lubricant. Using published costs for the carry over tests and industry estimates of $85,000 for an M11-EGR, $65,000 for a T-10, $60,000 for a 1Q, and $60,000 for a JDQ-78A (should it remain in the category), the cost to deliver a one-time pass in all of the proposed PC-9 tests is close to $360,000 for one core program in one basestock and one viscosity grade. If some consideration is given for a less than one out of one pass ratio plus the need for testing to qualify for the latest API "S" category, it is not too difficult to imagine one core program costing well over $1/2 million!

In June of 1998, an industry estimate of the reformulation cost for CH-4 was made based on RSI test registrations. At that time industry had spent just under $30,000,000 on engine tests to qualify oils for CH-4. If a similar estimate is made using the tests proposed for PC-9 along with their attendant prices, the probable reformulation cost for PC-9 is $39,500,000, or roughly 30% greater than the cost of CH-4. That cost could be reduced by close to $3,000,000 if the Sequence IIIF test could be substituted for the JDQ-78A test for oxidation.

Alternatives to PC-9: Given the EPA deadline for reduced NOx emissions in October 2002 and the absolute need to use EGR to reach those target levels of NOx, there is a definitive need to have PC-9 quality lubricants available. Although industry still has time to deliver this new category on time, history would suggest that the probability of success is not high. Like the test developments for both CG-4 and CH-4, it is likely that ASTM will deliver fit-for-purpose tests, but they will probably not be done by the required date of January, 2001. If this happens, the response of the OEM's is again likely to be exactly as it was for the previous delayed categories. Assuming the new test development programs actually complete sometime during the year 2001, on or about January 1, 2002 Cummins will probably issue a new lubricant specification, CES200XX; and on or about April 1, 2002 Mack will issue their EO-N specification. If industry has reached consensus limits to define PC-9, both of these specs will probably align with those limits. On the other hand, if consensus limits cannot be reached, both OEM's will establish whatever limits they feel are needed to protect their engines in the field. The bottom line is that API PC-9 quality oils will exist in the 2002 time frame either as an API category or a series of OEM specifications.

Formulation implications: Since none of the new PC-9 tests are available to begin development of new oil formulations, any implications listed here are pure prognostication. That said, there are a number of known changes which allow the prediction of at least directional differences from CH-4 tests. First, since it is known that EGR will result in acidic mist being fed into the engine power assemblies, it is likely that additional TBN will be required for the PC-9 tests. What is not known is whether bulk oil TBN is sufficient, or if some special method is required to deliver this TBN to the ring and liner interface. Is it better to have more reactive TBN or more stable TBN, or most likely a proper balance of both?

One of the directional impacts which is easy to predict is the need for increased dispersant potency. The target for soot loading in the M11-EGR is in the range of 8-10%, this represents roughly a 50% increase from the 6.5% rating point for CES20076 approvals. There is absolutely no doubt that this increase in soot will require a step increase in dispersant potency from CH-4 or any of the current OEM specifications.

Another concern at these very high soot loadings is how they will impact the oil's anti-wear performance. It is possible that wear control may require either very high ZDDP treats or some kind of supplemental anti-wear component. If this happens, it could drive a wedge between the anti-wear needs of heavy duty engines and the low phosphorus / catalyst compatibility needs of light duty engines. Although it is just speculation at this time, it is possible that the divergent performance needs of PC-9 and GF-3 could spell the end of the "universal" oil market in the U.S.

During the early planning for PC-9, the industry shareholders indicated a desire to maintain the long standing API protocol of "backward compatibility". That is, oils formulated to meet the newest, highest performance category can also be used to lubricate older engines which originally specified earlier API performance levels. There is some concern that the potential need for increased TBN and SASH to meet the performance tests in PC-9 may make the Caterpillar 1P test from CH-4 very difficult if not impossible. Acknowledging this concern, the NCET in its category needs statement indicated that backward compatibility is desirable, but it should not be used as an excuse to degrade PC-9 engine protection. The need to protect EGR-equipped engines outweighs the need for backward compatibility.

Initial engine data: Mack have been running T-10 test development studies in their Engine Test Laboratory in Hagerstown, MD. Some of this work has been done using the CH-4 category reference oil, TMC1005. Early testing with 12% EGR rate showed that all of the TBN reserve of TMC1005 was consumed in less than 100 hrs. Mack revised the EGR rate to just under 10%, a level which they feel may be reasonable for high-load NOx control, and TMC1005 was able to complete the 100 hr. oil conditioning phase with 3.5 TBN reserve. The used oil wear metals analysis showed 23 ppm of copper, 165 ppm of iron, and 16 ppm of lead. Contrasting these results to the T-9 test at 100 hours reveals that TMC 1005 still retains 6.3 TBN, and the used oil wear metals are 5 ppm of copper, 58 ppm of iron, and 4 ppm of lead. Clearly the EGR addition to the T-10 test attacks the TBN reserve of the oil and causes an increase in wear metals compared to the T-9. Obviously this comparison pits a single test development result against a well established data base, but the result does suggest that PC-9 performance will require a significant formulation change from CH-4.

Summary: Over the last eleven years on-highway diesel engines have been under increasingly tighter exhaust emissions controls by the U.S. Environmental Protection Agency. In order to meet these controls, the design of diesel engines has gone through a series of evolutionary developments. A number of these changes have been aimed at reducing particulate emissions, and in general they are designed to improve the combustion process and to more completely burn the fuel injected into the combustion chamber. Unfortunately, most of these changes to improve combustion also raise the peak flame temperature and cause an increase in the generation of NOx, another controlled pollutant. Conversely, other design changes have been designed to "mess up" the combustion process, drop the peak flame temperature, and reduce NOx emissions. Unfortunately these changes tend to aggravate the generation of particulate matter. Up to and including the 1999 emissions targets engine designers have been able to balance the trade-off between NOx and particulate

Table One
U.S. EPA Diesel Engine Emission Standards

Year	1998	1991	1994	1998	2002
Unburned HC	1.3	1.3	1.3	1.3	1.3
NOx	10.7	5.0	5.0	4.0	2.0*
Carbon Monoxide	15.5	15.5	15.5	15.5	15.5
Particulate Matter	0.6	0.25	0.1	0.1	0.1

All values are measured in grams per brake horsepower-hour

* Alternate target is a total of 2.5 for combined NOx and non-methane hydrocarbons

Limits apply to engines at "end of useful life"

FIGURE ONE:

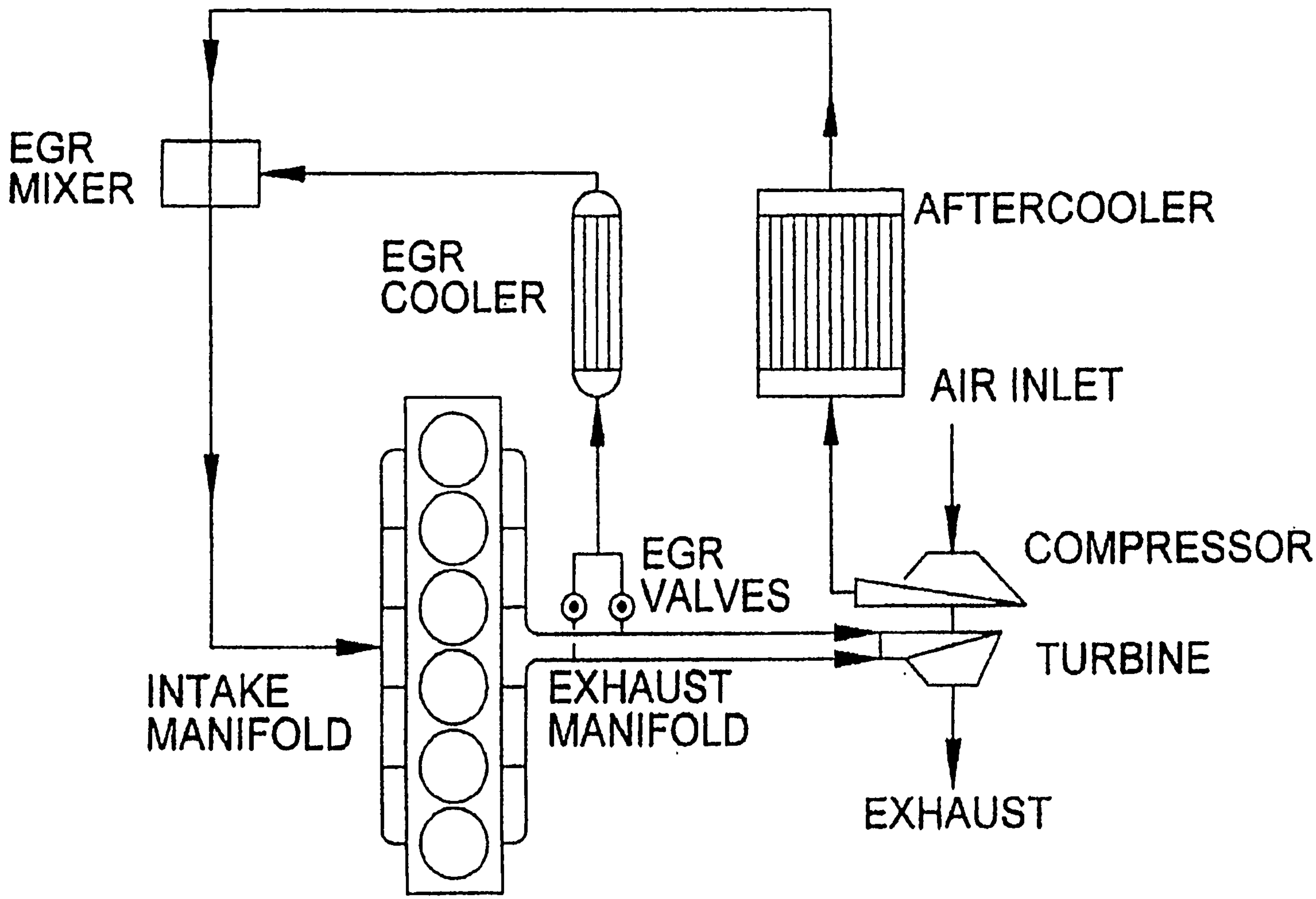
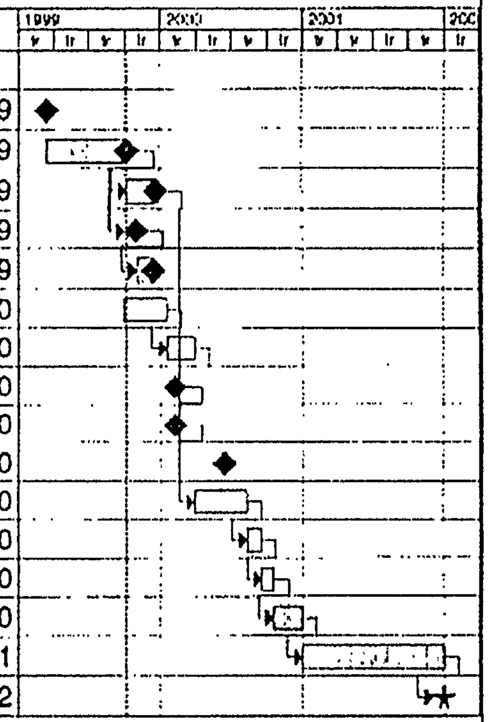

EGR
MIXER
EGR
COOLER
AFTERCOOLER
AIR INLET
COMPRESSOR
EGR
VALVES
TURBINE
INTAKE
MANIFOLD
EXHAUST
MANIFOLD
EXHAUST

FIGURE TWO:

Summary of Events Required for PC-9 Licensing

Brent Shoffner 9/21/99

ID	Task Name	Start	Finish
1			
2	Define PC-9 Performance Parameters	3/16/99	3/16/99
3	Design Prec. Mtx. Finalized	3/17/99	10/7/99
4	PC-9 Funding MOU Signed	10/8/99	12/20/99
5	Designate Base Stocks for Prec. Mtx.	11/1/99	11/1/99
6	Select additive suppliers for Prec. Mtx.	11/2/99	12/15/99
7	Identify Test Oils (with validation)	10/1/99	1/17/00
8	Blend Prec. Mtx. Oil Formulations	1/18/00	3/29/00
9	Final Acceptance of New Engine Tests *	2/9/00	2/9/00
10	Final Acceptance of Test Parameters	2/9/00	2/9/00
11	PC-9 Demonstration Oil is Validated	6/15/00	6/15/00
12	PC-9 Precision Matrix Testing	3/30/00	8/9/00
13	Precision Matrix Data Analysis	8/10/00	9/15/00
14	HDEOCP Post Matrix Test Acceptance	9/18/00	10/17/00
15	Finalize Pass/Fail Criteria (Sub B Mtg)	10/18/00	12/29/00
16	New Product Development	1/1/01	12/31/01
17	API Licensing Allowed	1/1/02	1/1/02



* Acceptance of each engine test (by HDEOCP) for discrimination and preliminary precision prior to starting the precision matrix. What is the criteria? Minimum of one test on 1005-1 and one on a prototype PC-9 oil?