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A Low Pressure Natural Gas Vehicle Storage System

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Abstract

A complete low pressure natural gas adsorbent storage system is described. This work was carried out by the Atlanta Gas Light Adsorbent Research Group, (AGLARG), and co-funded by the US Department of Energy.

The objective of the project was to install in a vehicle an adsorbent storage system capable of delivering 150 V/V from a fill pressure of 3.5 MPa (500 psi) at ambient temperature.

Three breakthroughs with this system are reported. First, a carbon adsorbent in a form capable of storing greater than 170 V/V was developed and produced. Secondly, a new design of flat tank to contain the adsorbent has been made. This has two principal advantages, it allows for more acceptable installation in the vehicle than cylindrical vessels and it greatly improves the adsorptive heat problem. Thirdly, a guard bed system has been used which prevents storage capacity loss due to non-methane components in the natural gas being irreversibly adsorbed on the carbon adsorbent.

This system has been installed in both a van and a light truck where pressure, temperature, flow and demand can be remotely measured in real time.

Introduction

Natural gas has become entrenched as an alternate vehicular fuel, particularly in countries where gasoline prices are high. Emission control legislation in other countries may also encourage further use of natural gas as a fuel. Currently Argentina leads with about 340,000 vehicles and there are about one million operating worldwide,(1).

As a fuel, natural gas ranks as one of the best, with its clean burning and low emission characteristics, but it suffers from a major drawback, it is difficult to store. Presently, it is predominantly stored as compressed natural gas, (CNG), at pressures about 20 MPa, (3000 psi) and even higher pressures have been suggested. Only, perhaps, a thousand vehicles are operated using liquefied natural gas, (LNG), this being limited mainly to heavy duty vehicles operating nearly continuously, twenty-four hours a day.

An alternative to these storage methods is an adsorbent storage system, usually referred to as adsorbed natural gas, (ANG). Here the natural gas is adsorbed by a porous material where the storage density of the adsorbed methane is greater than that of the gas phase at the same pressure. This provides an enhancement in the storage capacity.

To be a commercially viable system, it is generally considered that a delivered gas volume at STP, 150 times greater than the storage volume, 150 V/V, is necessary. This can be achieved relatively easily using existing carbon adsorbents by either cooling the adsorbent below ambient or by using fill pressures in excess of 7 MPa, (1000 psi). However, cooling cannot be considered practical and the use of pressures greater than 7 MPa creates similar problems to those of CNG.

Recognizing this, the US DoE co-funded a research program by a consortium of oil and gas utility companies and a carbon manufacturer, collectively known as AGLARG, (Atlanta Gas Light

Adsorbent Research Group). The target of this research program was to produce an ANG system capable of delivering 150 V/V from a fill pressure of 3.5 MPa, (500 psi), at 298K. This was considered to be a demanding but possibly achievable goal. However, this storage capacity was not the only objective of the program. The system as a package was to use advantageously the attractive properties of ANG while at the same time addressing some of the problems known to exist with ANG storage.

The Storage System

Gains in gas storage density by adsorption occur at pressures less than 10 MPa, (1500 psi), but if simplicity and ease of use is considered, then the pressure should be limited to that achievable by using only single stage compression, less than 5 MPa. This pressure is about gas trunk line pressure and so in some places recompression could be avoided. However, the de facto value, somewhat arbitrarily chosen, has been 3.5 to 4 MPa. Thus an adsorbent material, with properties which optimize storage capacity at this pressure, had to be developed. Secondly, design of a storage vessel for this material had to be undertaken.

This relatively low pressure does not mandate the use of cylindrical shaped vessels, and so other shapes for the storage vessel could be considered. With limited available space, an alternative to a large gas cylinder appears attractive.

Earlier work on ANG storage has shown that the storage capacity gradually reduces with repeated refueling. For a successful ANG storage system, this problem has to be overcome, and so the AGLARG group examined the use of a guard bed to protect the adsorbent from the undesirable higher hydrocarbons, minor components of natural gas, which are mainly responsible for this reduction.

The complete storage system therefore comprised of a new type of carbon adsorbent maximizing storage density, a new design of storage vessel taking advantage of the relatively low pressure and a guard bed to ensure no reduction in storage capacity on repeated refueling.

The Adsorbent

Presently, carbon adsorbents would appear to be the best for natural gas. What kind of carbon is required to achieve 150 V/V delivered ?

For delivery of 150 V/V, it will be necessary to store about 175 V/V since some methane remains adsorbed at less than 0.1 MPa, (1 Bar). This is equivalent to 117 grams gas per liter of storage volume.

Since adsorption only takes place in micropores, pores of less than 2 nm, the micropore volume of the adsorbent should be maximized.

Parallel slit pore models suggest that a maximum density of 170 g methane per liter of micropore occurs in pores of 0.78 nm width, (two methane molecules wide), at 298K and 3.5 MPa,(2).

To store 117 grams, 0.69 liters of ideal micropore, (0.78 nm width), will be needed.
Only 0.31 liters per liter of storage volume will remain for the skeletal carbon atoms.

Using a graphite density of 2.2 g/mL, 0.31 liters of carbon atoms will weigh 690 grams.

So, 690 g carbon with 690 mLs of ideal micropore per liter of storage volume will be necessary to achieve 150 V/V delivered. (Carbon density 0.69g/mL, 1.0 mL micropore per gram.)

The next questions then become, "How do we make a carbon with these properties ?" , and, "How do we know how close we have come to this ideal structure ?"

The direct measurement of storage capacity by packing a vessel with adsorbent and measuring methane delivery, is not always practical when creating adsorbent carbons. Often only a few grams of carbon are made. Characterization measurements on these materials can be carried out and methane isotherms measured using less than one gram quantities. However, no reliable method for obtaining a pore size distribution, (PSD), of these carbons is available. Using the methane isotherm at 298K, a new method was developed for the assessment of PSD,(3). This provides a "picture" of any prepared carbon, which enables us to see how close the prepared carbon is to the "ideal" structure. Any change in preparation conditions can be monitored against any change in the PSD. Figure 1 shows the 298K methane isotherms for two carbons prepared in the same way but at different temperatures and Figure 2 shows how this change in preparation conditions altered the PSD of the carbon adsorbents,(4). The carbon used in this present study had a pore volume of 1.30 ml/g, 37% of which was in the ideal pore size region.

<u>The Storage Vessel</u>

With adsorbent storage, large diameter cylindrical tanks are not necessary and indeed are undesirable. They are difficult to pack the carbon into, and are not efficient in removing heat from the carbon during filling, (adsorption), or supplying heat during fuel use, (desorption). In practice a 25 - 30 cm diameter densely packed, carbon filled vessel can take many hours to return to an equilibrium state after one fill-empty cycle.

Cylindrical tanks are also space intrusive, in that, nearly always, they are placed in areas which otherwise would be used for passengers or baggage. Also, the space occupied by these is, in reality, greater than their simple geometric volume.

The design of an ANG tank should therefore consider several factors.

It should

(a) take advantage of the lower pressure used in ANG
(b) minimize heat effects
(c) be easy to fill with adsorbent
(d) be space efficient and easier to locate into the vehicle
(e) be relatively light in weight
(f) be easy to manufacture
(g) must be safe and certifiable as a pressure vessel

Figure 3 shows the design chosen for this study. The twenty-two cell alŭminum single step extrusion with welded end caps incorporates all of the above criteria in its design. Its low flat profile offers a great deal of flexibility for incorporation into any vehicle, and it can be of any length without requiring any redesign or retooling. The profile and interior web aids greatly in the heat management during filling and emptying. It is relatively lightweight, although this is fully offset by the weight of the carbon adsorbent. These vessels were designed to meet the British Standard , BS5500 safety code using extensive finite element analysis. A program of pressure fill-empty cycle testing on sample tanks was carried out to establish fatigue life and safety factors. After 380,000 cycles from 0.5 to 4.5 MPa, a pinhole leak developed at a weld. A sample tank split close to a weld at 21.5 MPa, (3200 psi), during a burst test, giving a factor of safety of at least five . An adsorbent filled vessel will not immediately depressurize on rupture. Rather, there will be a relatively slow loss of pressure as the adsorbed methane desorbs over a few seconds. Further slowing the evolution of gas from the adsorbent is the considerable cooling associated with rapid desorption.

For test purposes, both on the vehicle and also on a stationary fill-empty cyclic test-bed, tanks were filled with granular carbon and with monolithic blocks. Presently extruded carbon pieces are being prepared and will be tested in the near future.

The Guard Bed

The problem of deterioration of storage capacity using adsorbents is largely due to the cumulative adsorption of the higher hydrocarbons, C5 and above, which are present in small amounts in natural gas. These are continually adsorbed by the highly microporous carbon adsorbent, but because of their higher adsorption potential, unlike methane, are not desorbed during fuel use. Thus they gradually fill micropores which otherwise would be available to methane. Other components in natural gas, such as nitrogen, carbon dioxide or the lighter hydrocarbons, C2 - C4, are desorbed as the pressure is reduced. Table 1 shows a typical natural gas composition and the potential for uptake of each of the components. Possible odorants are also included in this table. It is clear that the only odorant likely to be retained by the storage carbon would be diethyl sulfide. Other odorants would odorize the complete system but would be desorbed as the tank is emptied.

For rapid filling of a storage tank, the gas flow rate through an adsorbent guard bed is very high, making the capture of small amounts of C5+ hydrocarbons difficult. Thus a narrow micropore carbon structure somewhat similar to the storage carbon structure is favored. However, since facile desorption of C5+ hydrocarbons from the guard bed carbon is required to prevent retention, a carbon with a more open pore structure is desirable. Evaporative loss control devices, (ELCD's), used for the control of gasoline emissions, use an upper micro, lower mesopore type of carbon. This type of carbon appears to be suitable for use in the guard bed.

Presently, a three liter cylindrical shaped guard bed packed with granular carbon is being tested. The guard bed is placed in line just in front of the main storage tank. On filling the storage tank, gas must pass through the guard bed, where the C5+ hydrocarbons are adsorbed, before entering the main storage tank. The guard bed has built in electric heaters. During fuel use, (desorption), these heaters are switched on and gas from the storage vessel again passes through the guard bed. The C5+ hydrocarbons are desorbed from the heated granular carbon in the guard bed and swept along in the gas stream for consumption in the engine.

Results and Conclusions

Small scale experiments, with vessels of less than one liter, gave deliveries in excess of 150 V/V using packed granular carbon. However, difficulty was encountered in packing the granular carbon into the full size tank to a sufficiently high density to obtain a delivery of 150 V/V.

This same carbon was then briquetted as shaped monoliths to fit the cell dimensions, avoiding wasted void space. In its briquetted form, the carbon had a higher density than the packed granular material, and in this form has been consistently delivering in the low 140 V/V on both the stationary test bed and on the vehicles. The tests, to date, indicate that the guard bed is doing its job and that no deterioration in storage capacity has been observed.

The tank design has given flexibility for fitting within the frame of a Dodge "B" van. In the past few weeks, four tanks have been fitted to a Dodge Dakota truck bed, a protective false bed has been placed on top of the tanks raising the bed by about five inches.

The goal of delivering 150 V/V has not been met to date using a flat tank, but 94% of this goal has been achieved. It is felt that over the next few months, briquettes of higher density will be produced so that this 150 V/V delivered target can be met. Extrusion forming, which is just underway, could also help in reaching this goal.

It is important to bear in mind that this study was undertaken as a "proof of concept". The tank design is sound but will no doubt be further refined. The guard bed is effective. The carbon used for this study is only a development carbon. It is not yet available for commercial application and a further objective is to be able to commercially produce a carbon with these properties at a competative price.

Acknowledgment

AGLARG wishes to thank the US Department of Energy for co-funding this study. DFQ thanks AGLARG for their continued support for carbon research.

References

1. J.M. Seisler, European Natural Gas Vehicle Association, (ENGVA), 1996
2. K.R. Matranga, A.L. Myers and E.D. Glandt, Chem. Eng. Science, 47 1569 (1992)
3. K. Sosin and D.F. Quinn, J. Porous Materials 1 111 (1995)
4. T.L. Cook, C. Komodromos, D.F. Quinn and S. Ragan, Chap XIII "Adsorbent Storage for Natural Gas Vehicles" in Carbon Materials for Advanced Technologies, editor T. Burchill, publisher, Elsevier, in press.

Figure 1

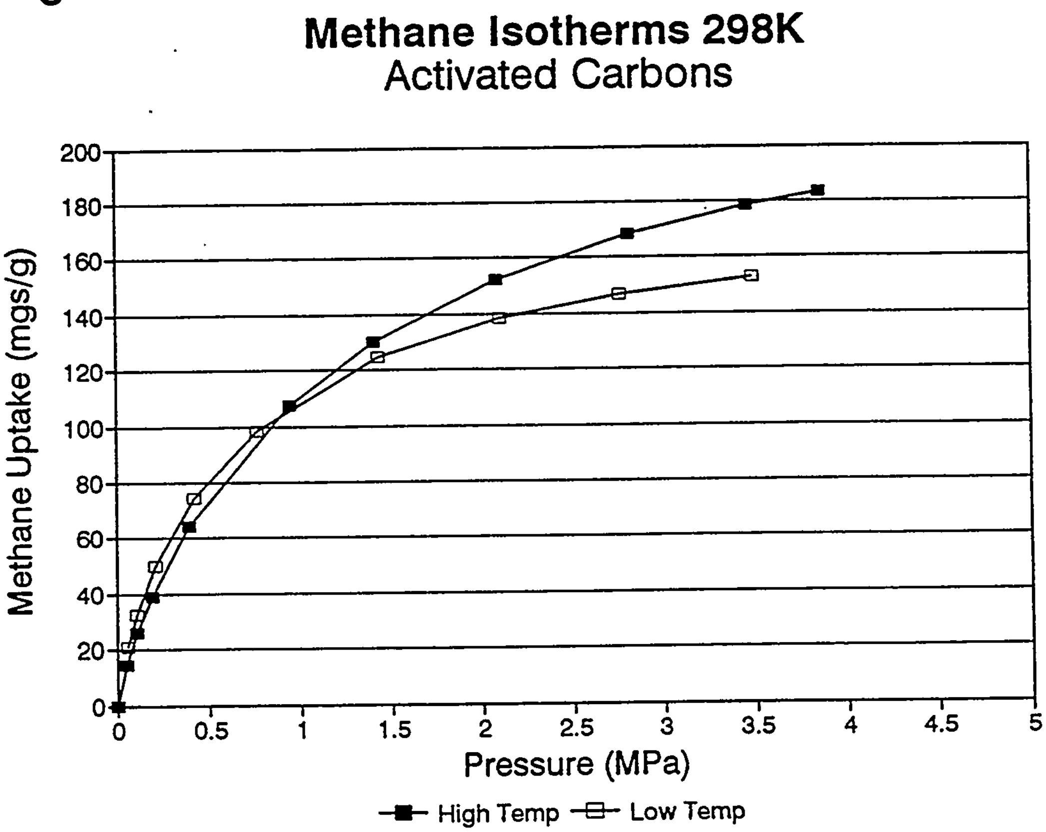
Methane Isotherms 298K
Activated Carbons
Methane Uptake (mgs/g)
200
180
160
140
120
100
80
60
40
20
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Pressure (MPa)
High Temp
Low Temp

Figure 2

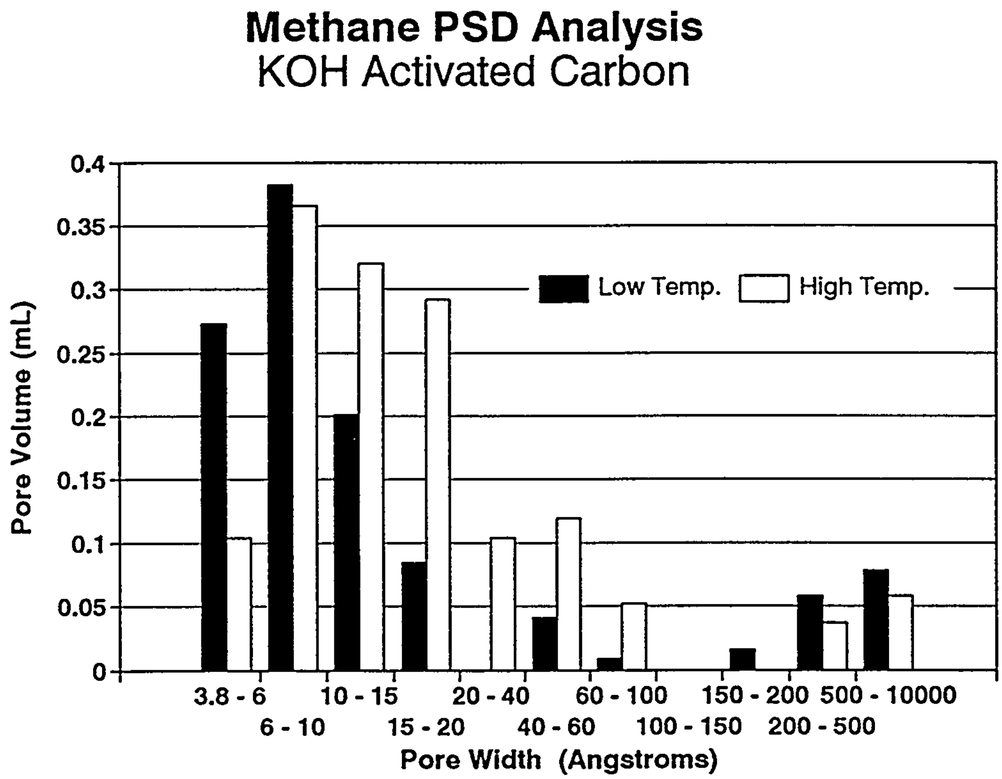
Methane PSD Analysis
KOH Activated Carbon
Low Temp.
High Temp.
Pore Volume (mL)
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
3.8 - 6
6 - 10
10 - 15
15 - 20
20 - 40
40 - 60
60 - 100
100 - 150
150 - 200
200 - 500
500 - 10000
Pore Width (Angstroms)

Figure 3

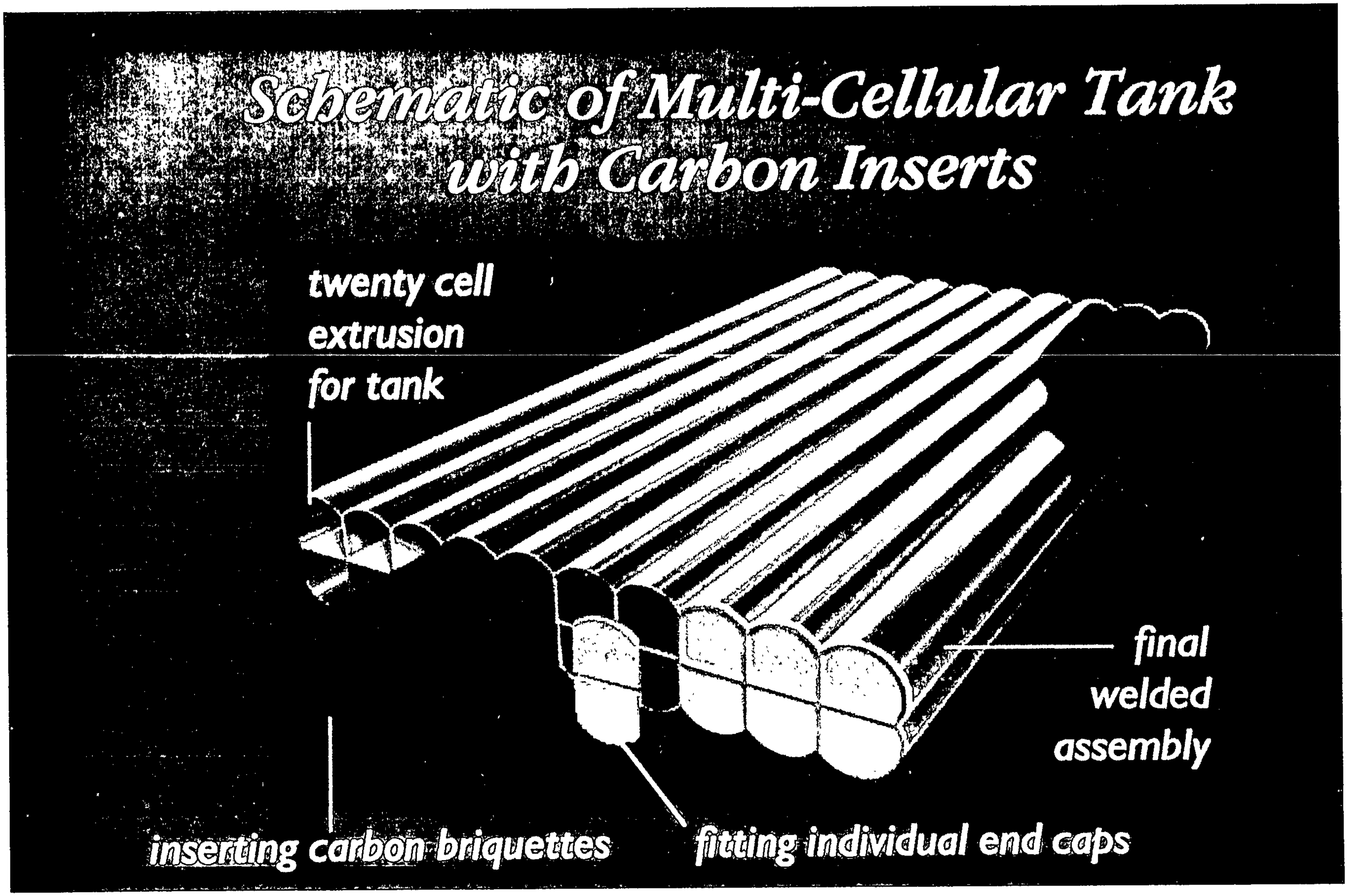
Schematic of Multi-Cellular Tank
with Carbon Inserts
twenty cell
extrusion
for tank
final
welded
assembly
inserting carbon briquettes
fitting individual end caps

TABLE 1
Typical Composition of Natural Gas (Bacton Terminal)

Component	Concentration vol.%	Relative Pressure	Potential Uptake g/g
Carbon dioxide	0.25		
Nitrogen	3.17		
Hydrocarbons			
Methane	92.81		
Ethane	2.84	7.320E-04	
Propane	0.58	2.350E-04	0.019
Butane	0.20	9.480E-04	0.068
Pentane	0.067	1.370E-03	0.127
Hexane	0.032	2.240E-03	0.176
Heptane	0.017	3.970E-03	0.232
Octane	0.007	4.800E-03	0.259
Nonane	0.001	2.220E-03	0.262
Benzene	0.022	2.960E-03	0.127
Odorants			
Diethyl sulfide	7.00E-04	1.160E-04	0.143
Methyl ethyl sulfide	6.00E-05	4.260E-06	0.029
Ethyl mercaptan	6.00E-05	1.180E-06	8.600E-04
Tert. butyl mercaptan	1.20E-04	8.500E-06	0.079

DETROIT DIESEL SERIES 50 PROPANE DEMONSTRATION PROJECT

James A.Gray

Detroit Diesel Corporation

(Presentation unavailable at time of publication)

SESSION 4

PROPANE

Chair: **Bob Larsen, Argonne National Laboratory**

PROPANE (LPG) VEHICLE TECHNOLOGY - PRESENT & FUTURE

Shawn Yates
Propane (LPG) Program Coordinator
Chrysler Canada Ltd.

1996 Windsor Workshop on Alternative Fuels
Toronto Colony Hotel
Toronto, Ontario
June 4, 1996

SLIDE 1: INTRODUCTION LABEL

Good morning. My name is Shawn Yates and I work in the Product Development & Engineering Group at Chrysler Canada. I would like to thank the organizers of this propane session for allowing me to be here with you. This presentation is a brief overview of two main areas of propane or LPG vehicle technology; fuel metering and fuel storage; from both a traditional and future technology perspective.

SLIDE 2: PROPANE CHARACTERISTICS

Propane, as a member of the hydrocarbon family, can exist as either a liquid or a vapour, depending on the pressure or temperature surrounding it. Propane is usually stored and transported as a liquid under pressure. Under atmospheric pressure conditions, propane vaporizes becoming a gas at -44°F.

SLIDE 3: GASEOUS FUEL METERING #1

Almost all presently available propane fuel systems meter fuel in the gaseous state. The majority of these systems operate at low fuel delivery pressures but the emergence of higher pressure gaseous metering systems has begun. Shown in this slide is a traditional gaseous metering system. Whether it is low pressure or high pressure metering, liquid propane is first delivered from a fuel tank by natural flow to a fuel shut off device. The liquid propane then flows through a regulator or vaporizer, to reduce the fuel pressure and vaporize the propane by allowing the propane to absorb heat from its surrounding area. If there is not enough heat available to satisfy the vaporization requirements, some propane will not change state and could enter the metering system as a liquid and cause engine flooding. In a more traditional gaseous fuel metering approach, propane is then delivered to the engine in a gaseous state at low pressure, through venturi or air valve mixers mounted above the throttle blades. In the venturi system, properly sized metering jets and openings at the throat area of the venturi nozzle are used to control the flow of fuel in response to the differential pressure signal created in proportion to the air flow. The air valve system uses a fuel metering valve that opens in proportion to the intake air flow. For a given air flow, the air-fuel ratio is primarily controlled by the contour of the metering valve. Systems like this are normally designed to operate at very low fuel delivery pressures which considerably extends their low temperature capability compared to other systems. These low pressure systems have also been in existence for many years, but without the use of electronic control systems to improve the accuracy of fuel metering characteristics, fuel economy and performance can be sacrificed.

SLIDE 4: GASEOUS FUEL METERING #2

Design activity aimed at producing higher pressure gaseous propane fuel systems have begun. The benefits of high pressure metering are largely based on the improved control possible with a high speed solenoid valve or fuel injector and the associated control electronics. Fuel injector response would have to be fast enough to give predictable flow characteristics down to millisecond pulsewidths and opening and closing rates, in order to ensure adequate performance at high engine speeds. Also, the required increase in operating pressure to the injectors, may seriously affect the low temperature (below 32°F) operating capability of the system. This would not be as much of a problem in the southern United States as it would in Canada. Other factors such as injector lack of lubricity, durability and noise characteristics would have to be assessed to ensure the fuel system performance would be unaffected.

SLIDE 5: LIQUID FUEL METERING #1

The primary incentive for attempting to produce a liquid propane fuel metering system, is associated with the power benefit derived from the cooling effect of vaporizing liquid fuel in the intake air stream. Another incentive is the potential enhancement of cold start ability of propane vehicles at temperatures approaching -20°F. The higher charge density and the resulting power increase creates the potential to operate a standard gasoline engine, without a loss in power. Electronic control and a pressure sensor are essential to provide optimum mixtures to the engine with liquid fuel metering. Single-Point Metering or Throttle Body Metering usually meter fuel with an intermittent opening and closing of a calibrated orifice above the throttle blades. Operation of the control system would be quite similar to that of present gasoline electronic control systems which are usually engine mapped based systems, with manifold vacuum and engine speed as the primary factors used to determine the fuel requirements. Feedback control would be essential to provide the required mixture consistency and accuracy to compensate for component variations or wear.

SLIDE 6: LIQUID FUEL METERING #2

Multi-Point liquid fuel metering systems offer the same advantages as single-point fuel metering and feature a few unique advantages of their own. Improved cylinder-to-cylinder fuel distribution is possible with multi-point systems. Engine packaging requirements, closely resembling gasoline fuel metering systems, are also an advantage of multi-point liquid fuel metering systems.

The most obvious problem associated with liquid propane metering is the fuel's tendency to change state as a result of an increase in the local temperature anywhere in the fuel lines, or at the fuel injectors. The only way to avoid this problem is to ensure that the fuel is metered as saturated liquid by using a pump to boost the delivery pressure beyond the fuel's accompanying boiling point. This system would basically require a fuel pump in place of a vaporizer in the gaseous fuel metering systems.

SLIDE 7: TRADITIONAL PROPANE FUEL STORAGE

All current motor fuel tanks are designed and manufactured to standards set by the ASME code and usually involve cylindrical steel construction or a combination of cylindrical steel construction. The fuel tank on a propane vehicle has a system of valves and safety features to fill the tank, remove fuel from the tank for delivery to the engine, measure how much fuel is in the tank, and relieve the tank should the pressure increase excessively. The problem with the traditional fuel storage is to optimize capacity using cylindrical shapes in a rectangular envelope that is usually allocated for gasoline fuel storage.

SLIDE 8: GASOLINE FUEL STORAGE

Gasoline fuel storage systems of today usually utilize light weight "blow molded" plastic technology to optimize fuel capacity within a given envelope. The fuel tank attaching methods used on gasoline fuel tanks are very "simple"; straps are usually used to hold the tanks in place. As well, gasoline fuel storage systems must meet the corrosion, environmental resistance and safety standards as specified by federal regulations. Corrosion and environmental resistance, durability, and weight, become main issues with traditional propane fuel tanks, especially when they are mounted external to the vehicles structure.

SLIDE 9: CONFORMABLE PROPANE FUEL STORAGE

Design activity aimed at the development of "conformable" propane fuel storage systems has begun. As discussed earlier, weight reductions, improved materials selection, capacity increases and corrosion and environmental resistance benefits are potentially available with conformable designs. Plastic or composite propane fuel storage systems, that further resemble gasoline fuel storage systems, are still a few years away.

SLIDE 10: PROPANE VEHICLE CHALLENGE

As you have just heard, advanced propane vehicle technologies have emerged this past week, as thirteen colleges and universities from across North America competed in the 1996 Propane Vehicle Challenge.

SLIDE 11: PROPANE VEHICLE CHALLENGE #2

Gasoline powered 1996 NS Chrysler Minivans were modified, totally at the discretion of the school, to operate on dedicated propane fuel systems. Almost all of the technology I have discussed was displayed at the Challenge, even with the time constraints imposed on the schools. Gaseous carburetion and high pressure metering was used by many schools. Liquid fuel injection technology was also displayed at the competition, but there are still many areas of improvement available for next year.

SLIDE 12: PROPANE VEHICLE CHALLENGE #3

Maybe next year we will see more advanced fuel storage systems, but I am sure we will experience closer resembling gasoline equivalent vehicles. Students, your experiences and efforts have been so valuable in preparing you for "real world" problem assessments.

SLIDE 13: CONCLUSION

Whenever new technology is discussed it should be kept in perspective. The cost of a propane fuel system is a big factor to fleet customers analyzing their potential payback. Emission performance is also a big factor to fleets, as they are becoming more regulated. Gasoline vehicle technology is improving every model year and propane vehicles have a lot of catching up to do. The competition to propane is not other alternative fuels like CNG, but it is gasoline. Without the advancement of propane vehicle technology, the industry will lag behind gasoline and any "perceived advantages" of propane over gasoline will simply not be true.

I think this years' Propane Vehicle Challenge has gone a long way to advance propane vehicle technology and keep the propane minivans rolling down in Texas next year.

Thanks for your attention, good luck to the schools and participants in this years' Challenge and thanks again for the opportunity of being here today.

Injected Heavy Duty Propane Engine

1996 Windsor Workshop on Alternative Fuels

G. Campbell Perry, Bibi Ursu — BC Research Inc.
Tony Filetti — Mogas Sales Inc.
Doug Yip — Digicon Engineering

BCRI

Introduction

- Project Objectives
- Project Team
- Technical Approach

Project Objectives

- To Develop and Demonstrate Low Emissions Truck Engine
- Use a Spark Ignition Cummins C8.3 Engine
- Phase 1: Engine Development
- Phase 2: Vehicle Demonstration

BCRI

Project Team

- BCRI
- Mogas
- Digicon Engineering
- Cummins Engine Company
- ICG Propane
- Inland Kenworth/Paccar

Technical Approach

- Spark Ignition Version of C8.3 Engine
- Lean Mixture Operation
- Liquid Propane Injection

BCRI

Engine Description

- Cummins C8.3
- 6 Cylinder In-Line
- Turbocharged-Aftercooled
- 8.3 L Displacement
- Diesel Power Ratings
  157-224 kW (210-300 HP)

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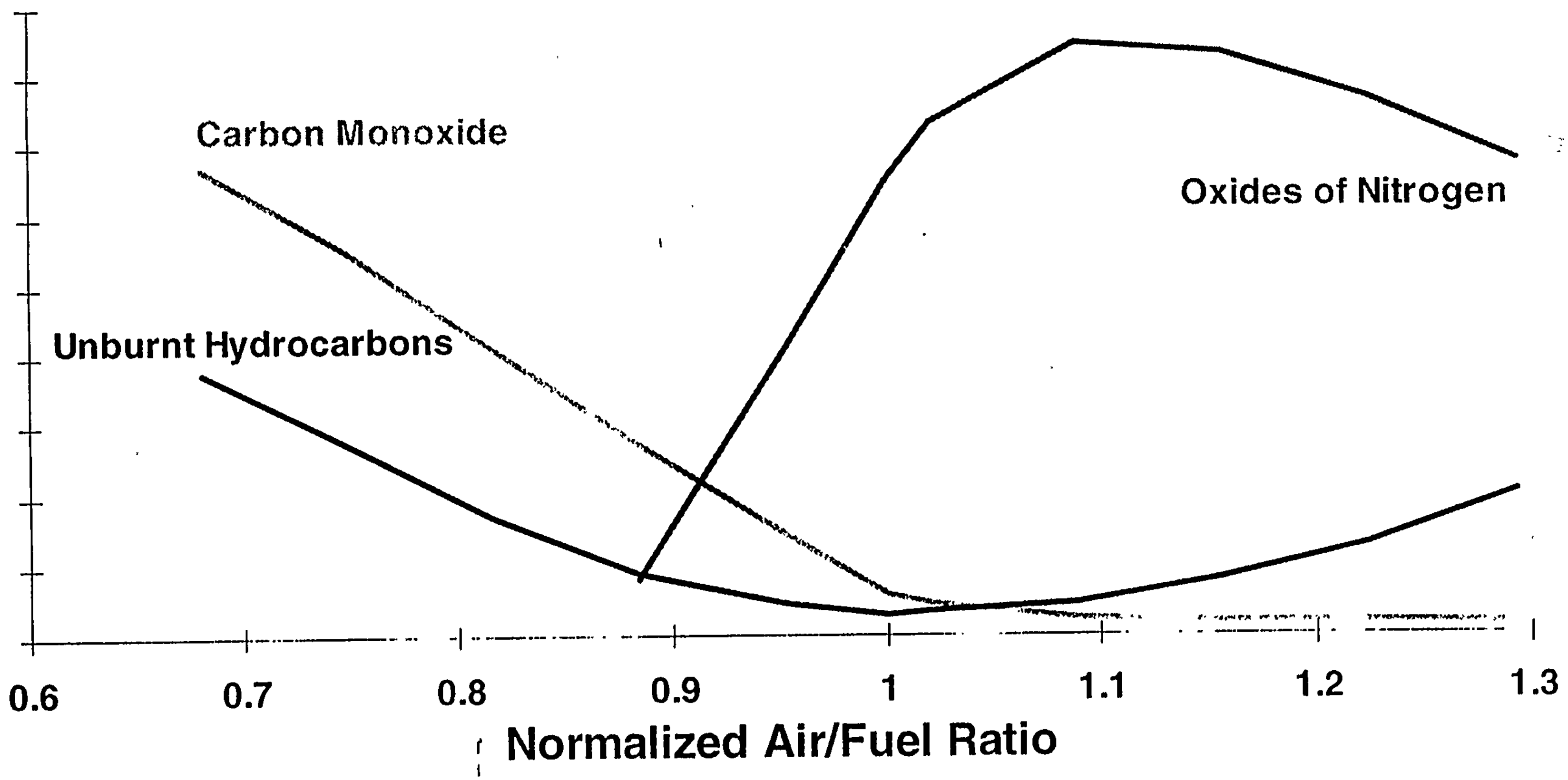
Lean Mixture Operation

- **Reduction of NOx Emissions**
- **Simplified Emissions Control**
- **Reduced Thermal Stress on Engine**

Lean Mixture Operation

- Reduction of NOx Emissions
- Simplified Emissions Control
- Reduced Thermal Stress on Engine

Emissions vs Normalized Air/Fuel Ratio



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Liquid Propane Injection

- Consistent Fuel Properties
- Reduced Cold Start Difficulties
- Additional Charge Cooling
- Good Mixing

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Engine Modifications

- Spark Ignition Head
- Pistons with Special Combustion Chamber
- Throttle Body
- Turbocharger
- Ignition System

Conversion System

- Microprocessor Controlled
- Feedback with Lambda Sensor
- Electronic Injectors Designed for Liquid Propane
- Single Point Injection

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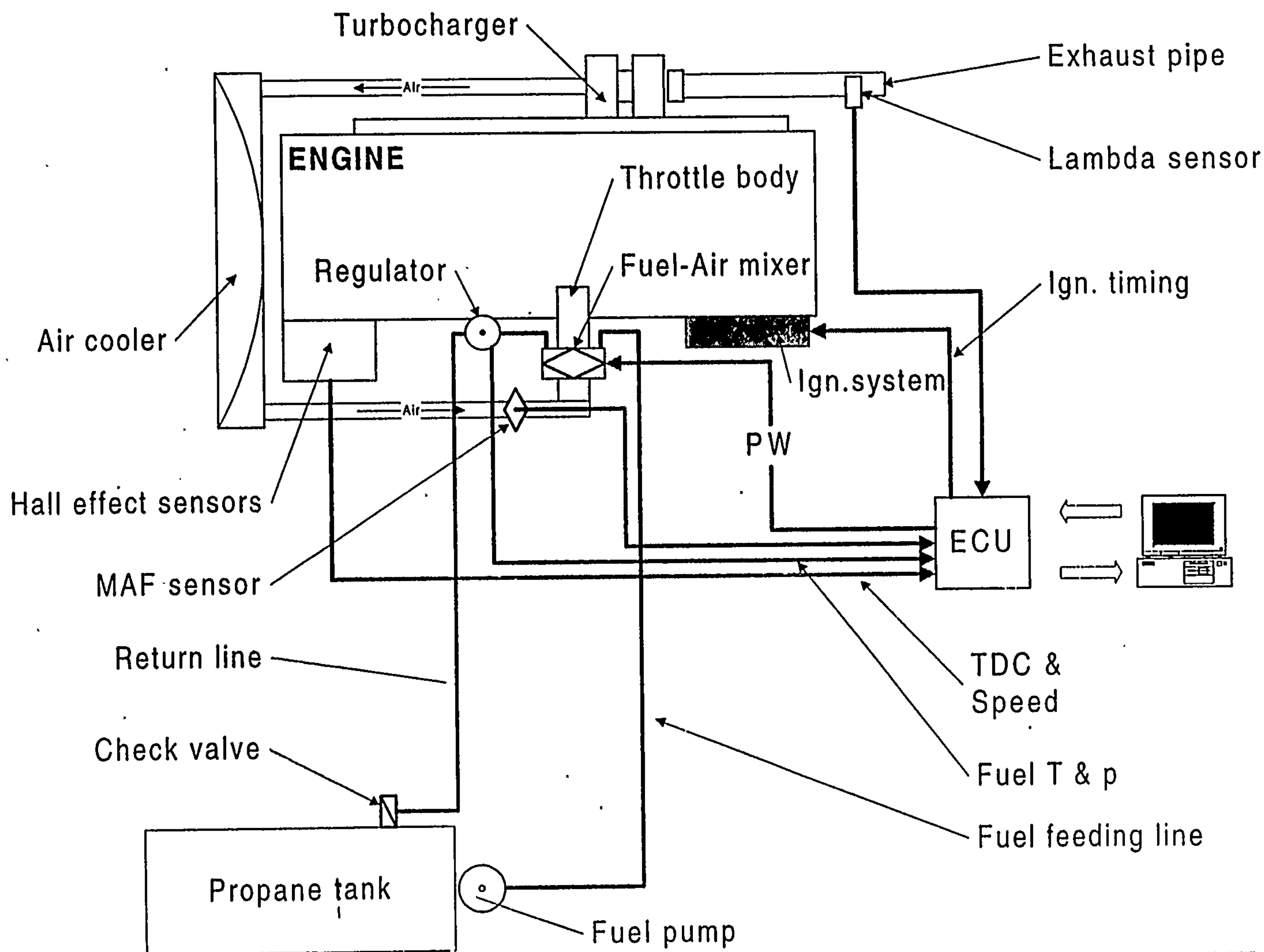
Fuel System Schematic



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Fuel System

- **Liquid Propane**
- **Siemens Injectors**
- **Electric Pump**
- **Single Point Injection**

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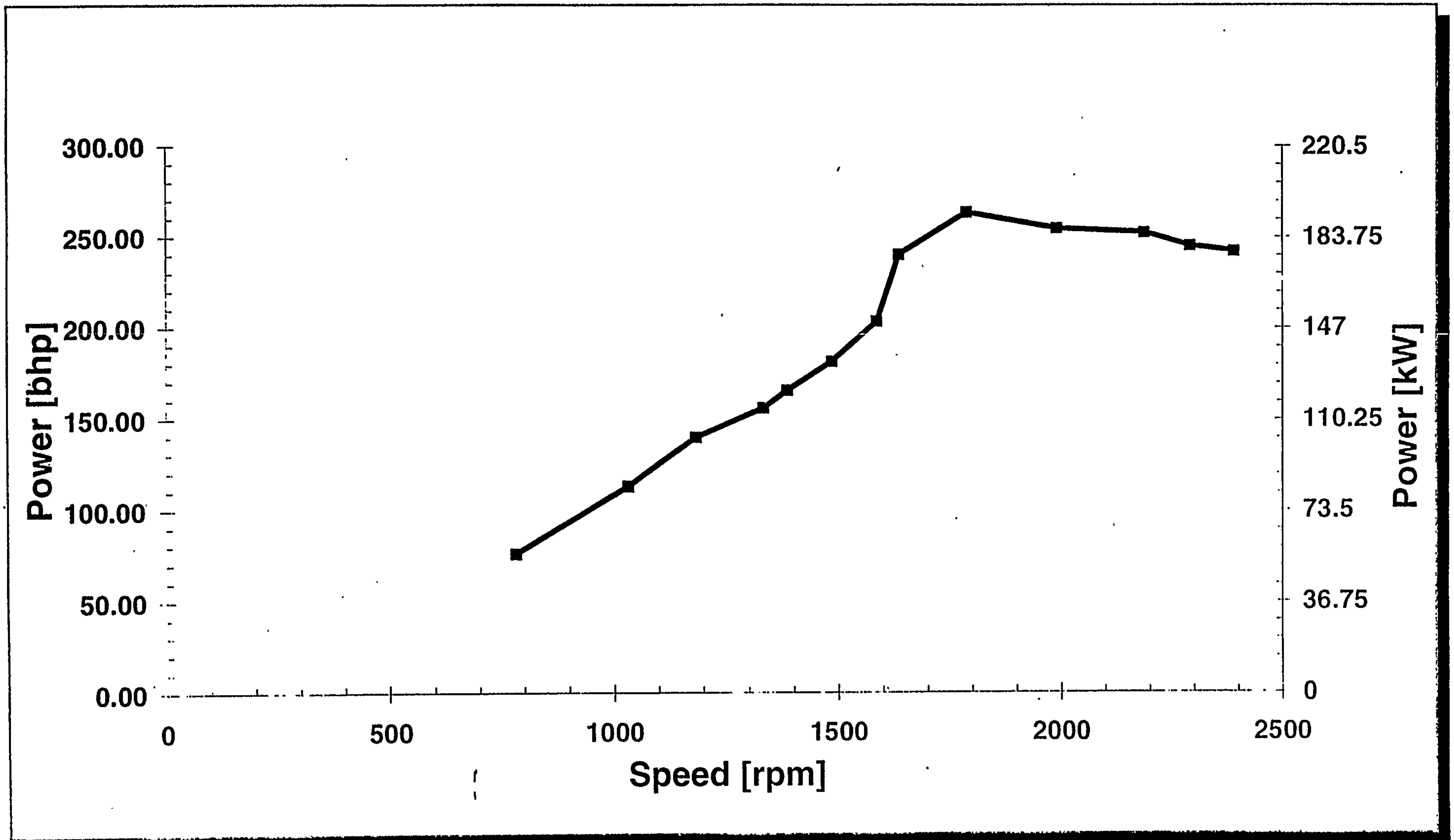
Ignition System

- Timing and Dwell Controlled by ECU
- Hall Effect Triggering
- Single Spark

BCRI

Power vs Speed



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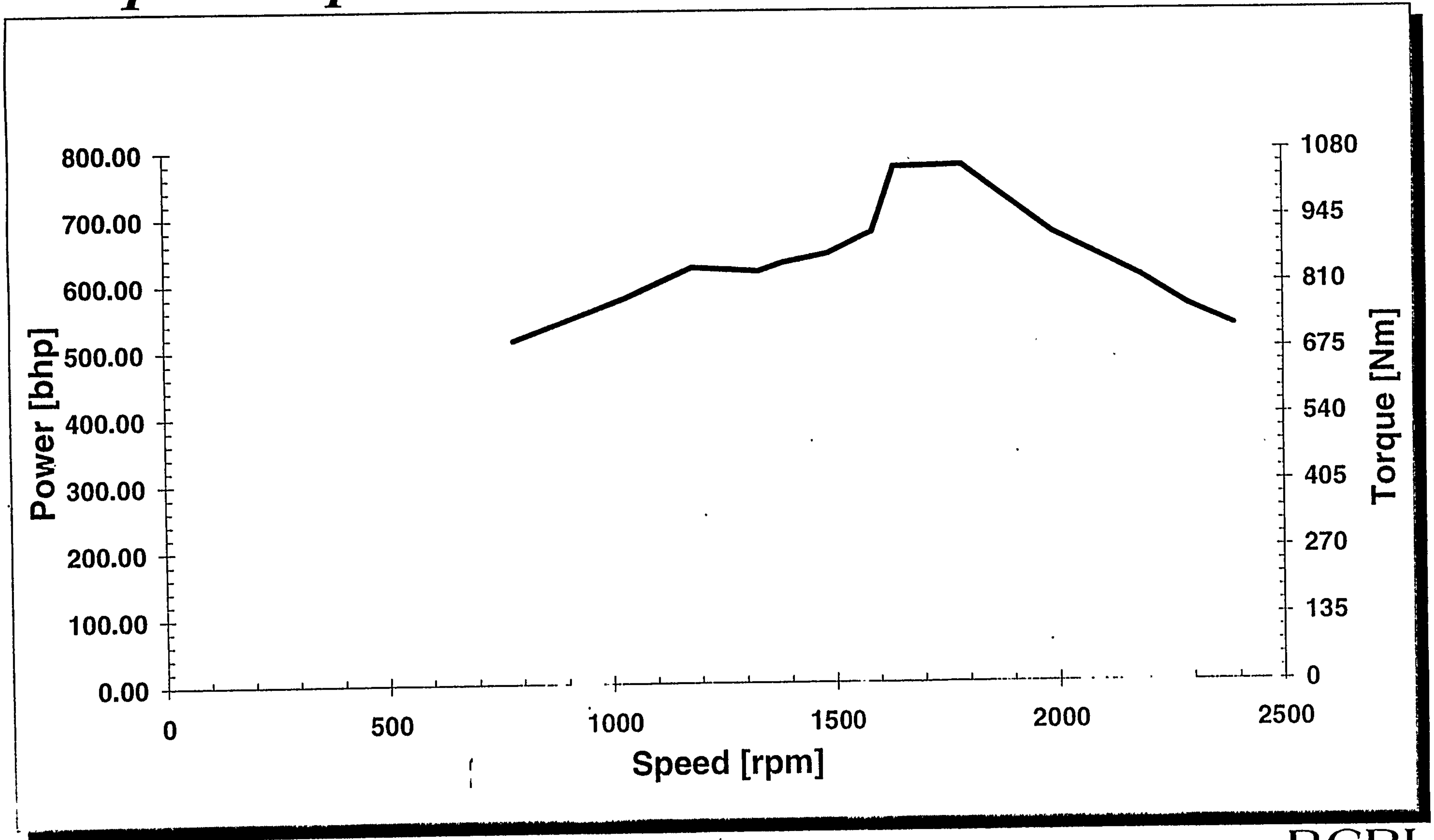
Torque vs Speed



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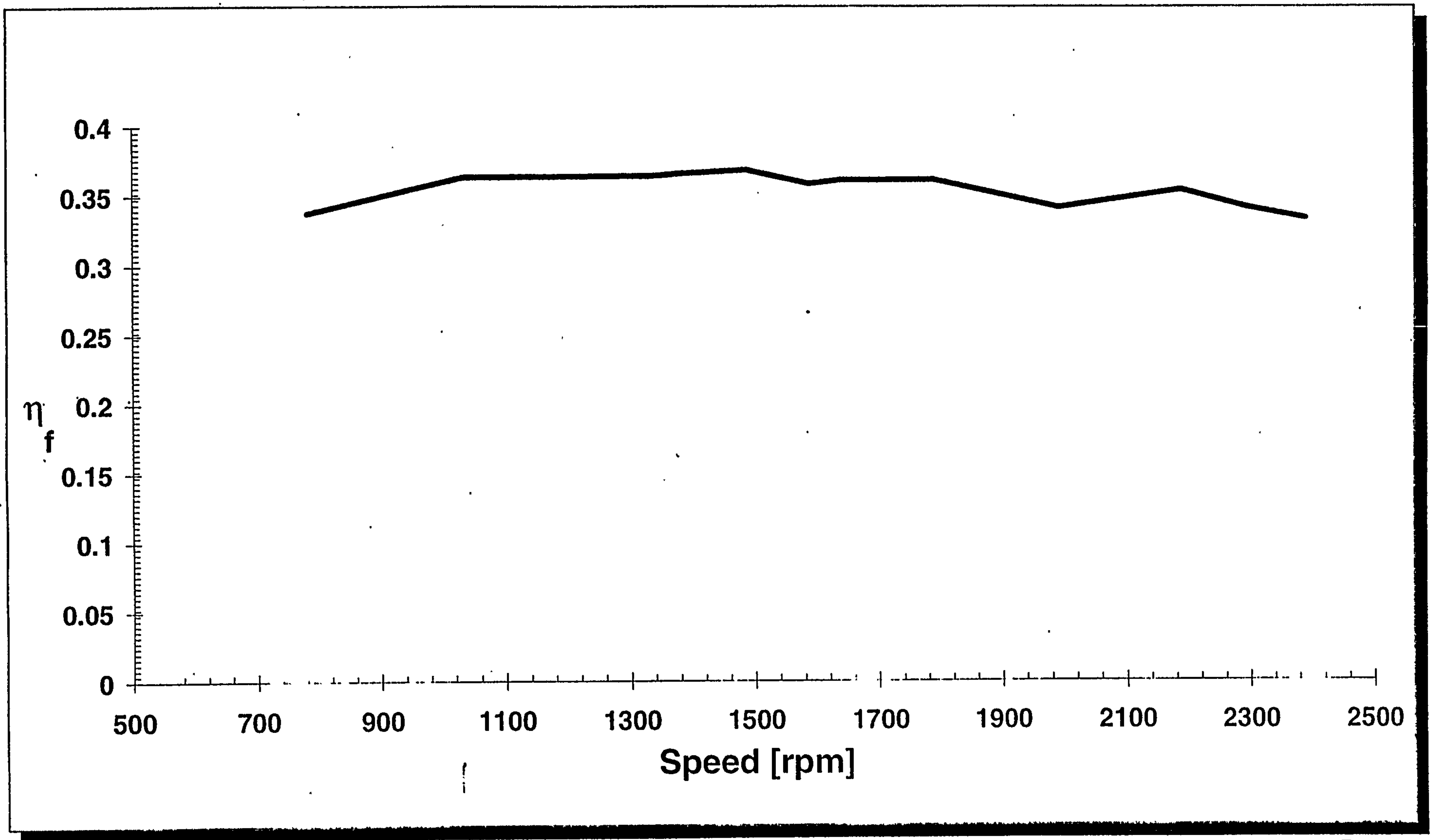
Thermal Efficiency vs Speed



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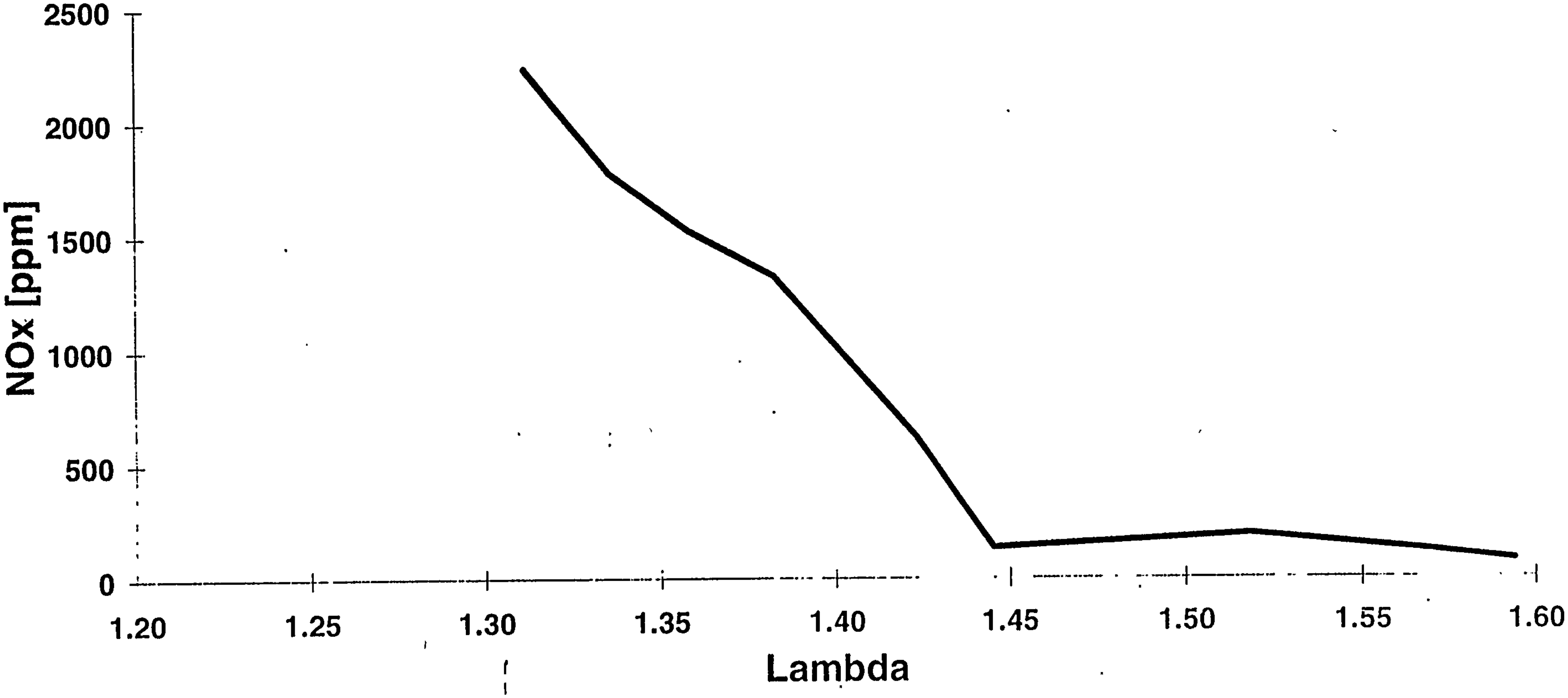
NOx vs Lambda

1600 RPM Max Load



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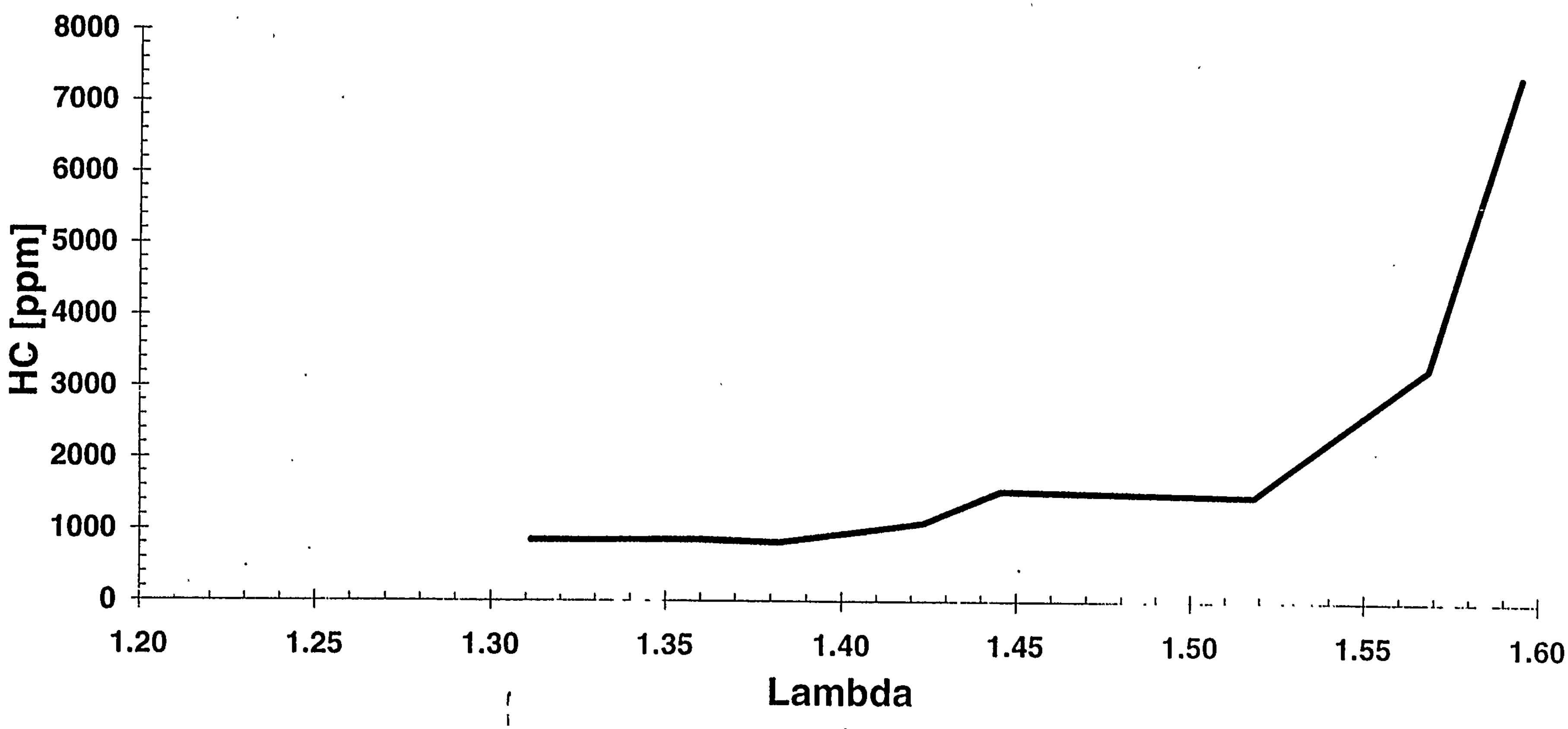
HC vs Lambda

1600 RPM Max Load



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Conclusions

- Liquid Propane System Promising
- Emissions on Target
- Feedback Control Essential for Low Emissions

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Funding

- Natural Resources Canada (CANMET)
- Science Council of British Columbia

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SESSION 5

ENGINE DEVELOPMENTS

Chair: **Wendel Goetz, ORTECH Corporation**

Design & Development of a Novel Fuel Injection System for Dimethyl Ether

Natural Gas Engine, Vehicle & Fuel Technology TOPTEC,
May 6, 1996

AVL
Powertrain Engineering

Scope

- Background
- DME Properties & Characteristics
- Engine Test Results Summary
- Common Rail Injection System Concept
- Computer Modeling/Simulation Results
- Bench Test Methodology/Initial Results
- Summary

AVL Powertrain Engineering

Background

- Ultra-Low HD Emissions Needed
- Diesel Technology Stalled Above ULEV
- Alcohols/Natural Gas Fuels- Problems!
- Dimethyl Ether (DME) Evaluated:
  - Ultra-Low Emissions Capability Established
  - Fuel System Requirements & Design Identified
- NREL/DOE Sponsoring DME Fuel System Development & Emissions Demonstration Program

AVL Powertrain Engineering

Alcohols/Natural Gas Fuels

...Problems...

- Alcohols
  - Low Cetane-Ign. Aids Required
  - Corrosive/Toxic (Methanol)
- Natural Gas
  - Thermal Efficiency Low (Otto Cycle)
  - Fuel Storage Complex/Expensive

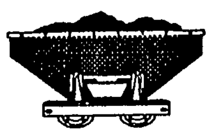
Neither Fuel Suitable for Compression-Ignition

AVL Powertrain Engineering

DME Characteristics

- Evironmentally Benign, Non-Toxic
- Liquid at 5 Bar...Like LPG
- Moderate Energy Density
- ~60 Cetane, Sootless, Visible Flame
- Abundant and/or Renewable Feedstocks
  - Natural Gas

  - Coal



  - Biomass

Powertrain Engineering

Relative Merits

...Alternative Diesel Fuels...

Characteristic	DME	Natural Gas	Methanol
Cetane	Excellent	Poor	Poor
NOx Emissions	Excellent	Excellent	Excellent
HCHO Emissions	Excellent	Excellent	Poor
Noncorrosive	Excellent	Excellent	Poor
Fuel Quality Sensitive	Excellent	Poor	Good
Retrofittable	Excellent	Poor	Poor
Fuel Efficiency & Range	Excellent	Poor	Good
Fuel Availability	Poor	Good	Poor
Engine & Vehicle Costs	Excellent	Poor	Poor

AVL Powertrain Engineering

Engine Test Results

- Naviatar 7.3L DI V-8 (HEUI Injectors)
- AVL 1 Cyl. Research Engine (2.0L, 4 Valve DI)

AVL Powertrain Engineering

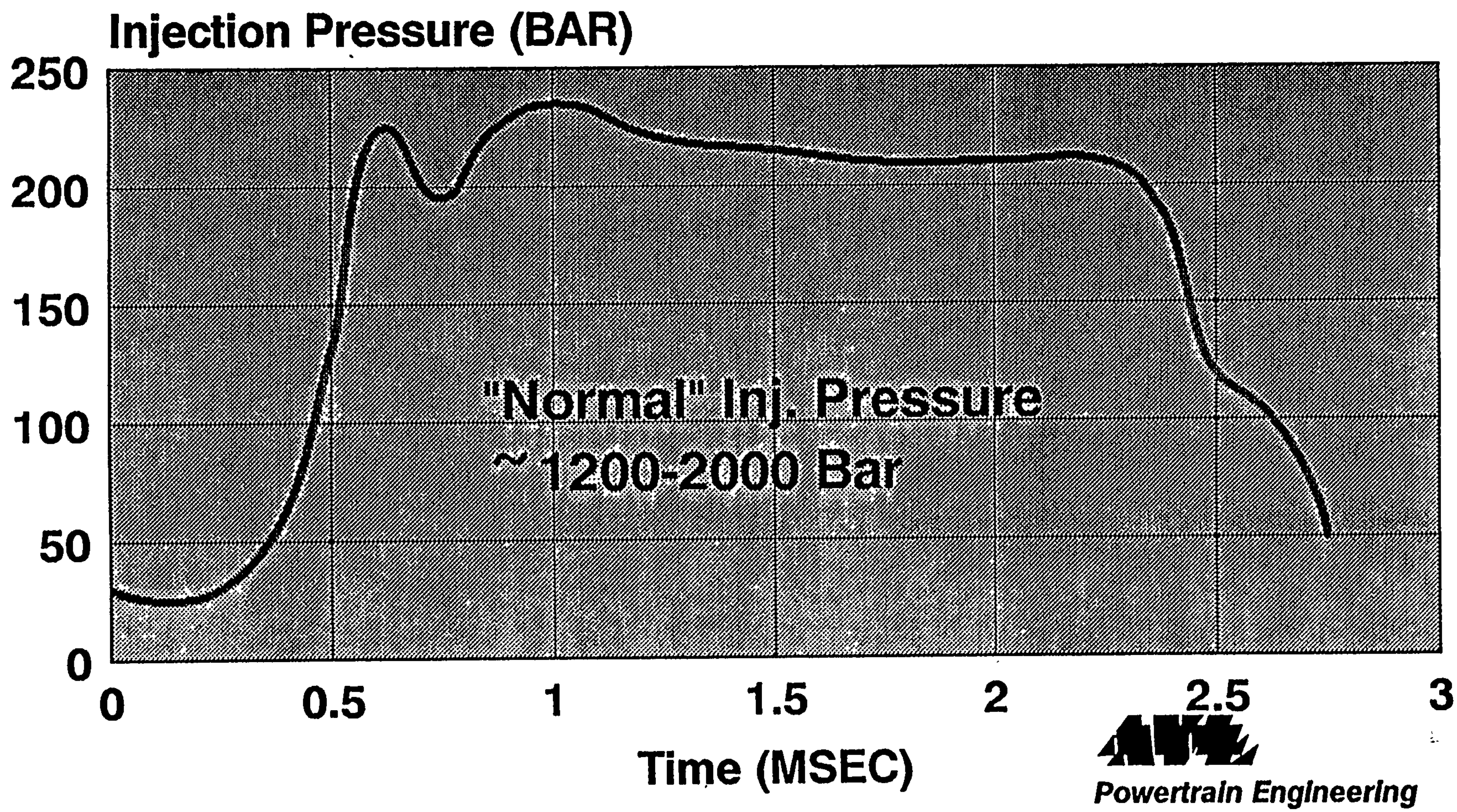
Navistar 7.3L V-8 DI Truck Engine

...Test Program Summary...

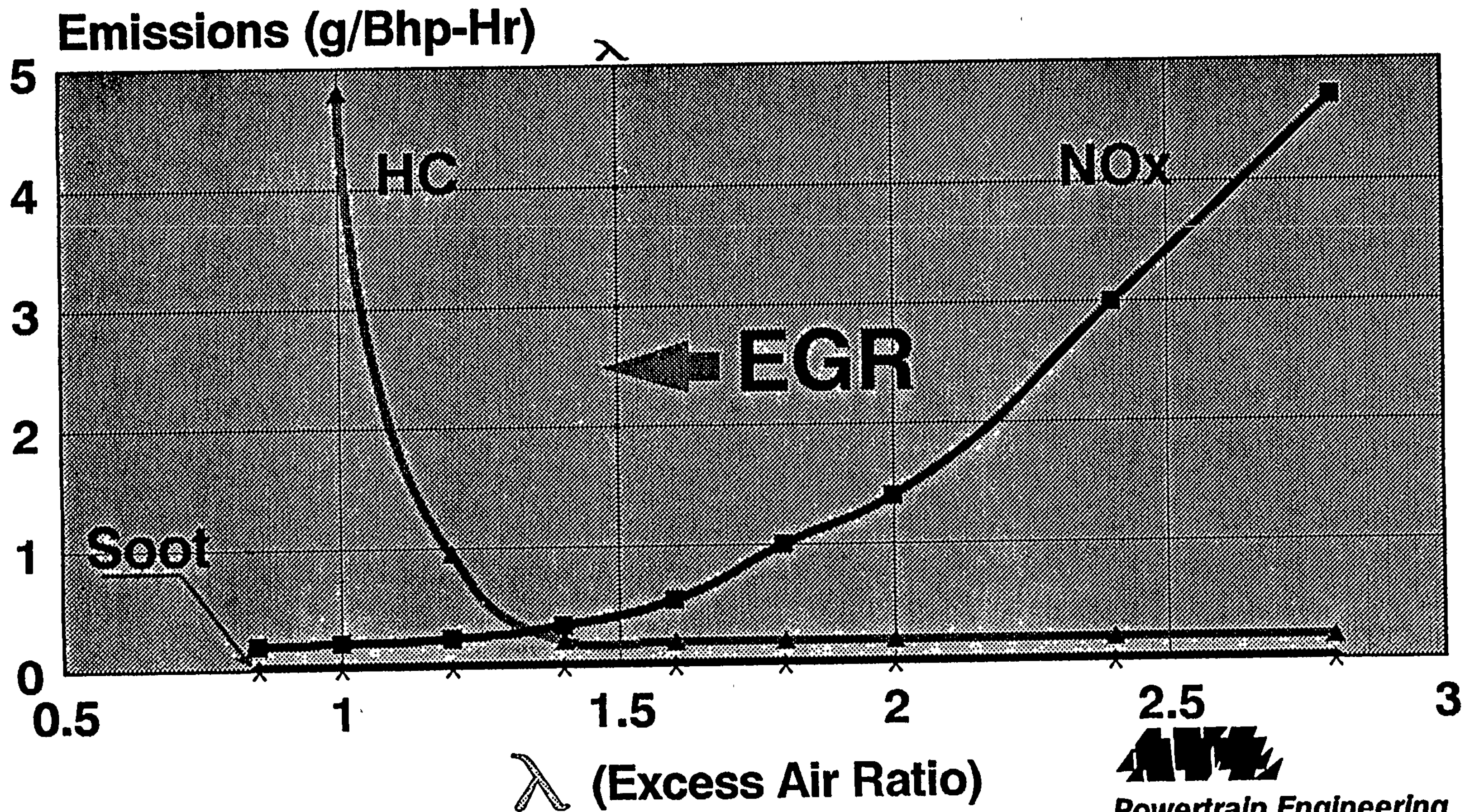
- No Basic Engine Design Changes Req'd.
  - Modified Injectors (Plungers, Orifices)
  - Optimized Timing, EGR, Inj. Press. (220 Bar)
- Mapped Emissions & Performance
  - Energy Efficiency = Diesel
  - Totally Smokeless
  - Very Low NOx, CO, HC & HCHO
- Simulated HDD Transient Emissions
  - Surpassed ULEV Requirements

AVL Powertrain Engineering

Full Load Injection Pressure

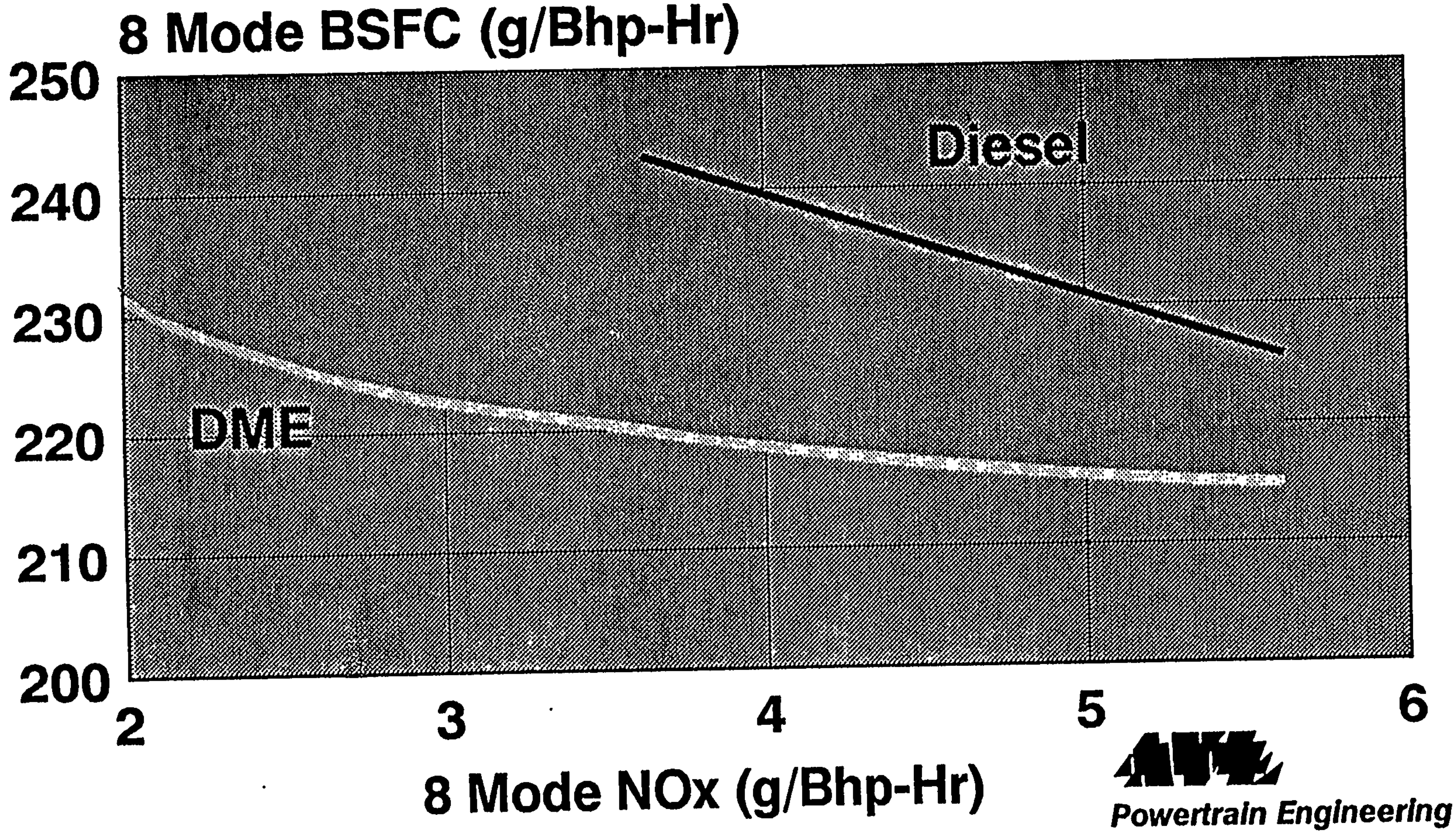


Effects of Lambda on Emissions



Powertrain Engineering

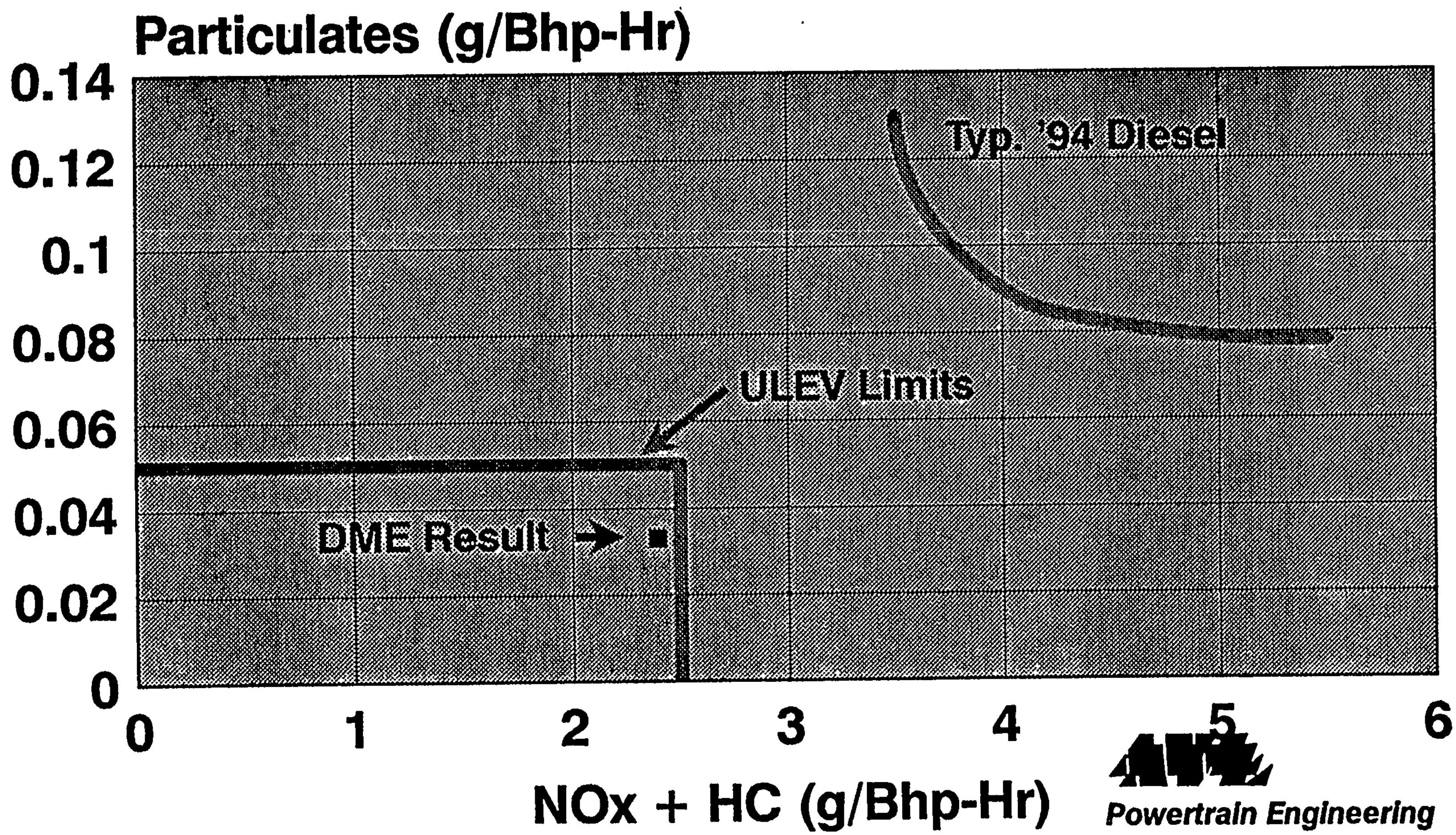
NOx/BSFC Tradeoffs
(Diesel Equivalent BSFC)



Powertrain Engineering

HDD Transient Cycle Emissions Simulation

...AVL 8 mode Test With DME...



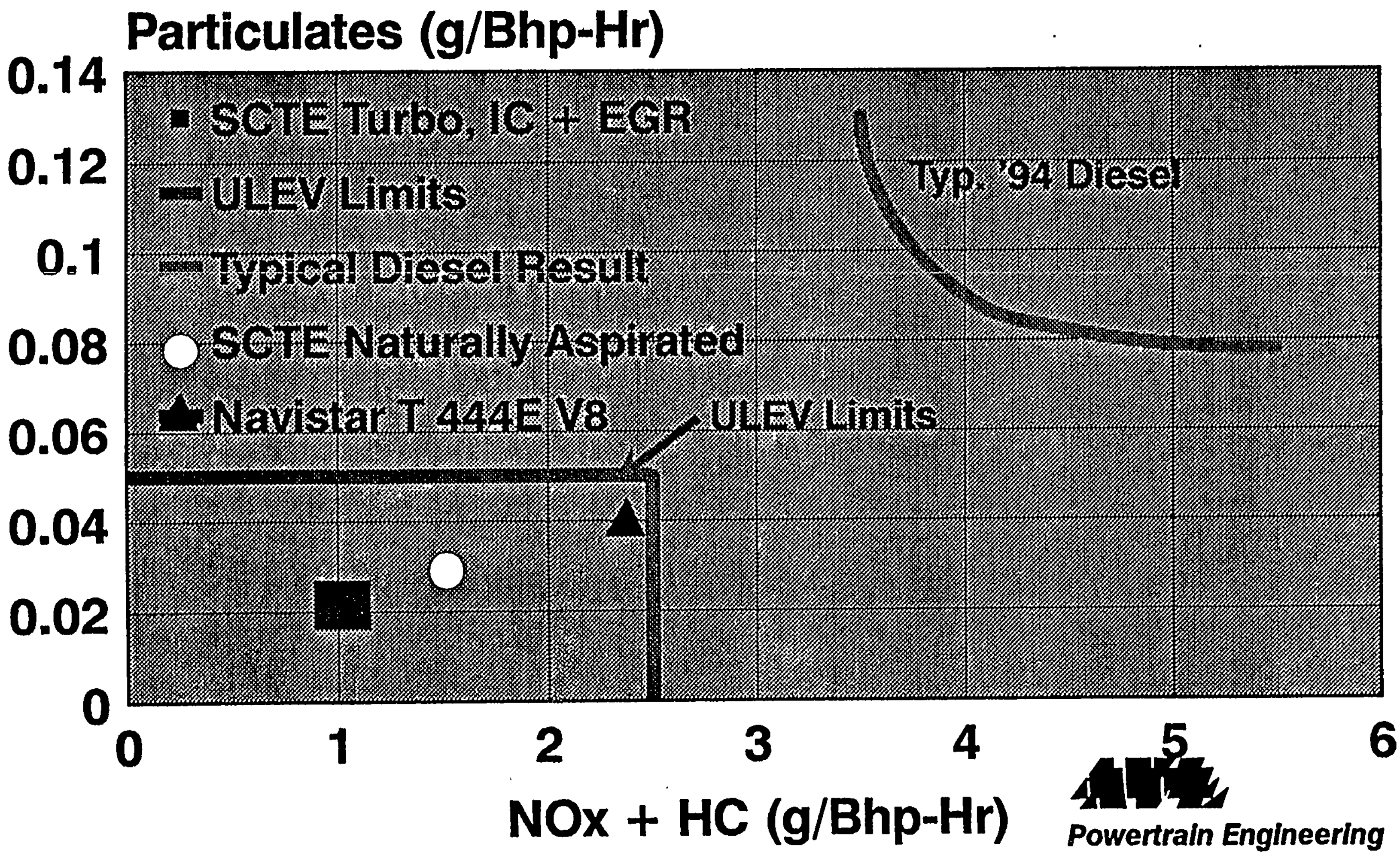
AVL 2.0L Single Cyl. Research Engine

Test Program Summary

- Special Fuel Injection System
  - Highly Rate Shaped
  - Low Peak Pressures(<300 Bar)
- Low Swirl Head
- Emissions Achievements
  - Naturally Aspirated...1.5 g/bhp NOx
  - Turbo/Intercooled... ~ 1.0 g/bhp NOx
  - Totally Smokeless
  - Diesel Efficiency
  - Gasoline Noise Levels

AVL Powertrain Engineering

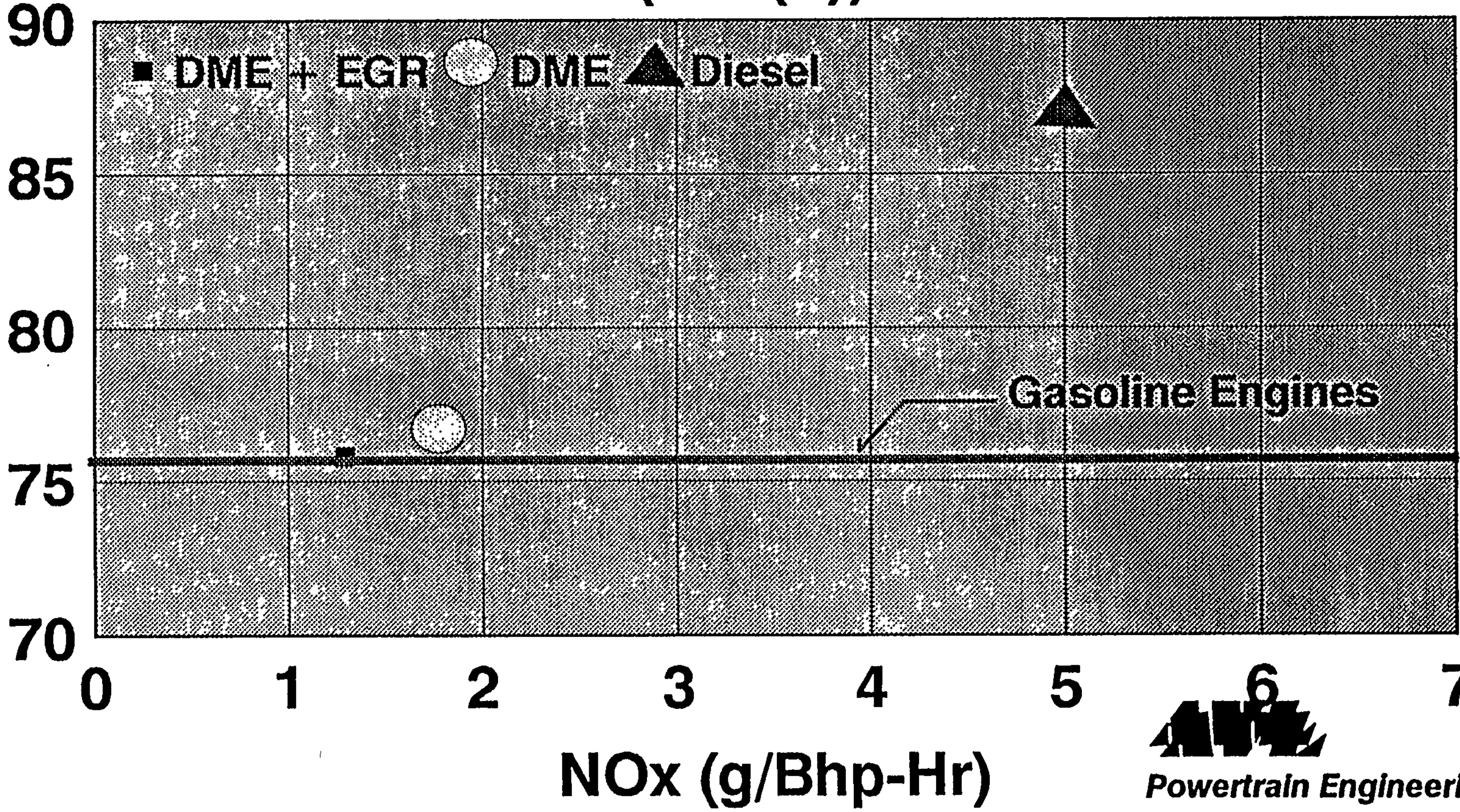
DME Emissions Results



Powertrain Engineering

Combustion Noise Survey

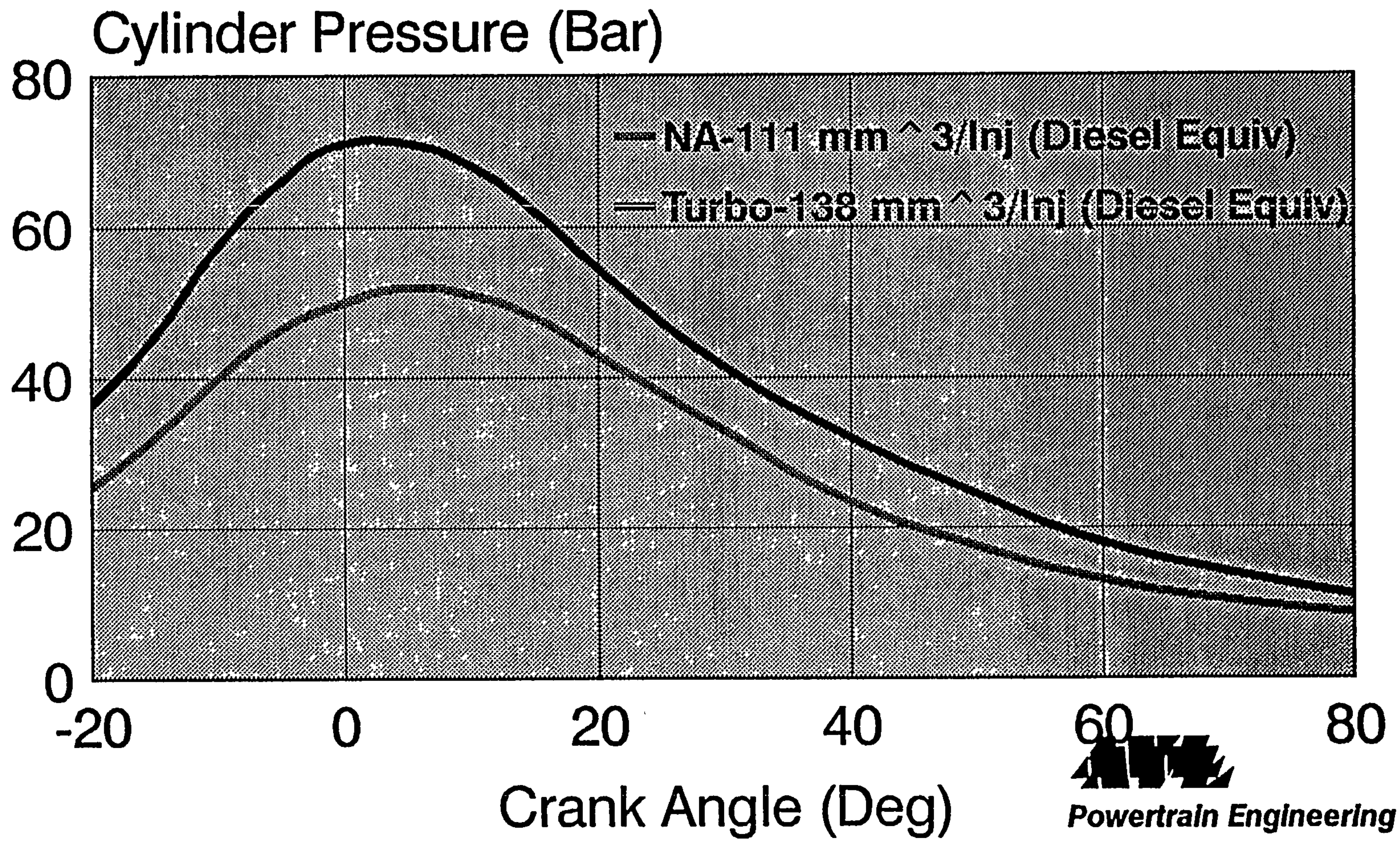
...DME & Diesel Fuel...



Powertrain Engineering

Cylinder Pressure Diagrams

...DME Fuel w/Proprietary EFI System...



Powertrain Engineering

Common Rail Injection System Design Concept

AVL
Powertrain Engineering

Design Objectives

...DME Injection System...

- Low Peak Pressures (< 250 Bar)
- Flexible Injection Rate Shaping
  - Very Low Initial Injection Rate (NOx/Noise)
  - Electronically Variable (W/Speed & Load)
- 300 MM ^ 3/Inj. Delivery in <40 Deg Crank (300 BHP)
- "Bolt On" Existing Engines

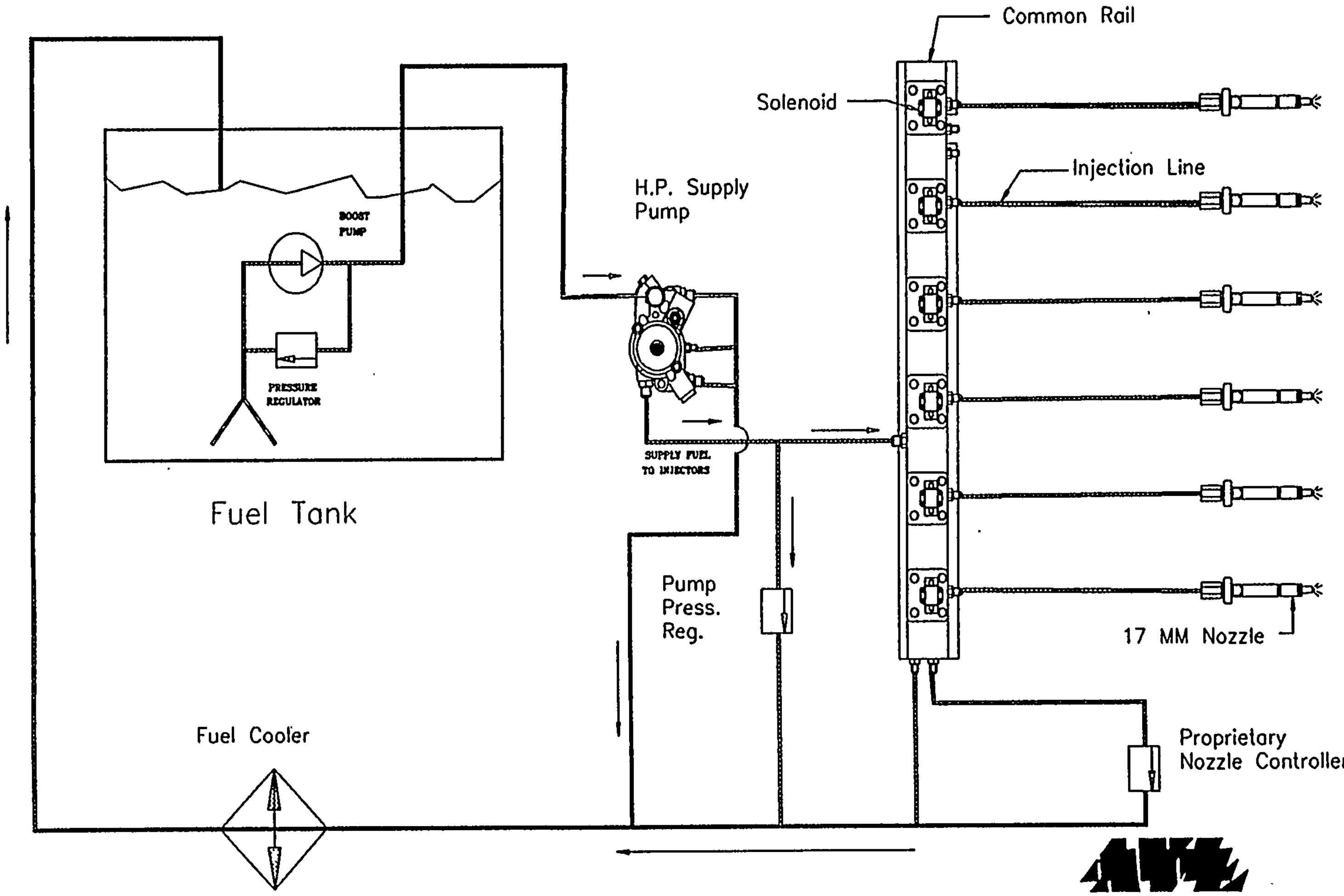
AVL Powertrain Engineering

DME Injection System Design Concept

- Low Pressure (<250 Bar) Common Rail
- Swash Plate Piston Pump-Bellows Sealed
- Solenoid Actuated, Electronically Controlled 17 MM Injectors
- Proprietary "Rate Shaping" Technology
- Propane Type Fuel Handling System

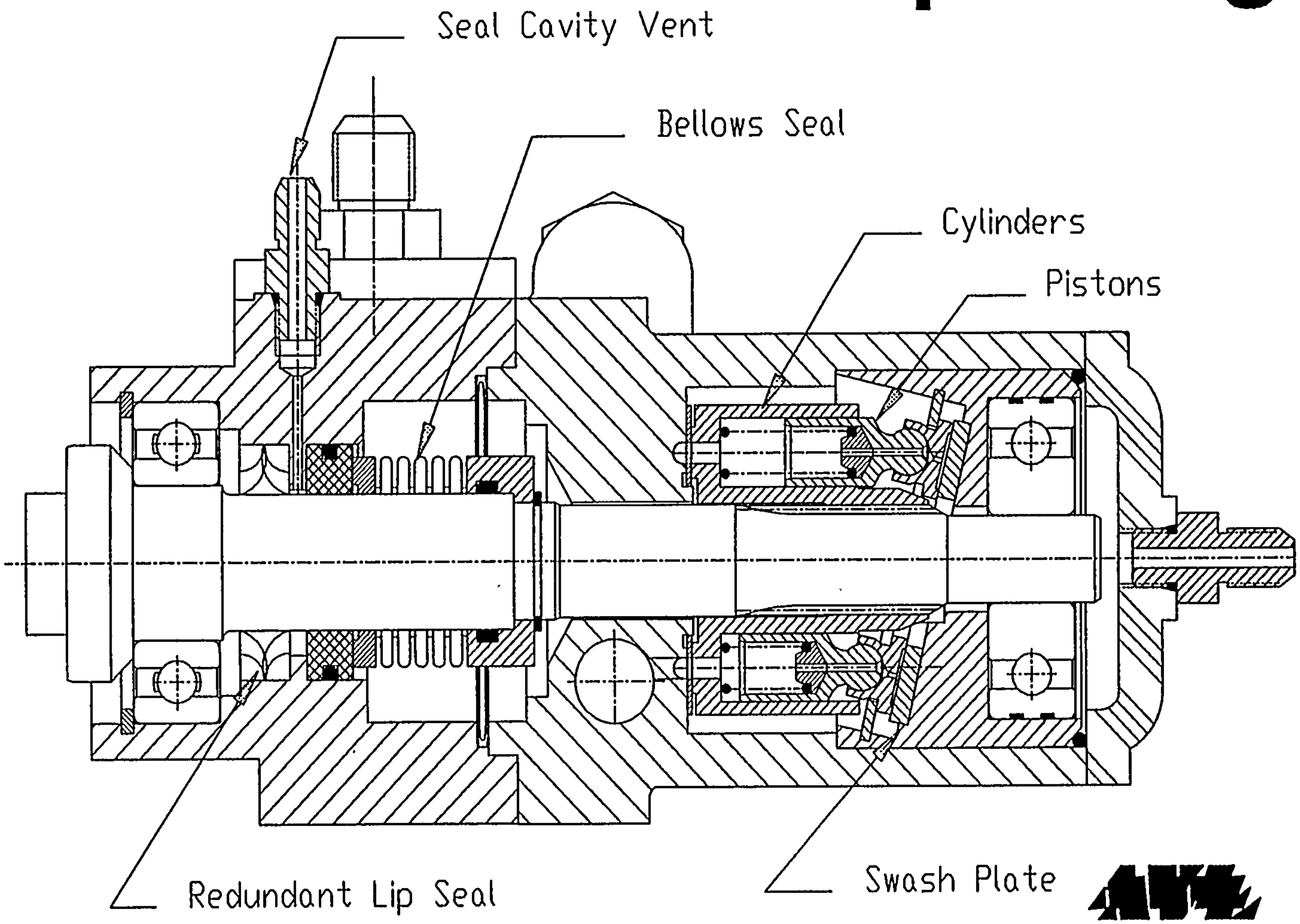
AVL Powertrain Engineering

DME Common Rail Injection System



AVL Powertrain Engineering

Swash Plate Pump Design



Powertrain Engineering

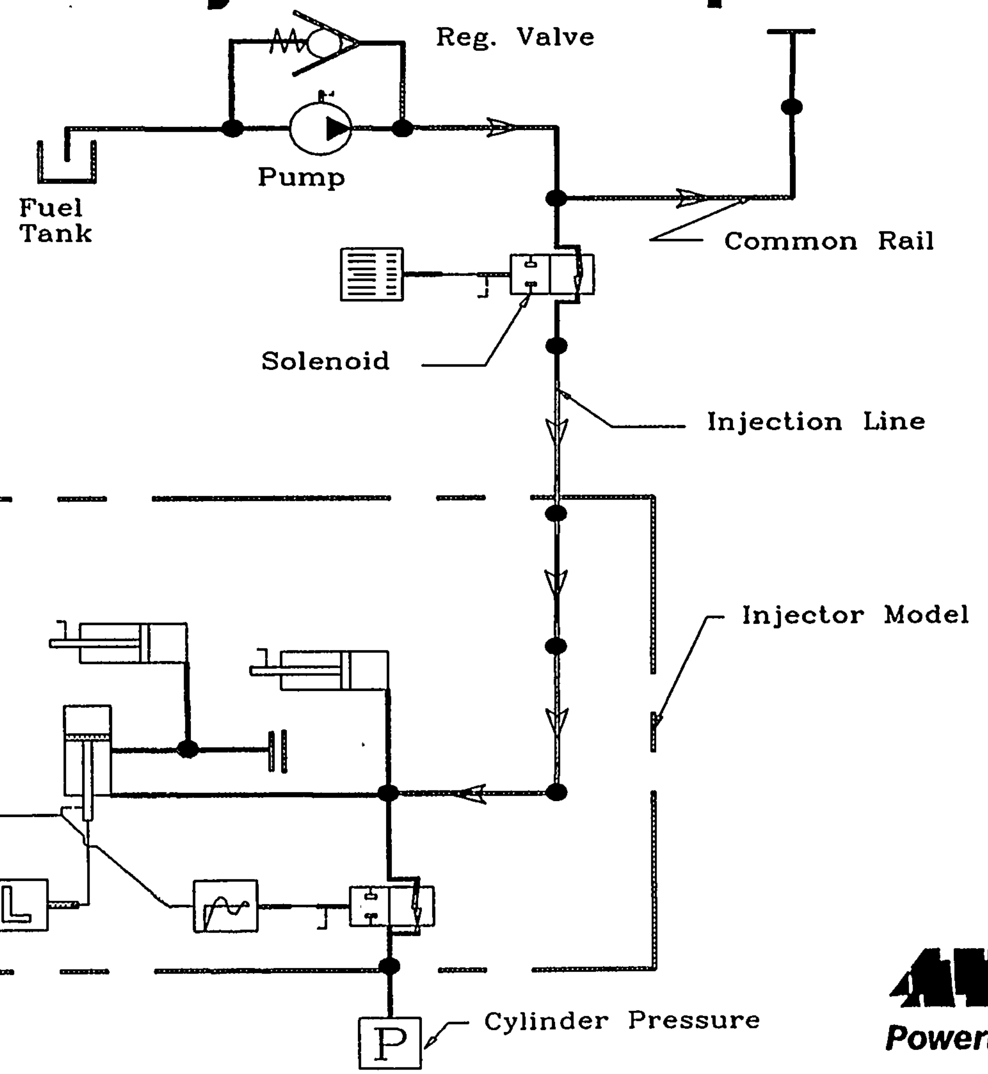
Computer Modeling & Simulation

- 1D Computer Model Constructed
- Fully Describes System & All Components
- DME Physical Characteristics Included
- Sophisticated Electronic **Rate Shaping Feature Developed
- System Fully Optimized & Proven Robust (200 Simulations)

***Rate Shaping Technology Will Not Be Disclosed*

AVL Powertrain Engineering

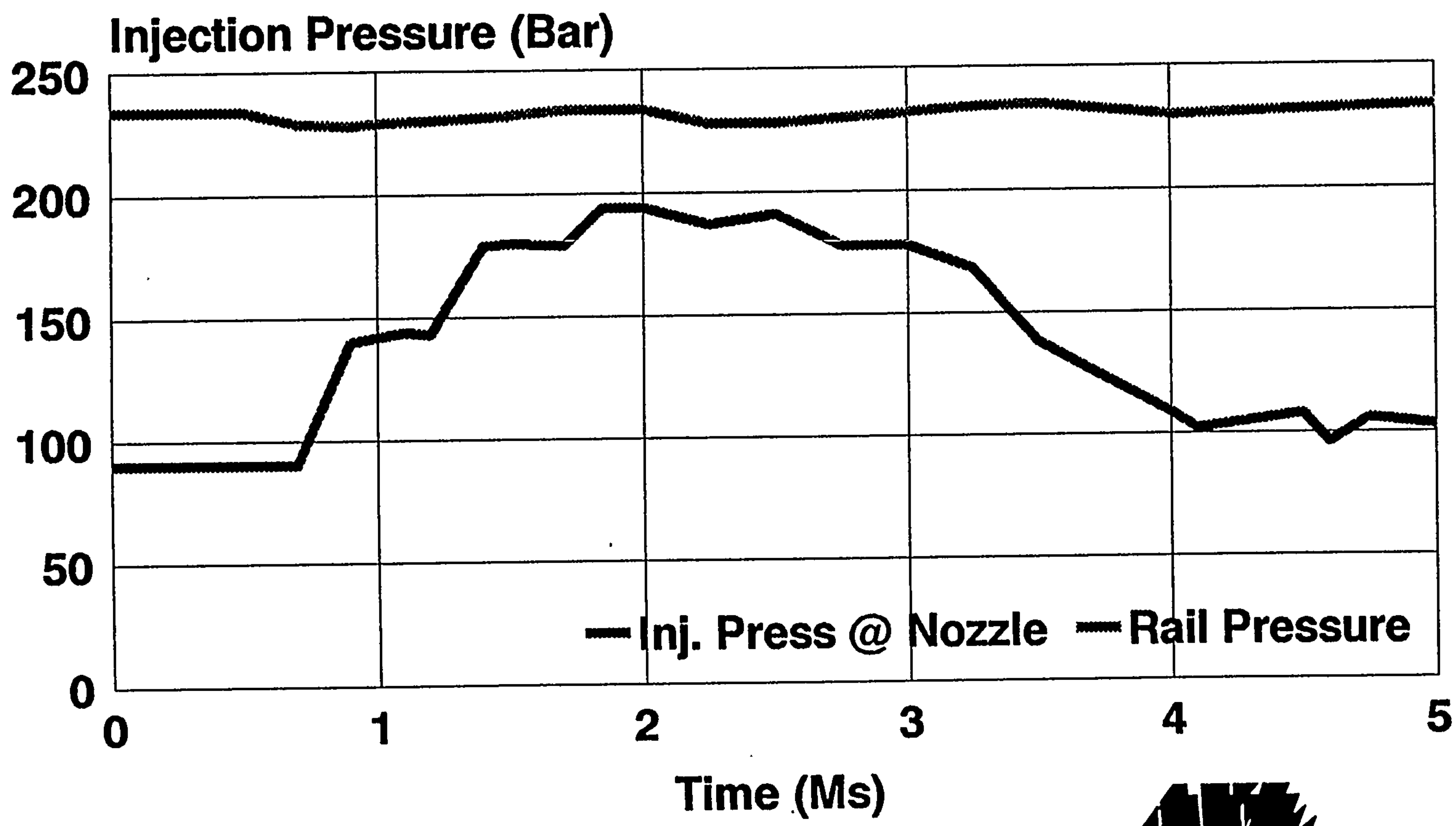
Injection System Computer Model



AVL Powertrain Engineering

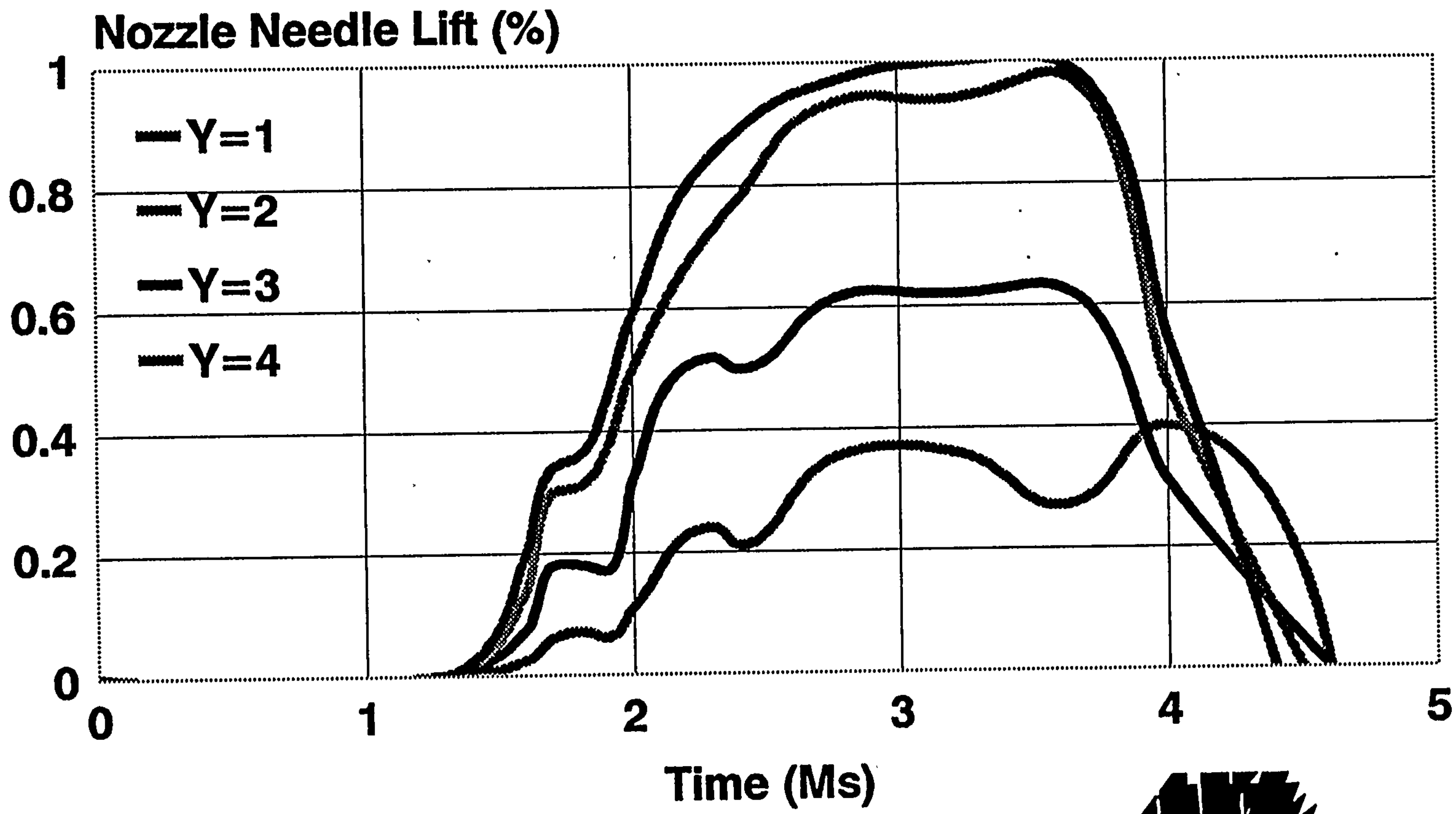
Injection Pressure History

...Simulation, 250 MM ^ 3/Inj...



Powertrain Engineering

Effect of Rate Shaping Parameter "Y"



Powertrain Engineering

Computer Modeling & Simulation

...Conclusions...

- System Performs as Expected
- Three Degrees of Freedom Demonstrated
  - *Duration (Pulse Width)*
  - *Rail Pressure (Press & Rate)*
  - *Initial Rate of Inj. (Rate Shaping)*
- Should Provide Very Low Emissions, Noise & Fuel Consumption

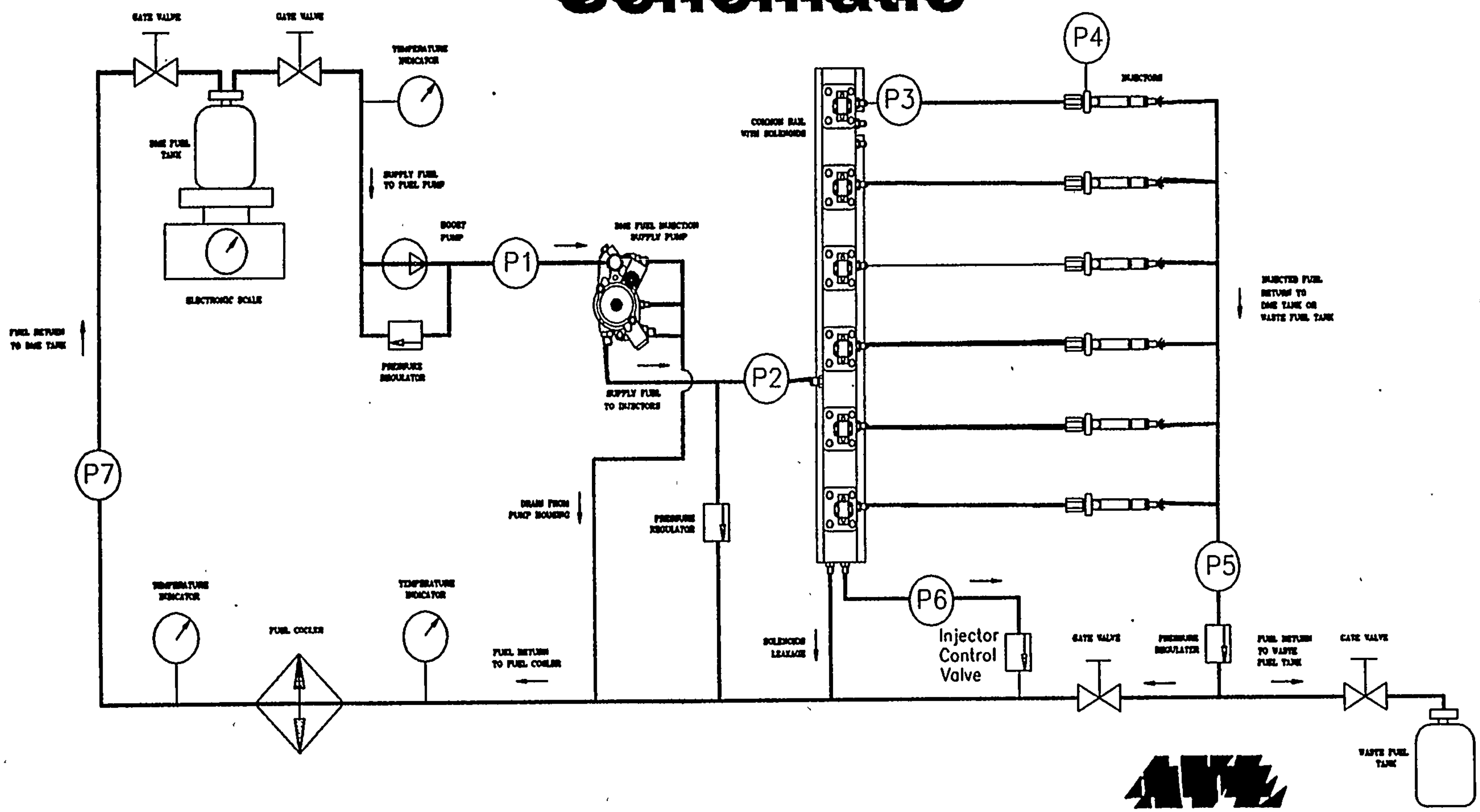
AVL Powertrain Engineering

Program Status

- Detail Design Completed
- Simulations Indicate Robust/Flexible Design
- Parts Procured
- Initial Bench Tests Underway
- Preliminary Results Substantiate Simulations
- Engine Testing to Begin ~ August, 1996

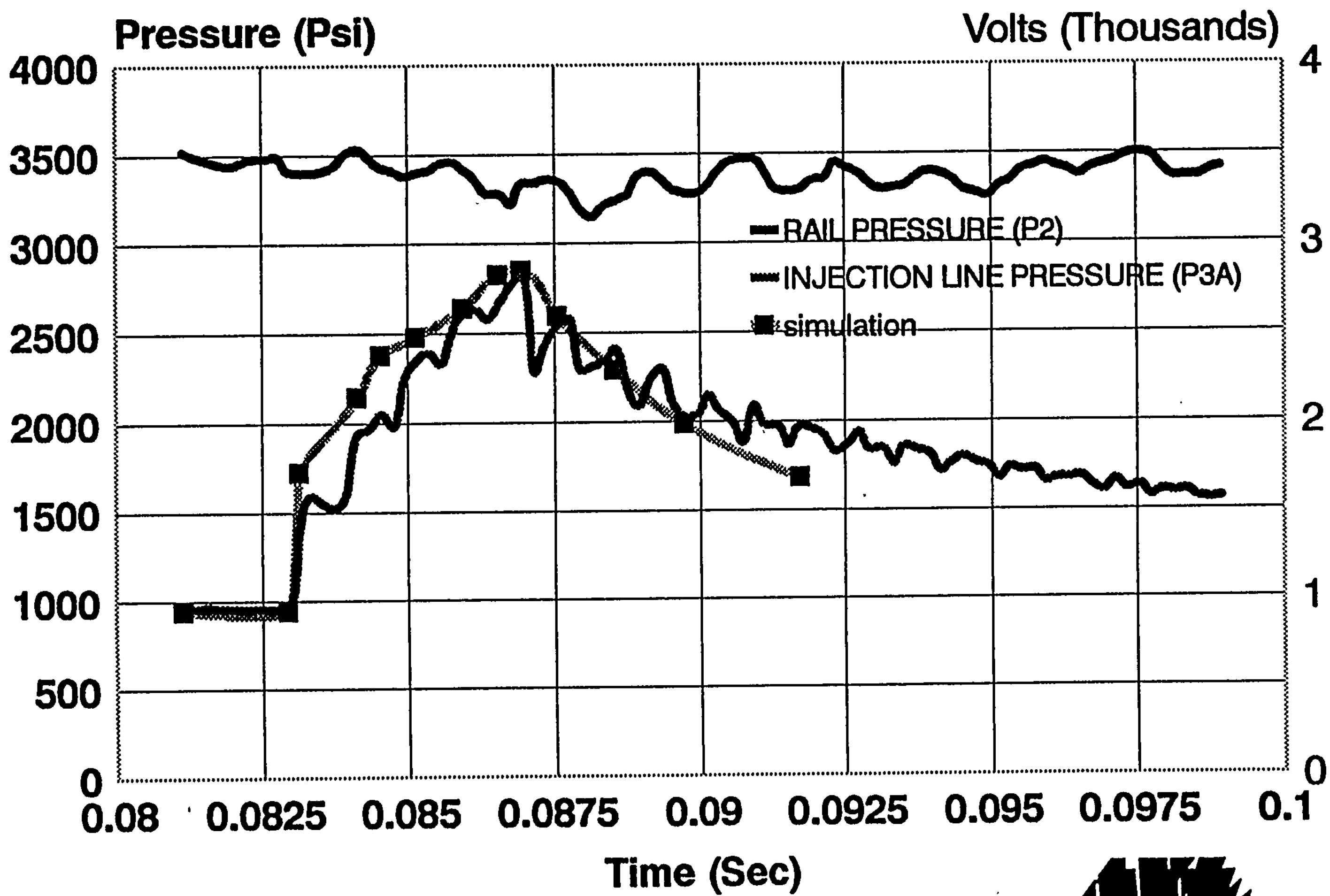
AVL Powertrain Engineering

DME Injection System Bench Test Schematic



Powertrain Engineering

Comparison of Simulation to Bench Test Results



AVL Powertrain Engineering

Summary

- DME is a Very Promising Fuel for H.D. Vehicles
  - Very Low Emissions & Noise
  - Economically Viable
- Key to Low Emissions are Injection Characteristics
- The Fuel System Shown Will Provide Req'd. Injection Characteristics
- Forecast: DME Will Become a Popular Truck Fuel in Urban Area's

Powertrain Engineering

Development of Ignition System and Combustion Monitoring Technology for Premixed Charge Alternative Fuelled Engines

D. P. Gardiner, R.W. Mallory, G.R. Pucher, M.K. Todesco
Thermotech Engineering
Kingston, Ontario

M.F. Bardon
Royal Military College of Canada
Kingston, Ontario

Acknowledgments

- Transport Canada
- Natural Resources Canada (CANMET)
- U.S. Department of Energy (NREL)
- General Motors of Canada Ltd. (Oshawa)

Light Duty Vehicle Applications (Stoichiometric Alcohol or Gasoline)

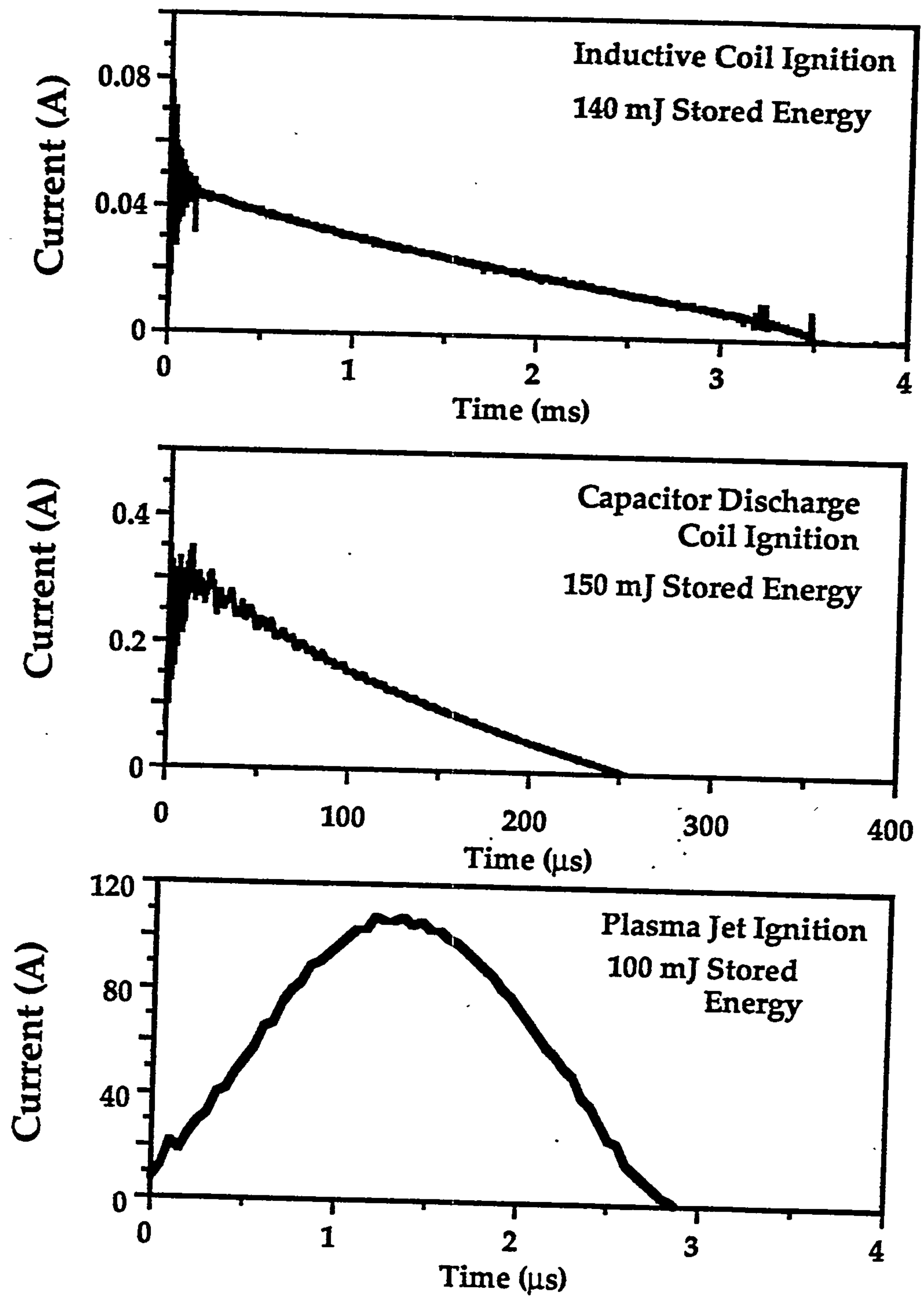
- Enhanced Ignition - intermittent duty high energy "boost" for cold starting
- Combustion Monitoring - on-board diagnostics (OBD II) for misfire detection

Medium/Heavy Duty Vehicle Applications (Lean Burn Natural Gas or Propane)

- Enhanced Ignition - continuous duty, low energy operation for lean burn (extend lean limit)
- Combustion Monitoring - closed loop air/fuel ratio control near the lean limit (detect poor combustion prior to misfiring)

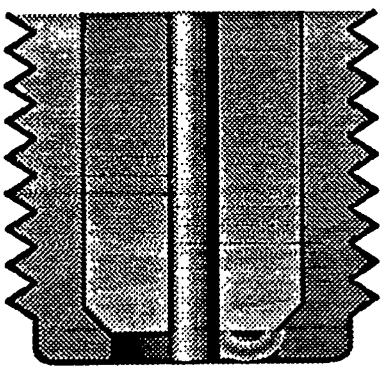
Low Energy Plasma Jet Ignition

- Ignition by plasma jets involves a different mechanism than ignition by conventional sparks
- Ignition by plasma jets does not necessarily involve higher energy levels than ignition by conventional sparks

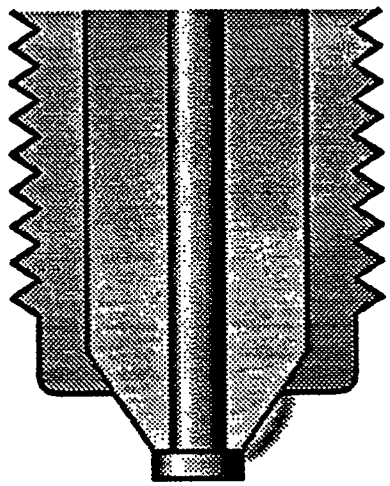


Typical Spark Current Profiles for Different Ignition System Types

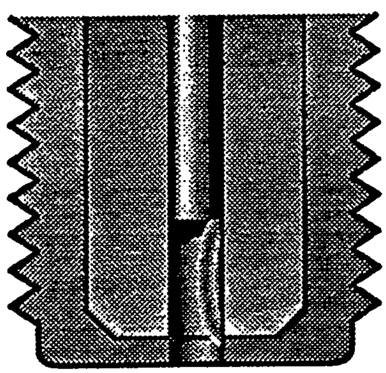
SURFACE DISCHARGE IGNITORS



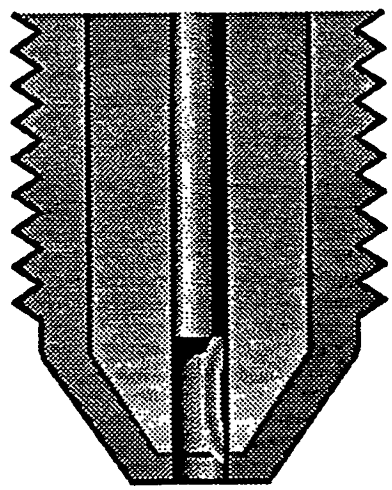
Flush Tip
Surface Gap



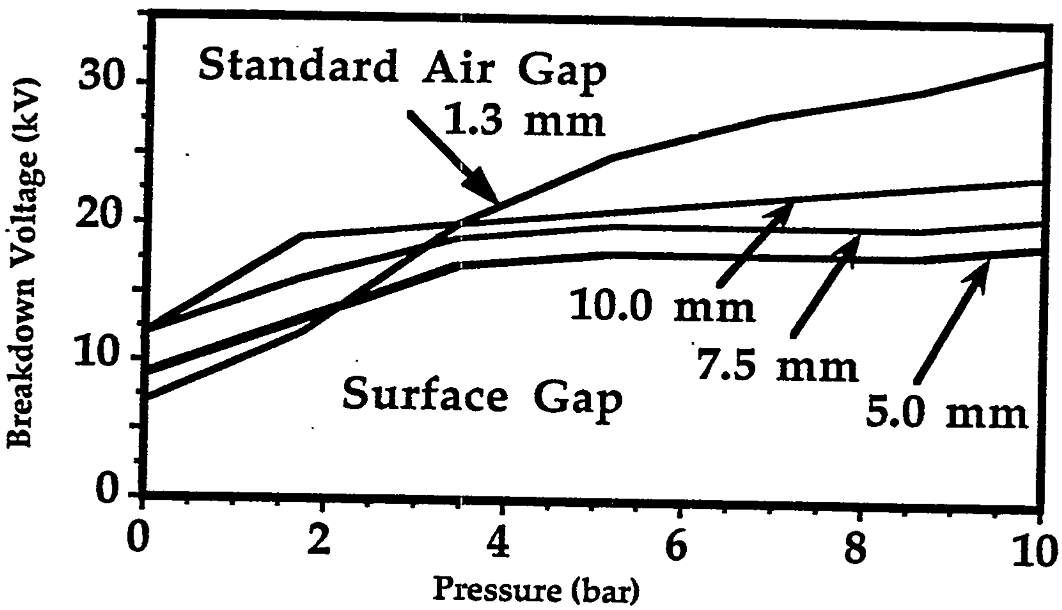
Projected Tip
Surface Gap



Flush Tip
Recessed Gap

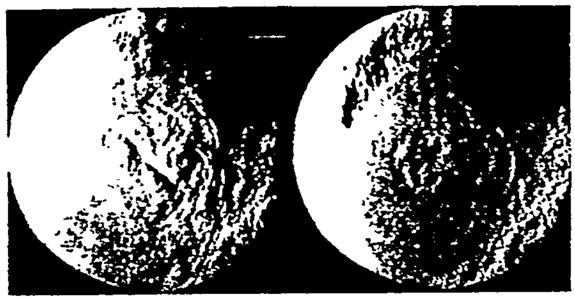


Projected Tip
Recessed Gap



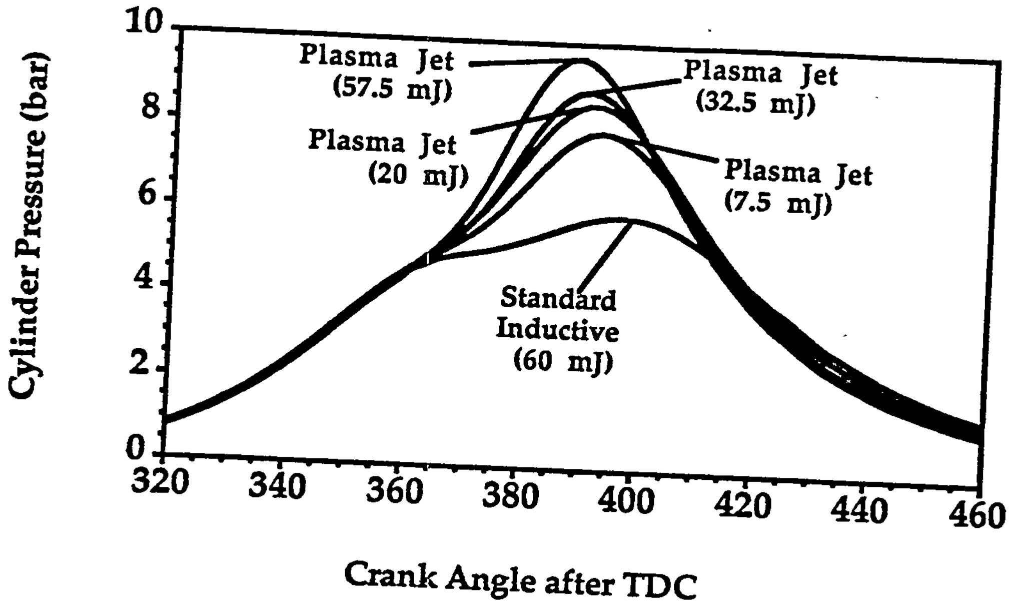
Effect of Pressure on Breakdown Voltage For Air Gap and Surface Gap Ignitors

Inductive Ignition
Standard Spark Plug

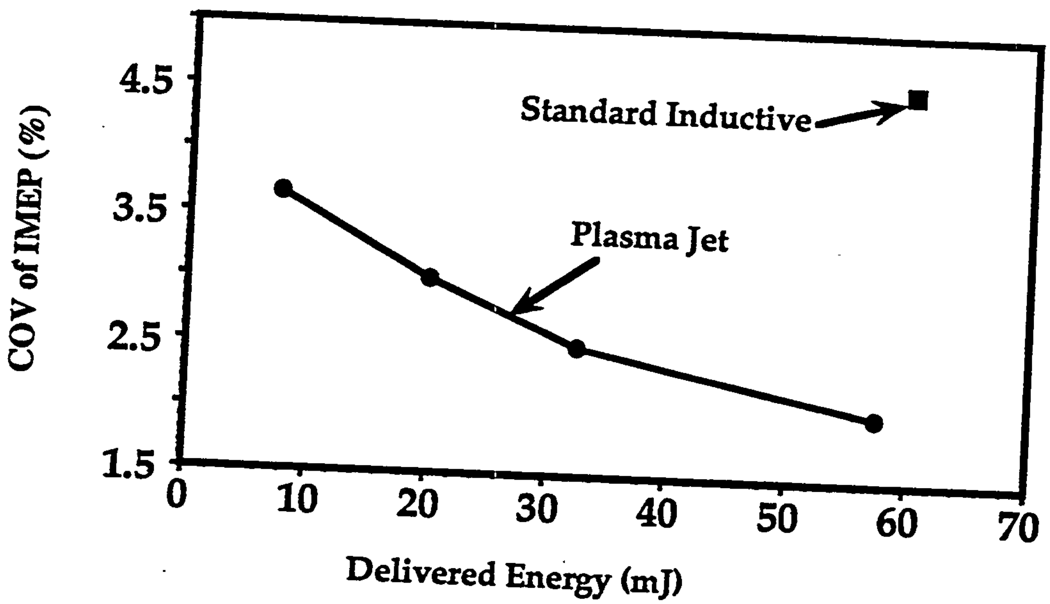


Plasma Jet
Ignition (300 mJ)

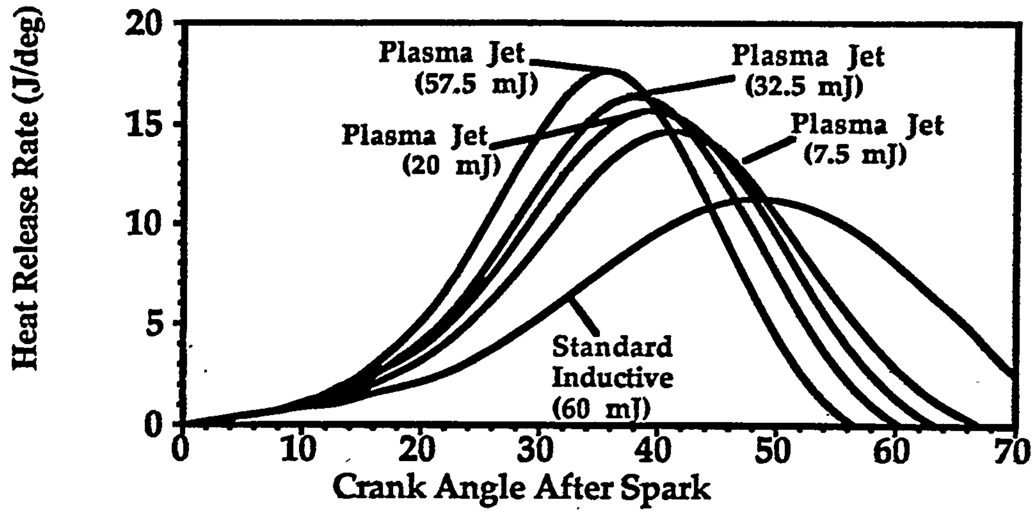
Ignition of Lean Methane-Air Mixtures with 10 m/s Swirl
(Murase *et al*, 1989)



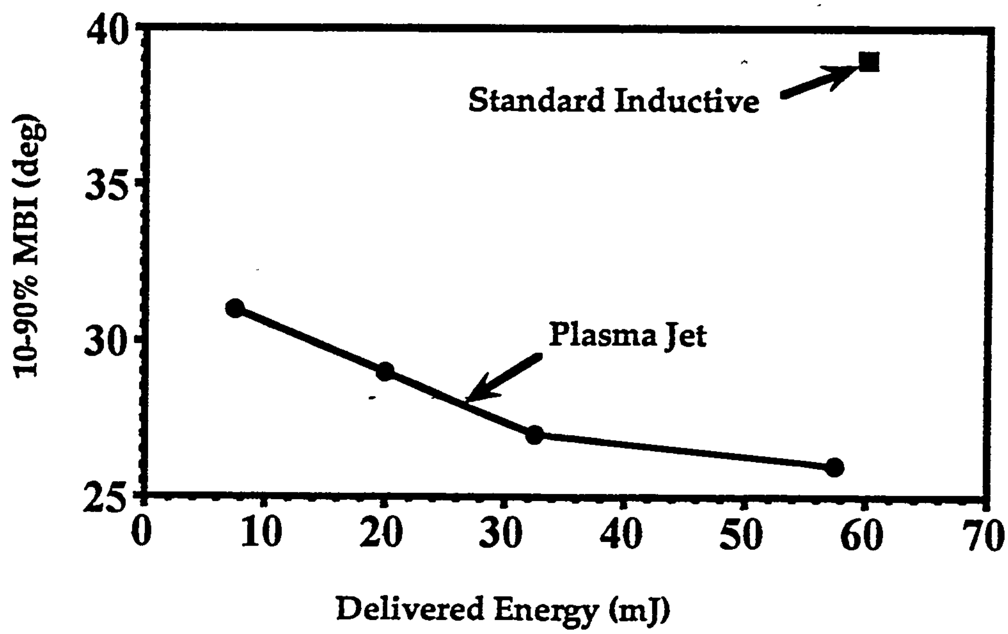
Effect of Delivered Ignition Energy on Cylinder Pressure



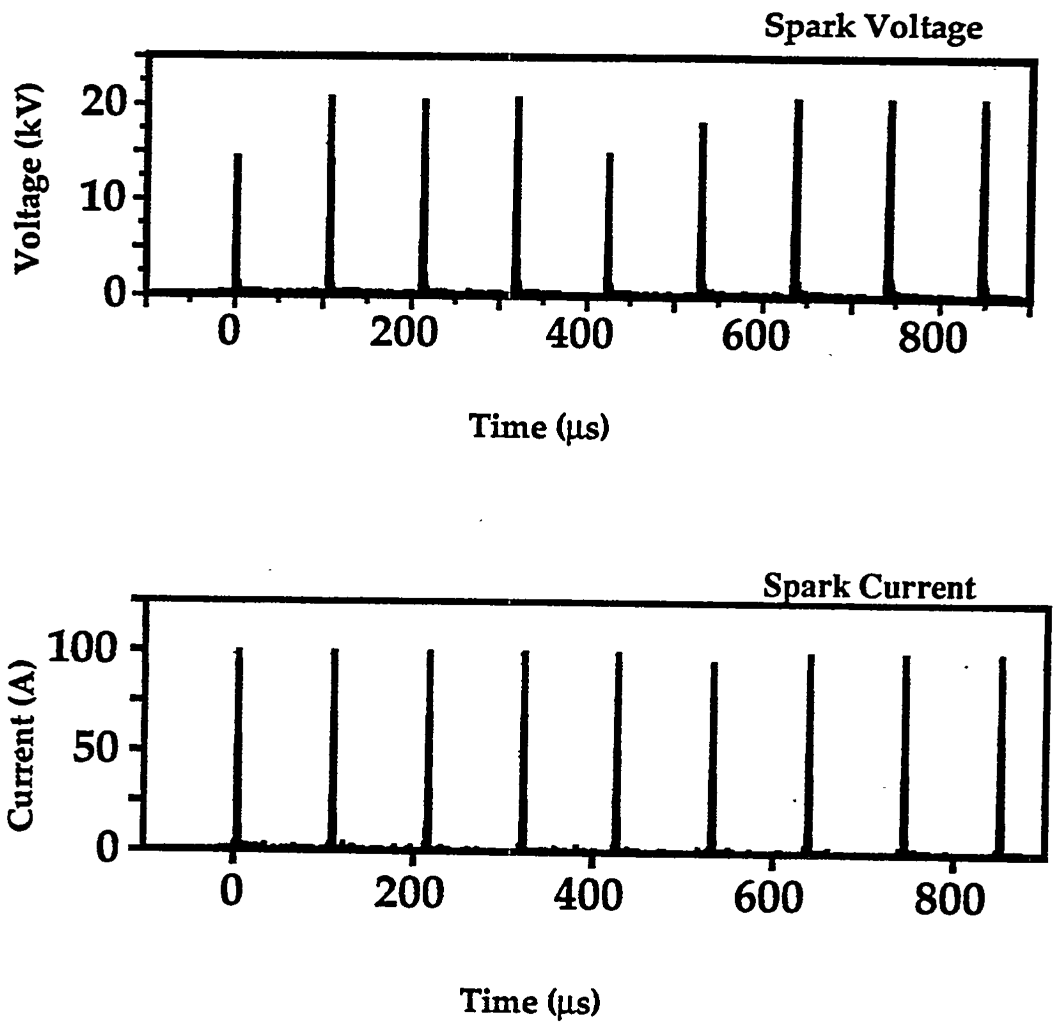
Effect of Delivered Ignition Energy on Coefficient of Variation of Indicated Mean Effective Pressure



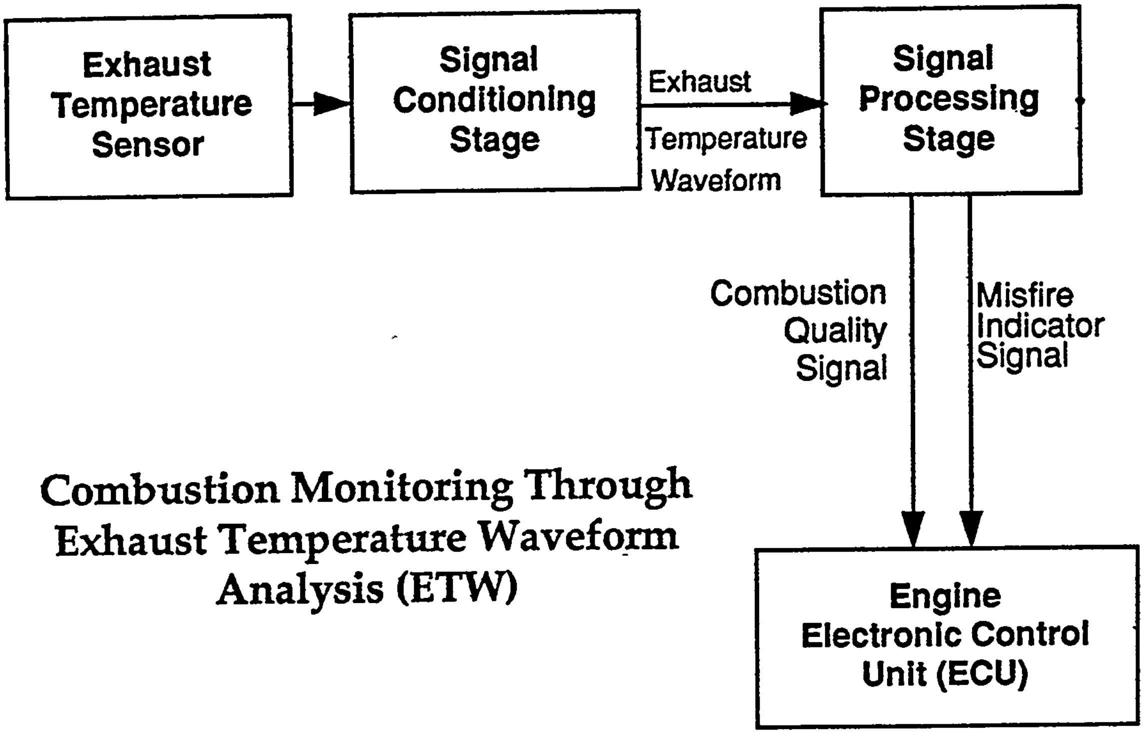
Effect of Delivered Ignition Energy on Heat Release Rate



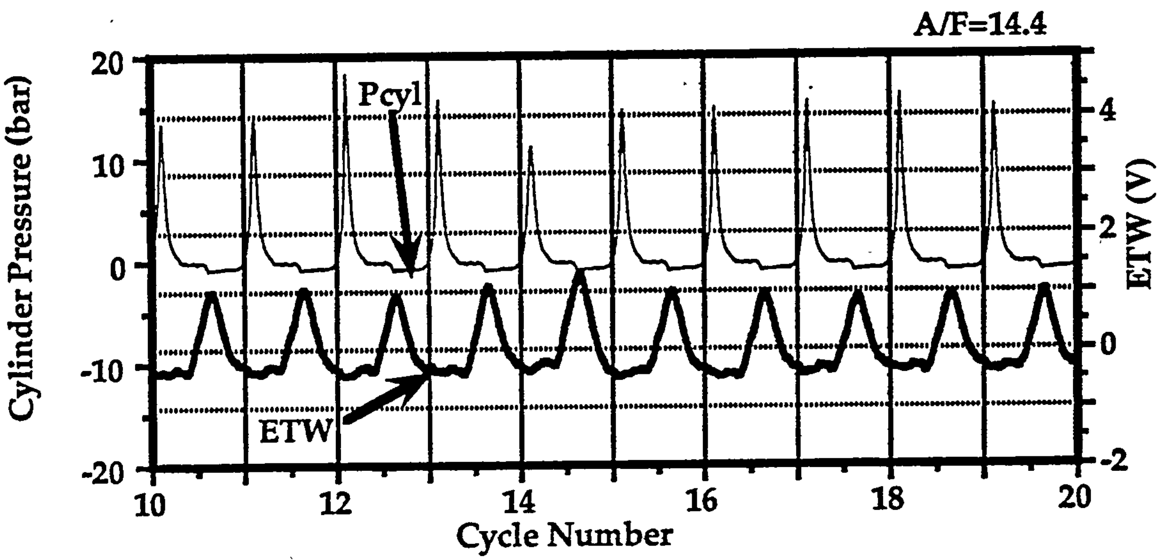
Effect of Delivered Ignition Energy on 10-90% Mass Burn Interval



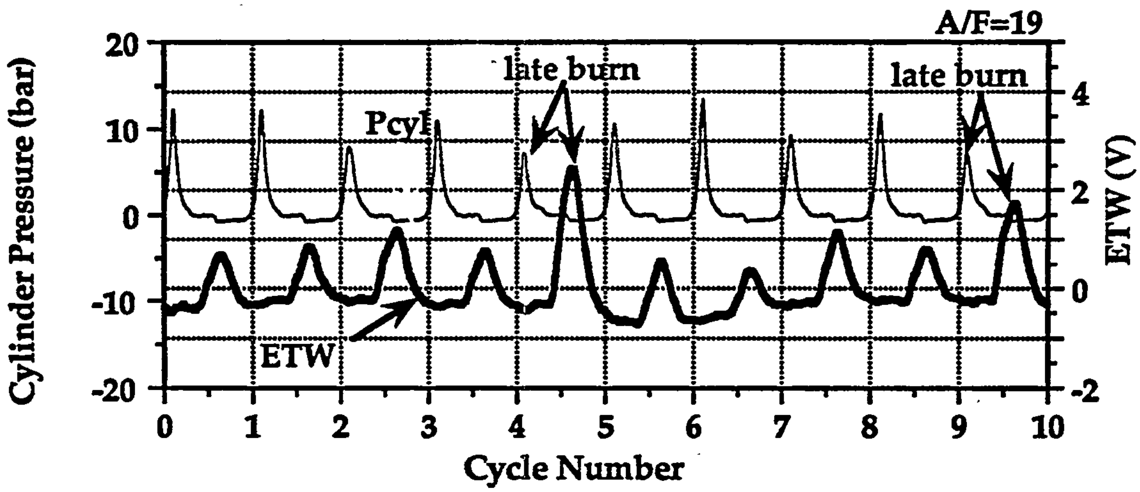
Multistrike Plasma Jet Ignition
(7.5 mm gap, 12.5 bar chamber pressure)



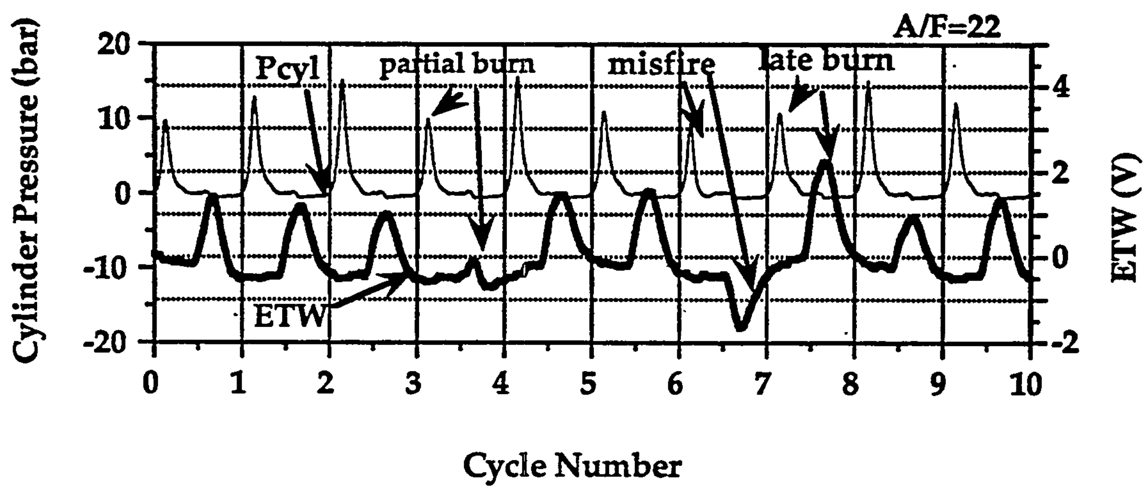
Combustion Monitoring Through Exhaust Temperature Waveform Analysis (ETW)



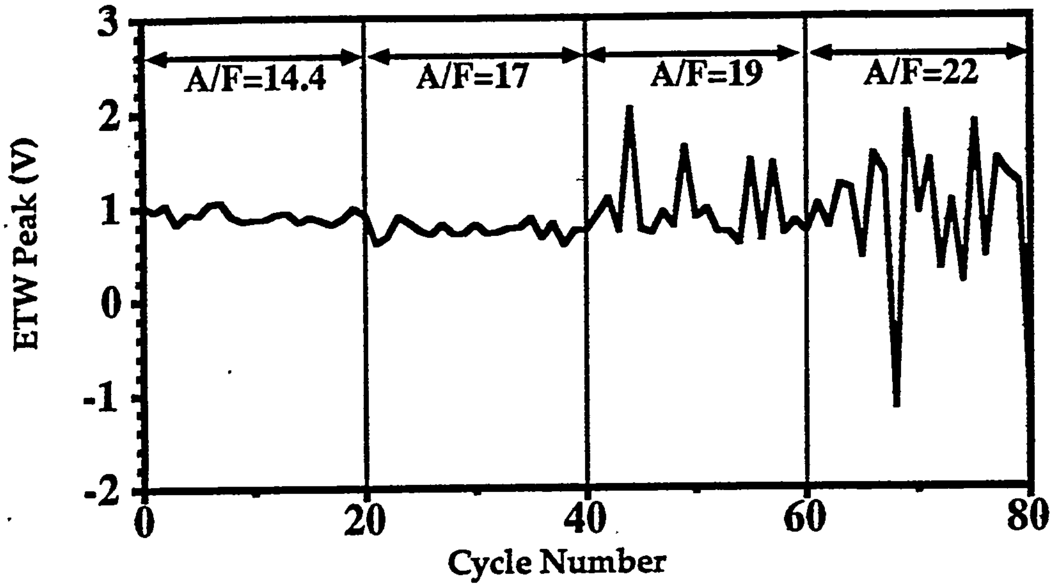
Lean Mixture Comparison of Cylinder Pressure and ETW Signal
(2000 rpm, 2 bar BMEP)



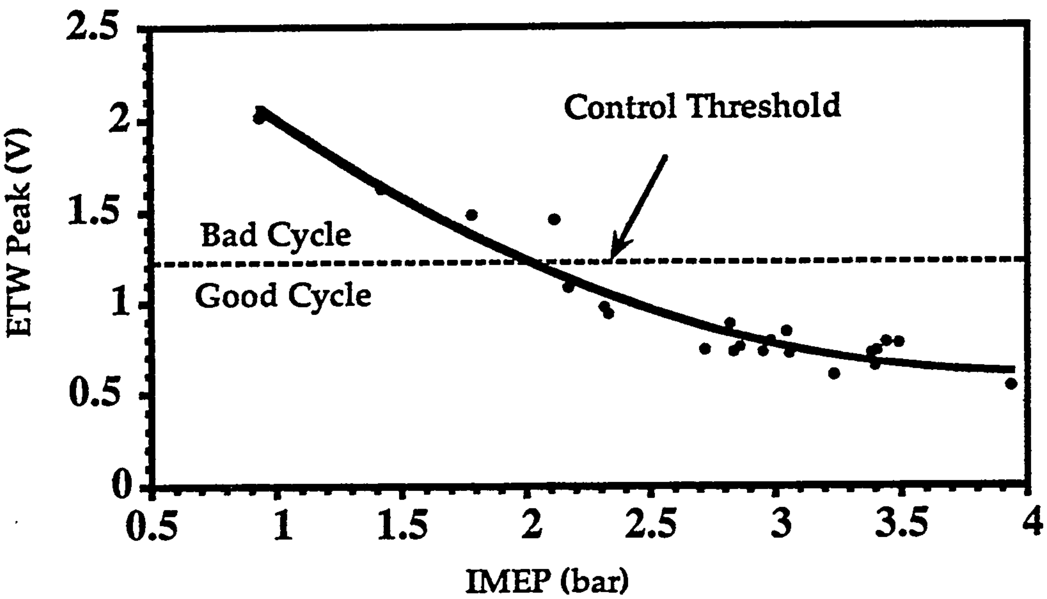
Lean Mixture Comparison of Cylinder Pressure and ETW Signal (2000 rpm, 2 bar BMEP)



Lean Mixture Comparison of Cylinder Pressure and ETW Signal (2000 rpm, 2 bar BMEP)



Effect of Air/Fuel Ratio on Cycle-to-Cycle Fluctuations in Peak ETW Value (2000 rpm, 2 bar BMEP)



Relationship Between Peak ETW Values and Indicated Mean Effective Pressure of Consecutive Cycles (A/F=19)

Synergy Between Ignition System and Combustion Monitoring Technology

- Plasma jet ignition can provide lean limits which are imposed by slow burning rather than ignition failure
- Exhaust Temperature Waveform monitoring is particularly sensitive to slow burning cycles

BIODIESEL - AN UPDATE

Steve Howell, National Biodiesel Board
Leon Schumacher, University of Missouri/Columbia
Wendel Goetz, ORTECH Corporation

(Presentation unavailable at time of publication)

SESSION 6

HOW CLEAN ARE ALTERNATIVE FUELS?

Chair: Greg Rideout, Environment Canada

Comparison of Off-Cycle and Cold Start Emissions from Dedicated NGVs and Gasoline Vehicles

Louis Lautman

Gas Research Institute
8600 West Bryn Mawr Avenue
Chicago, IL 60631

OUTLINE OF PRESENTATION

- OVERVIEW
- OBJECTIVES
- TEST VEHICLES & FUELS
- TEST CYCLES
- TEST MATRIX
- RESULTS
- OBSERVATIONS
- REMAINING WORK

OVERVIEW

- Compare exhaust emissions from OEM-built, dedicated NGVs with gasoline vehicles of same make and model
- Funded by Gas Research Institute (GRI)
- Managed by Engine, Fuel, and Emissions Engineering, Inc. (EF&EE)
- Emission testing by Automotive Testing Laboratories
- Testing to be completed in June 1996

OBJECTIVES

- Assess emission benefits of NGVs compared to gasoline vehicles
  - Federal Test Procedure
  - Realistic Driving Conditions
    - Aggressive driving (SFTP)
    - Air conditioning on (SFTP)
    - Low temperature (Cold FTP)
    - Wide open throttle (WOT)

TEST VEHICLES

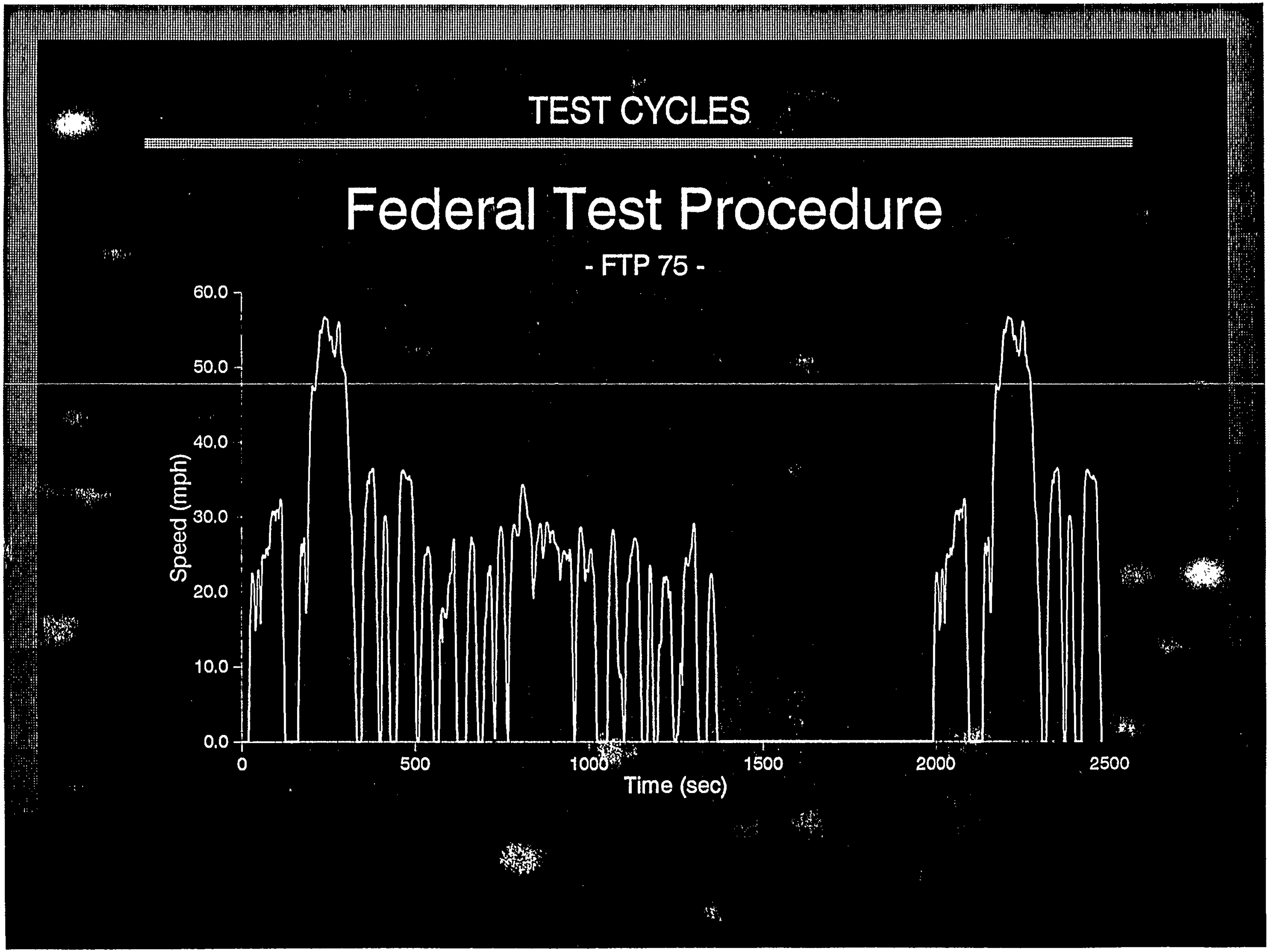
Vehicle #	Fuel	Model	Mileage
A	Gasoline	1995 Ram Van	in progress
B	Gasoline	1995 Ram Van	in progress
C	CNG	1994 Ram Van	24,570
D	CNG	1994 Ram Van	in progress
E	Gasoline	1996 Crown Vic	7,600
F	Gasoline	1996 Grand Mar	8,200
G	CNG	1996 Crown Vic	4,100
H	CNG	1996 Crown Vic	6,000
I	Gasoline	1995 Caravan	14,992
J	Gasoline	1995 Caravan	10,982
K	CNG	1995 Caravan	5,586
L	CNG	1995 Caravan	4,146

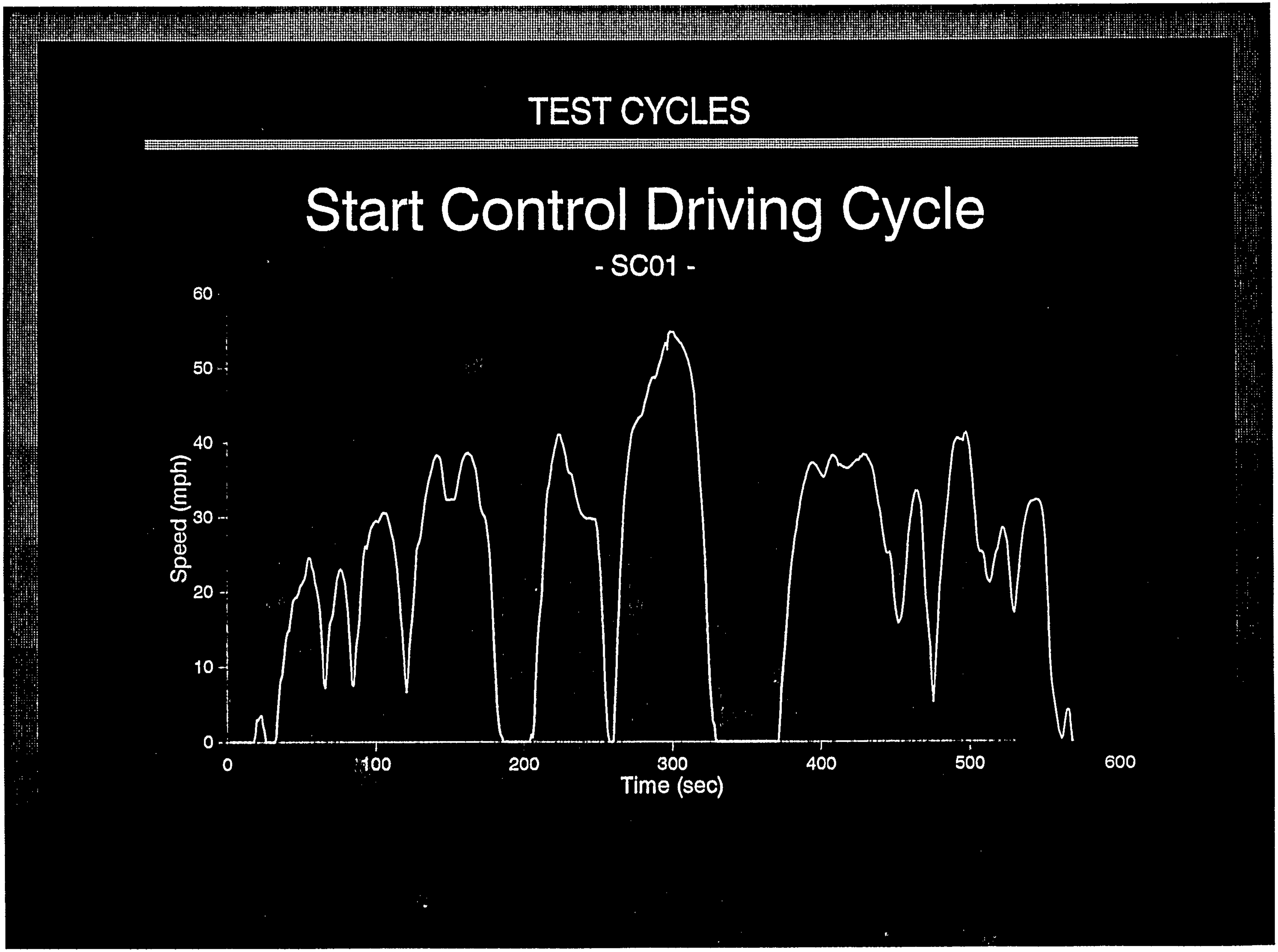
TEST FUELS

- RFA Fuel
  - Non-oxygenated "Industry Average" Gasoline
- RFG Fuel
  - Federal Phase 2 RFG with 2% MTBE
- CNG Fuel
  - CARB Certification Fuel
- Gasoline RVP adjusted with butane for Cold FTP testing

TEST CYCLES

- Federal Test Procedure (FTP)
- Supplemental Federal Test Procedure (SFTP)
  - 866 Cycle, FTP Bag 2 with air conditioning (SFTP Bag 4)
  - Start Control Cycle, SC01 (SFTP Bag 5)
  - Aggressive Driving Cycle, US06 (SFTP Bag 6)
- Cold FTP
  - Similar to FTP except testing is conducted at 20 degree F instead of 75 degree F

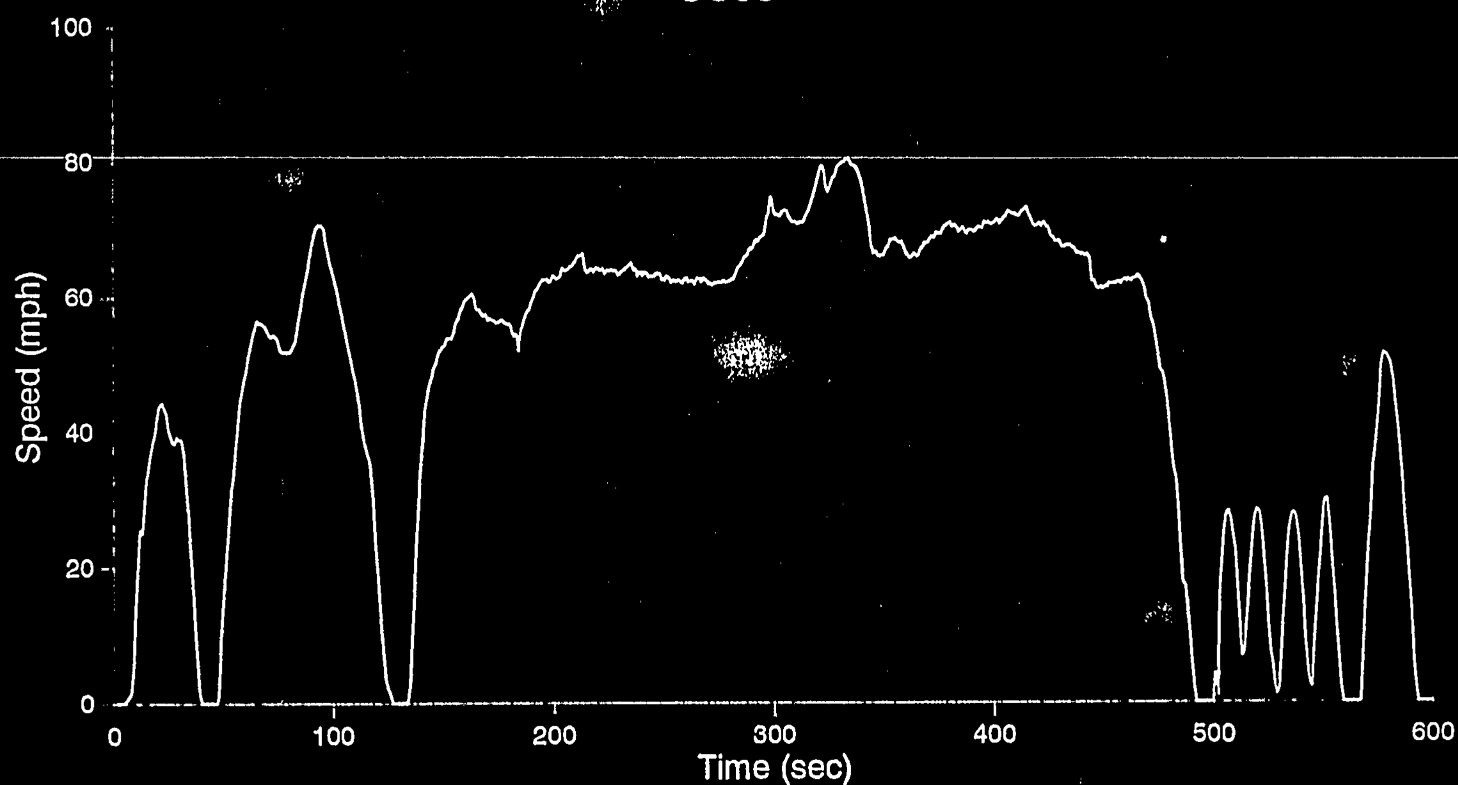

TEST CYCLES
Federal Test Procedure
- FTP 75 -
Speed (mph)
60.0
50.0
40.0
30.0
20.0
10.0
0.0
0
500
1000
1500
2000
2500
Time (sec)


TEST CYCLES
Start Control Driving Cycle
- SC01 -
Speed (mph)
60
50
40
30
20
10
0
0
100
200
300
400
500
600
Time (sec)

TEST CYCLES

Aggressive Driving Cycle

- US06 -



SUPPLEMENTAL FEDERAL TEST PROCEDURE

EPA Proposed Weighting Scheme for Pollutants in Composite Calculation

Test Cycle	(Bag #)	THC/NMHC	CO & NOx
FTP 505	(Bag 1)	0.21	0.15
866 with a/c	(Bag 4)	0.24	0.37
SC01	(Bag 5)	0.27	0.20
US06	(Bag 6)	0.28	0.28

TEST MATRIX

Vehicle #	Fuel	FTP	SFTP	Cold FTP	WOT	Speciation
RamVan A	RFA	1	1	1	1	1
	RFG	2	2	2	1	1
RamVan B	RFA	2	2	2	1	1
	RFG	1	1	1	1	1
RamVan C	CNG	1	1	1	1	1
RamVan D	CNG	2	2	2	1	1
CrownVic E	RFA	1	1	1	1	1
	RFG	2	2	2	1	1
GrandMar F	RFA	2	2	2	1	1
	RFG	1	1	1	1	1
CrownVic G	CNG	2	2	2	1	1
CrownVic H	CNG	1	1	1	1	1
Caravan I	RFA	1	1	1	1	1
	RFG	2	2	2	1	1
Caravan J	RFA	2	2	2	1	1
	RFG	1	1	1	1	1
Caravan K	CNG	2	2	2	1	1
Caravan L	CNG	1	1	1	1	1

DATA COLLECTION

- THC, NMHC, CO, NOx, CO_2, and CH_4 Emissions
- Fuel Economy
- Speciation Data
  - NMOG Emissions
  - Benzene, 1,3-Butadiene, Formaldehyde, and Acetaldehyde Emissions
- Other HC species
- Real Time Data (for WOT only)
  - THC, CO, NOx and CO_2 Emissions
  - Catalyst Temperature and Efficiency

REACTIVITY-ADJUSTED NMOG EMISSIONS CALCULATION

- The reactivity-adjusted NMOG was calculated based on the measured NMOG emissions, the specific reactivity (MIR) of the exhaust emissions, and the specific reactivity for RFG assigned by CARB

REACTIVITY-ADJUSTED NMOG EMISSIONS CALCULATION

EXAMPLE: CARAVAN FTP

	RFA	RFG	CNG
NMOG (g/mile)	0.179	0.153	0.009
Specific Reactivity (gO_3/gNMOG)	3.963	3.827	0.022

CARB's Specific Reactivity for RFG is 3.13 gO_3/gNMOG[1]

Therefore:

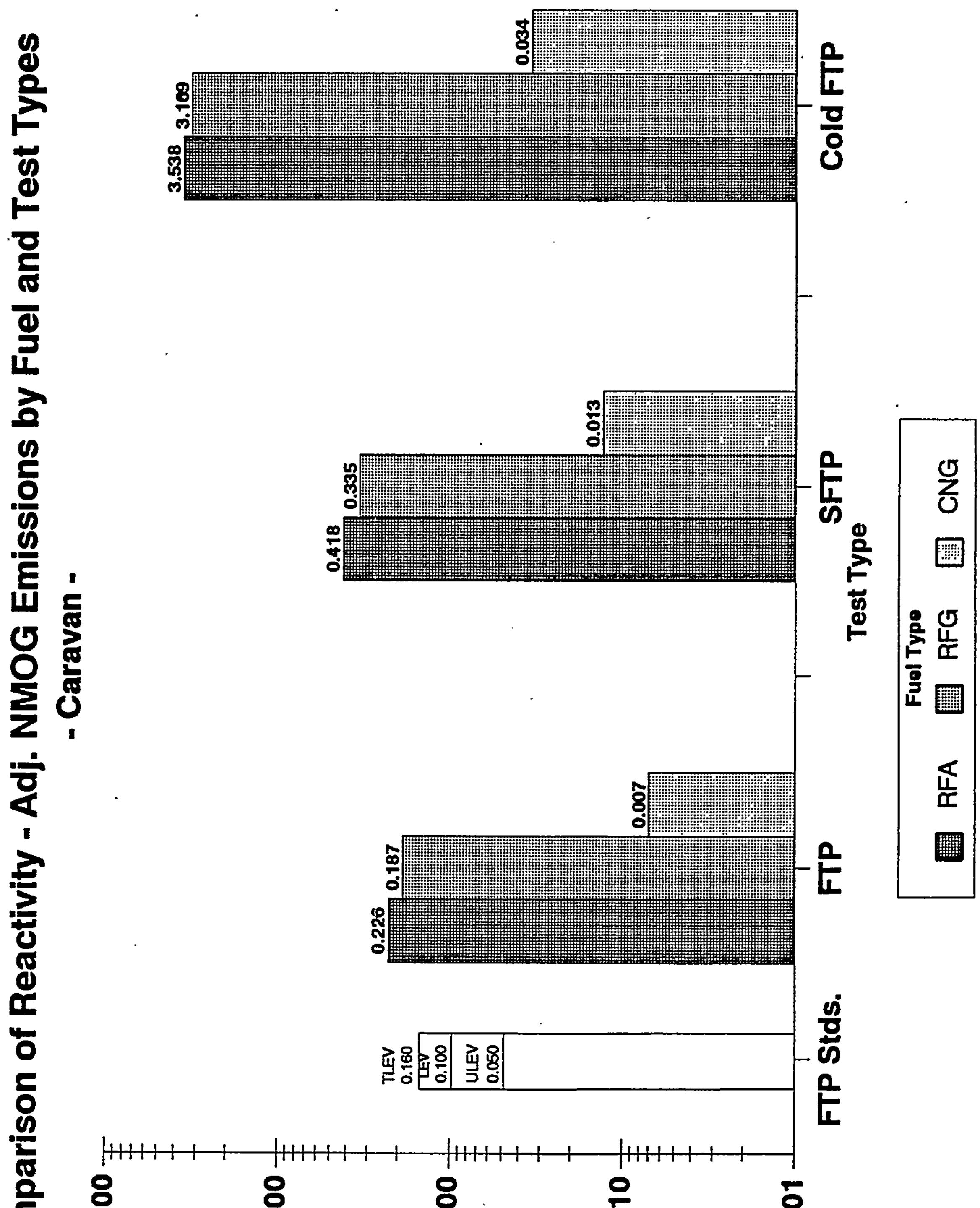
The Reactivity-Adjusted NMOG is

RFA: 0.179*3.963/3.13 = 0.226

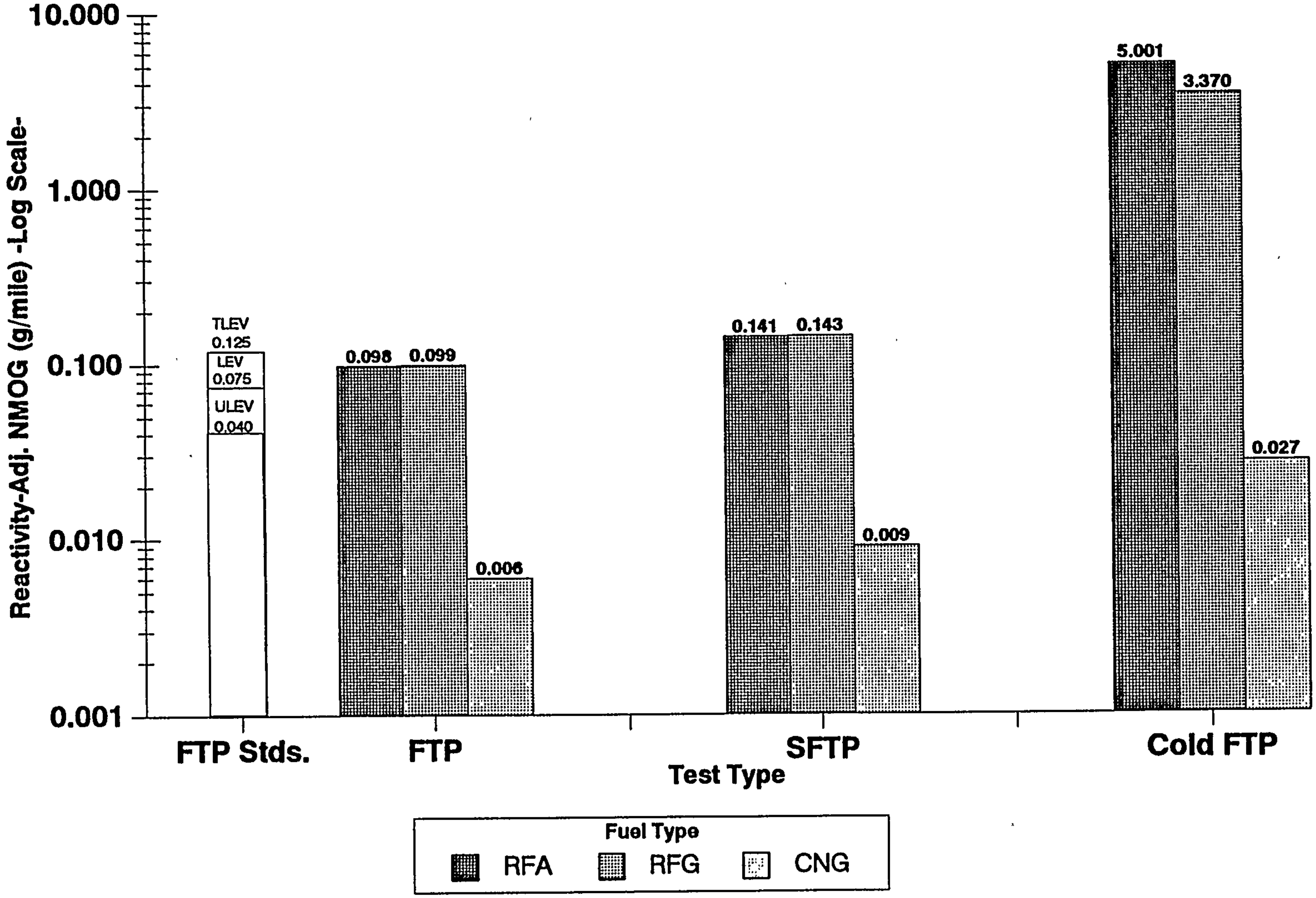
RFG: 0.153*3.827/3.13 = 0.187

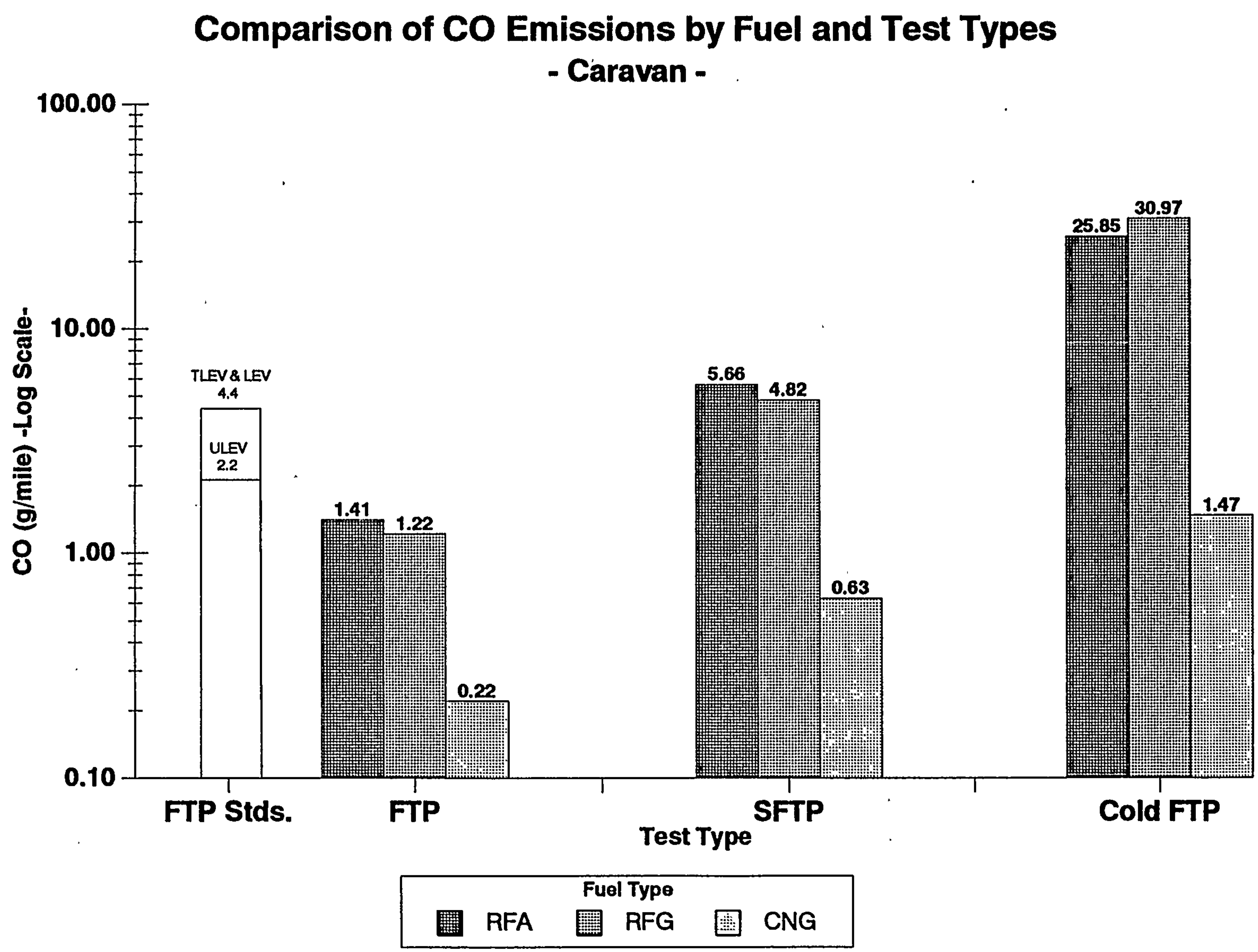
CNG: 0.009*2.417/3.13 = 0.007

[1] Reactivity Adjustment Factors, CARB 1993


Comparison of Reactivity - Adj. NMOG Emissions by Fuel and Test Types
- Caravan -
Reactivity - Adj. NMOG (g/mile) -Log Scale-
10.000
1.000
0.100
0.010
0.001
TLEV 0.160
LEV 0.100
ULEV 0.050
0.226
0.187
0.007
0.418
0.335
0.013
3.538
3.169
0.034
FTP Stds.
FTP
SFTP
Cold FTP
Test Type
Fuel Type
RFA
RFG
CNG

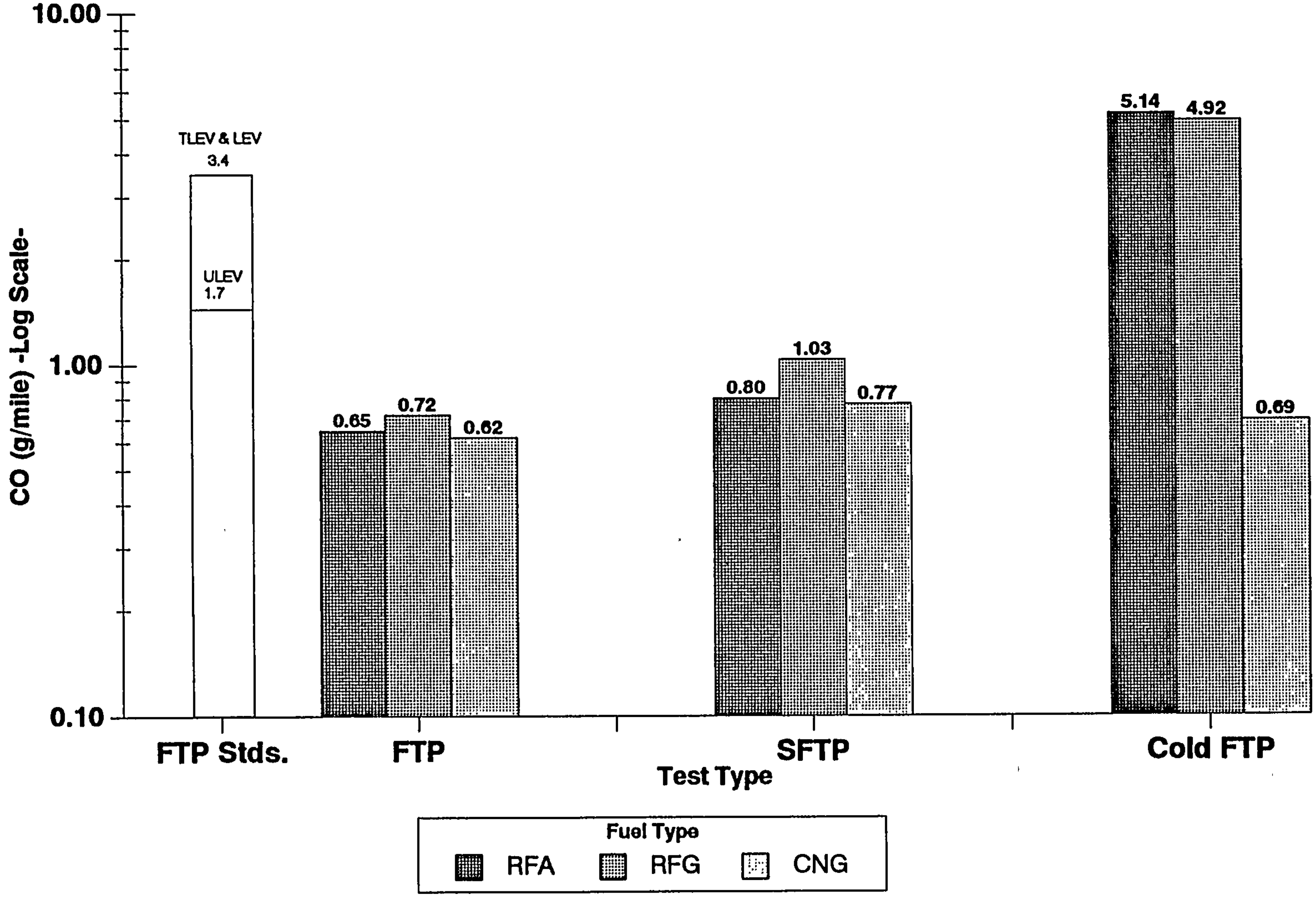
Comparison of Reactivity - Adj. NMOG Emissions by Fuel and Test Types
- Crown Victoria -

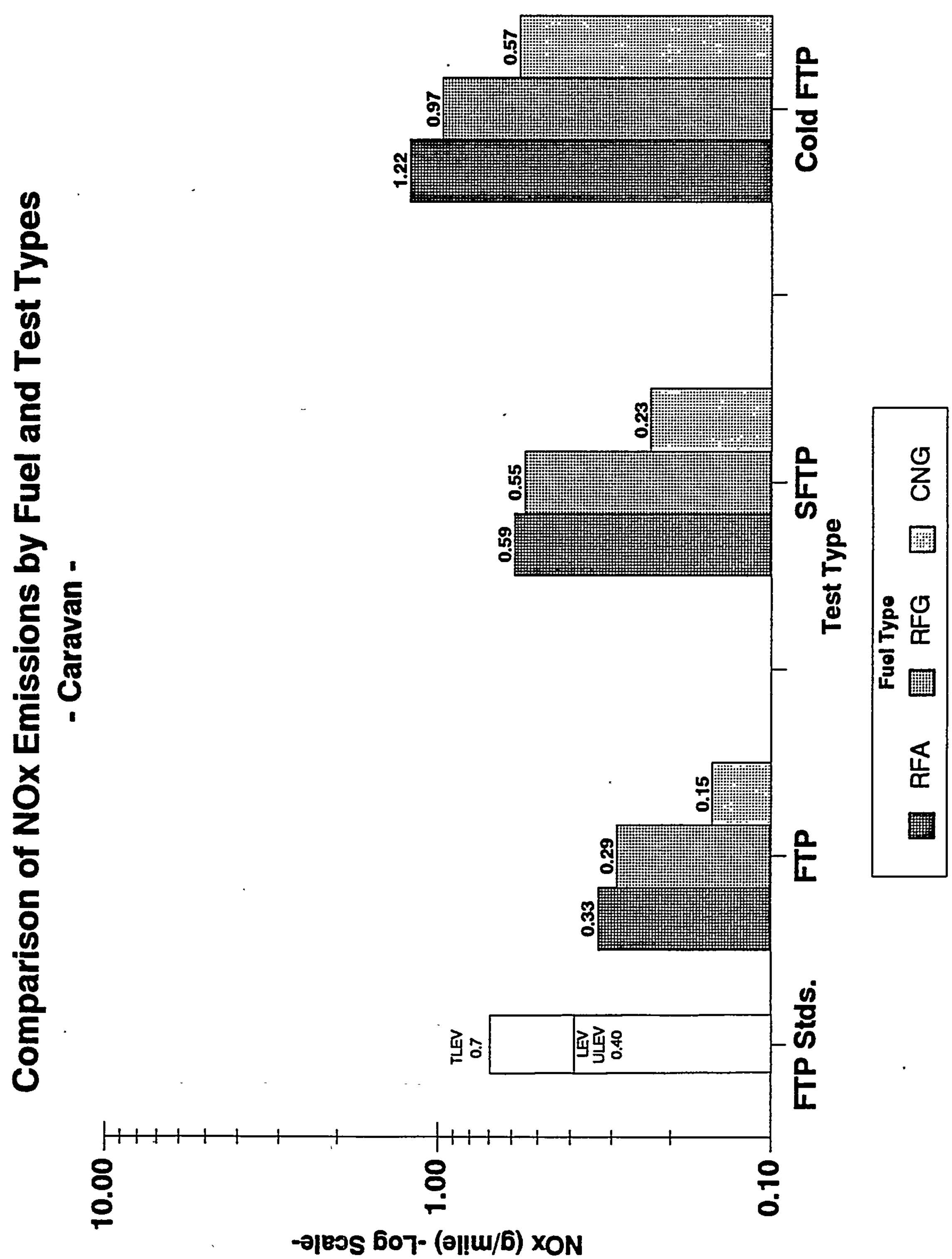


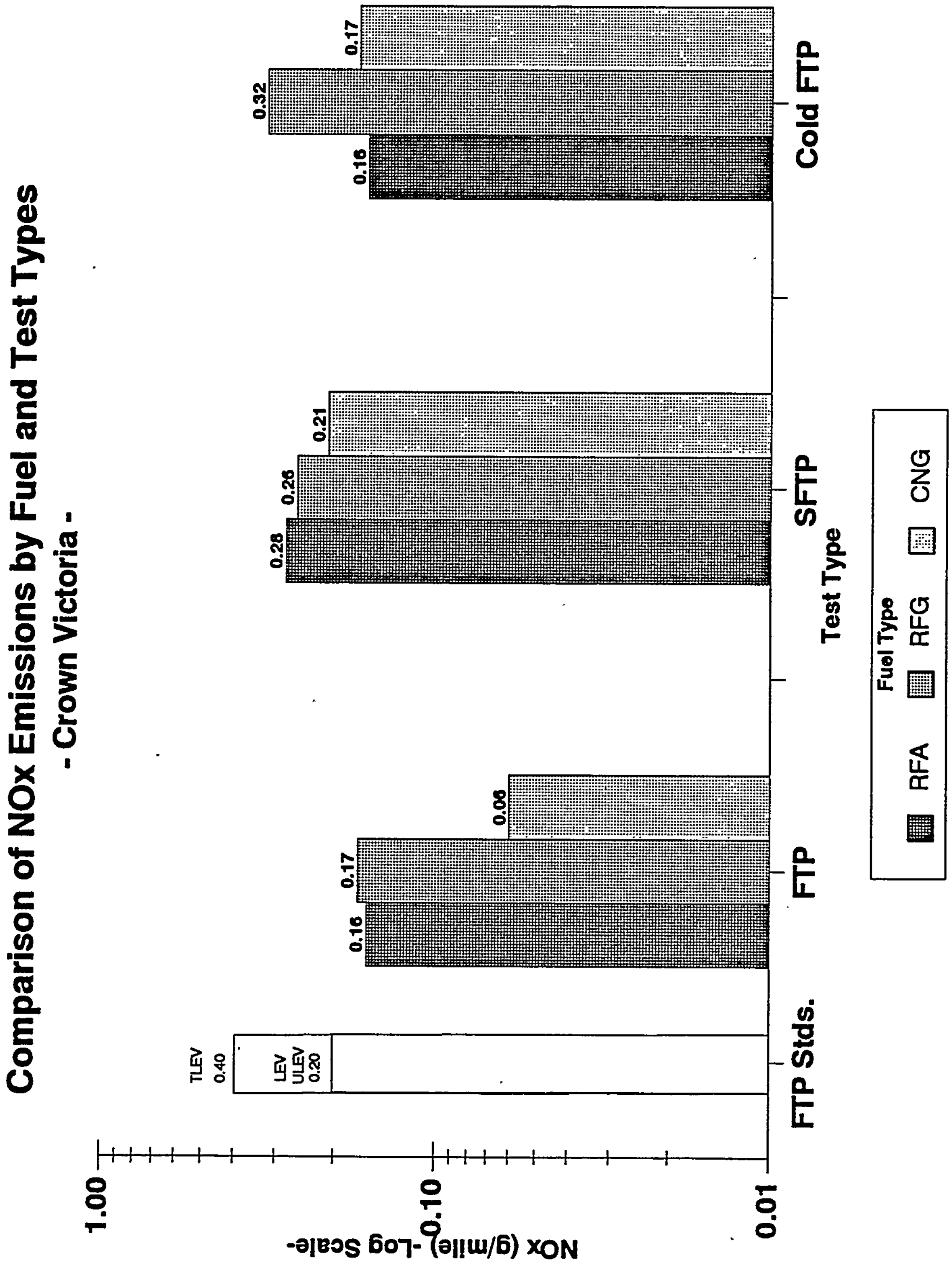


Comparison of CO Emissions by Fuel and Test Types
- Caravan -
CO (g/mile) -Log Scale-
100.00
10.00
1.00
0.10
TLEV & LEV
4.4
ULEV
2.2
1.41
1.22
0.22
5.66
4.82
0.63
25.85
30.97
1.47
FTP Stds.
FTP
SFTP
Cold FTP
Test Type
Fuel Type
RFA
RFG
CNG

Comparison of CO Emissions by Fuel and Test Types
- Crown Victoria -




Comparison of NOx Emissions by Fuel and Test Types
- Caravan -
NOx (g/mile) -Log Scale-
10.00
1.00
0.10
TLEV
0.7
LEV
ULEV
0.40
0.33
0.29
0.15
0.59
0.55
0.23
1.22
0.97
0.57
FTP Stds.
FTP
SFTP
Cold FTP
Test Type
Fuel Type
RFA
RFG
CNG



Comparison of NOx Emissions by Fuel and Test Types
- Crown Victoria -
NOx (g/mile) -Log Scale-
1.00
0.10
0.01
TLEV
0.40
LEV
ULEV
0.20
0.16
0.17
0.06
0.28
0.26
0.21
0.16
0.32
0.17
FTP Stds.
FTP
SFTP
Cold FTP
Test Type
Fuel Type
RFA
RFG
CNG

TOXICITY-WEIGHTED TOTAL TOXIC EMISSION CALCULATION

- The toxicity-weighted (benzene eqv.) total toxic emissions were calculated from the measured toxic emissions and relative toxicity factors taken from an EPA study[1]
- Toxicity factor was normalized to that of benzene

[1] Motor Vehicle-Related Air Toxic Study, EPA 1993

TOXICITY-WEIGHTED TOTAL TOXIC EMISSIONS CALCULATION

EXAMPLE: CARAVAN FTP

Toxic (mg/mi)	RFA	RFG	CNG	Risk Factor	Weight Factor
Benzene	6.980	4.610	0.070	30.000	1.000
1,3-butadiene	1.070	0.900	0.000	1013.000	34.200
Formaldehyde	3.375	3.790	1.170	46.000	1.600
Acetaldehyde	0.815	0.720	0.080	8.000	0.300

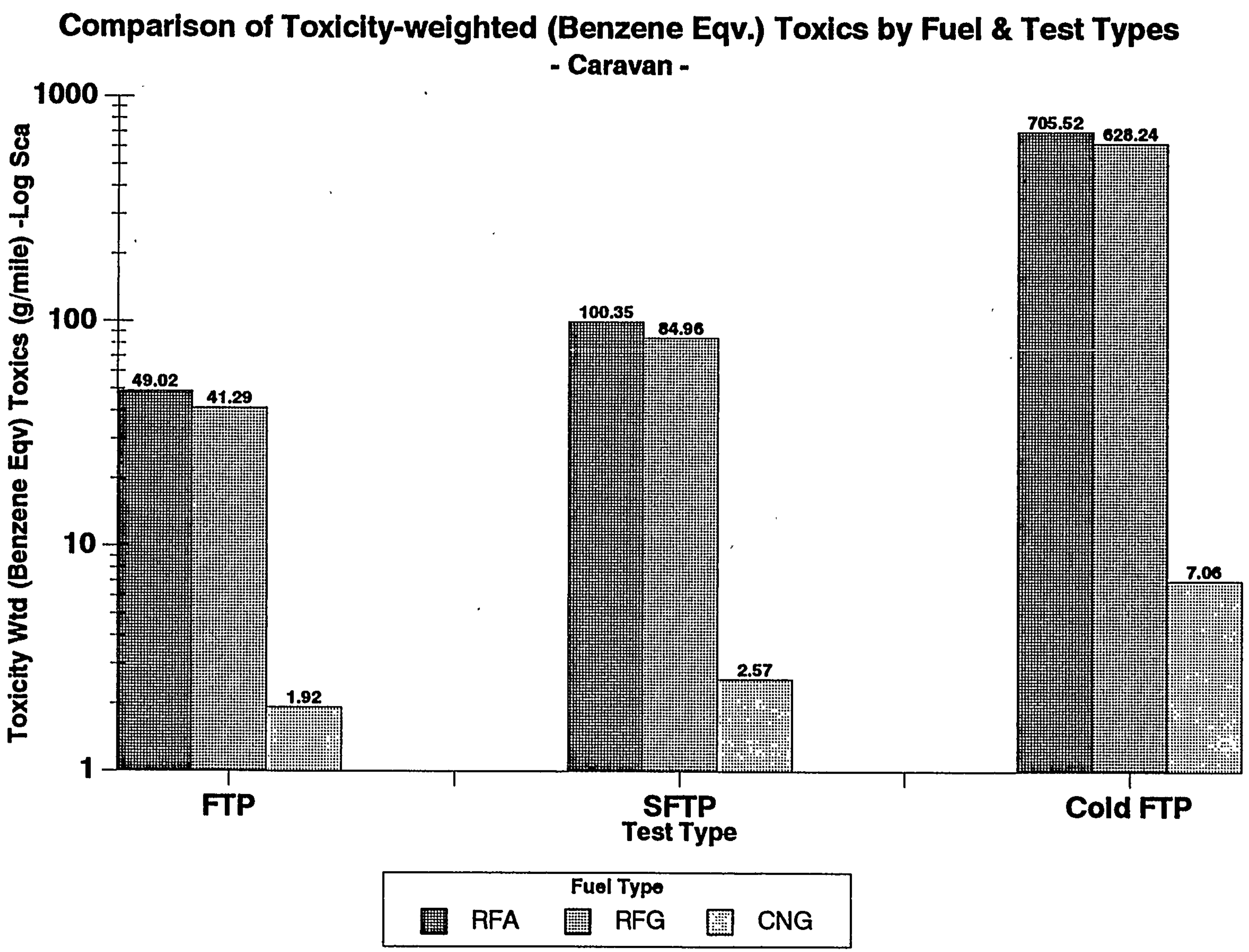
Therefore:

The Toxicity-Weighted (Bezene Eqv.) Total Toxic Emissions is:

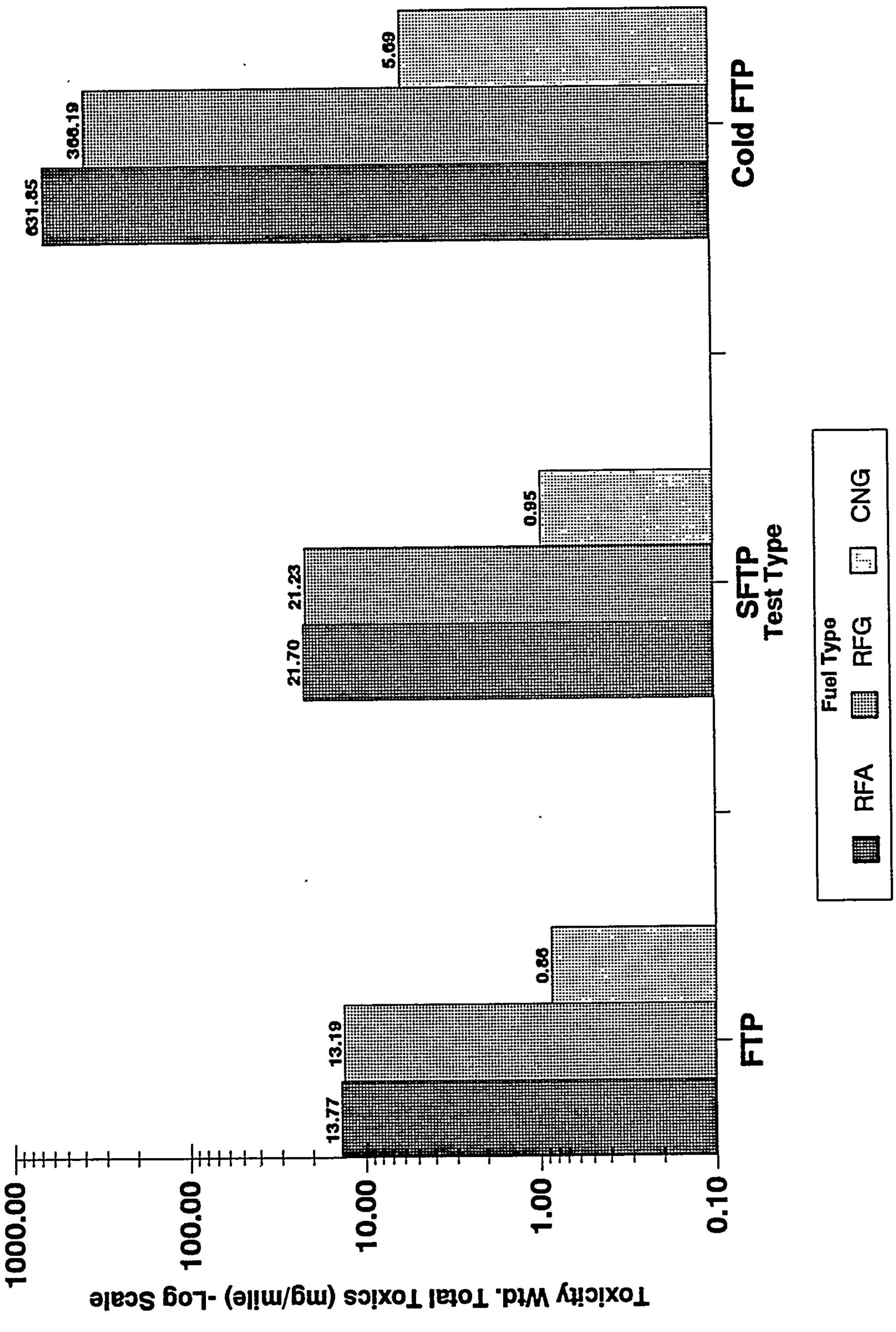
RFA: 6.980*1.0 + 1.070*34.2 + 3.375*1.6 + 0.815*0.3 = 49.02 mg/mi

RFG: 4.610*1.0 + 0.900*34.2 + 3.790*1.6 + 0.720*0.3 = 41.29 mg/mi

CNG: 0.070*1.0 + 0.000*34.2 + 1.170*1.6 + 0.080*0.3 = 1.92 mg/mi


Comparison of Toxicity-weighted (Benzene Eqv.) Toxics by Fuel & Test Types
- Caravan -
Toxicity Wtd (Benzene Eqv) Toxics (g/mile) -Log Sca
1000
100
10
1
49.02
41.29
1.92
100.35
84.96
2.57
705.52
628.24
7.06
FTP
SFTP
Cold FTP
Test Type
Fuel Type
RFA
RFG
CNG

Comparison of Toxicity-weighted (Benzene Eqv.) Toxics by Fuel and Test Ty
- Crown Victoria -



OBSERVATIONS

- Significant emission benefits for NGVs on FTP and real driving conditions
- Emission benefits from RFG fuel compared to RFA fuel were modest compared to CNG
- OEM gasoline vehicles are getting cleaner as a result of tightening emission standards

REMAINING WORK

- Complete testing on the last test vehicle (CNG Ram Van) and present the results on this vehicle group
- Analyze and compare unregulated pollutants from speciated data
- Analyze and compare composite and real time data for WOT condition
- Issue final report in August 1996 (Report #: GRI-96/0217)